

“DUNĂREA DE JOS” UNIVERSITY OF GALAȚI



DOCTORAL DISSERTATION

CONTRIBUTIONS TO THE OPTIMAL CONTROL OF WIND ENERGY CONVERSION SYSTEMS

by

Iulian MUNTEANU

under the scientific supervision of

Prof. Dr. Eng. Emil CEANGĂ



— 2006 —

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TEZĂ DE DOCTORAT

CONTRIBUȚII PRIVIND CONDUCEREA OPTIMALĂ A SISTEMELOR DE CONVERSIE A ENERGIEI EOLIENE

Doctorand: Iulian MUNTEANU

Conducător științific: Prof. Dr. Ing. Emil CEANGĂ

“My grandfather once told me that there are two kinds of people: those who work and those who take the credit. He told me to try to be in the first group; there was less competition there.”

Indira Gandhi

FOREWORD

This work has started at “Dunărea de Jos” University of Galați, Romania, following the preoccupation for wind energy conversion research area of Professor Emil CEANGĂ. I thank him for accepting the scientific supervision of this work from the moment he directed my activity towards the problems concerning wind turbines control. His guidelines and ideas, shared with me in the allocated precious little time, have made as result the fact that I have something to say in WECS control today. I thank Professor CEANGĂ for his advice and orientation and for the scientific support he gave to me all along my doctoral studies.

My sincere thanks are also going to Miss Antoneta BRATCU, Associate Professor at “Dunărea de Jos” University of Galați, for her good companionship, instruction, and advice on my entire work. She has taught me almost everything I know in automatic control and showed me how to solve rigorously a control problem, to write a scientific paper and generally how to disseminate my work. I also thank her for her efficient contribution at the realisation of this work, for her scientific and moral support all along my Ph.D. training period.

These people, Professors Emil CEANGĂ and Antoneta BRATCU have replaced an entire doctoral school system which consider the Ph.D. training as a very personal business and which has never normally functioned at “Dunărea de Jos” University of Galați from my – that is, a Ph.D. student – point of view. If some results concerning this work have ever been obtained, this is due mostly to their enthusiasm and altruism, professionalism and contumacy.

I wish to thank my colleague Nicolas CUTULULIS, who did a fine job in building a real time wind turbine simulator, that is, a good platform for real time experimenting some of the control approaches presented in this work. Our collaboration has given very good results.

I thank Professor Laurențiu FRANGU, head of the department where I have worked as a teacher during these years. His comprehension for the necessity of having extra time for scientific activities has accelerated these scientific results to be obtained and published.

My thanks go also to Professor Daniel ROYE from the prestigious Laboratoire d'Électrotechnique de Grenoble at the Institut National Polytechnique de Grenoble, France, for having accepted the scientific supervision of the three doctoral stages that I had at the above mentioned laboratory in these years of Ph.D. training.

I also thank Professor Seddik BACHA and Dr. Joël GUIRAUD from the same laboratory for their precious and also very competent scientific and technical support that they have friendly provided me with along my doctoral stages at the above mentioned laboratory.

My thoughts go to my colleagues and especially to Mr. Dan DULMAN, who by their aid, encouragement, kindness and good mood have backed me to the end of this work.

I could not finish this foreword without thanking my wife, Nicoleta, for her love, support, comprehension confidence and patience, which were precious ingredients of my success. I am also thankful to my brother, Cosmin, to my parents and to my parents-in-law, for having sustained me in all ways possible all along my doctoral studies.

Let all those who, from near or far, have contributed at the realisation of this work, find here the expression of my profound gratitude.

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LIST OF SYMBOLS, NOTATIONS AND ABBREVIATIONS

Wind power system

Aerodynamic subsystem and drive train

v, v_s, v_t	– total, steady-state and turbulence wind speed [m/s]
ρ	– air density [kg/m ³]
I_t, L_t	– turbulence intensity [–] and length [m]
Ω_l, Ω_h	– rotational speed of a wind turbine's rotor (low speed shaft), respectively of the high speed shaft [rad/s]
R	– blade length of a wind turbine [m]
$A = \pi \cdot R^2$	– swept area by the rotor's blades [m ²]
λ, λ_{opt}	– tip speed ratio of a wind turbine and its optimal value [–]
v_S, v_n, v_M	– cut-in, rated and respectively cut-out wind speed corresponding to a wind turbine [m/s]
P_{air}	– total power of a delimited moving mass of air [W]
P, P_{em}	– generated active power and respectively generator's mechanical power [W]
P_{wt}, P_n	– harvested and respectively rated power of a wind turbine [W]
$C_p, C_{p_{max}} \equiv C_{p_{opt}}$	– power coefficient of a wind turbine and its maximum value [–]
Γ_{wt}, Γ_h	– torque of a wind turbine's rotor (low speed shaft) and respectively high speed shaft [N·m]
P_{opt}	– maximum captured power from wind [W]
$\Gamma_{opt} = \Gamma_{wt}(\lambda_{opt}, v)$	– wind torque corresponding to the optimal tip speed ratio [N·m]
$C_\Gamma, C_{\Gamma_{max}}$	– torque coefficient of a wind turbine and its maximum value [–]
$C_{\Gamma_{opt}} = C_\Gamma(\lambda_{opt})$	– torque coefficient corresponding to λ_{opt} [–]
J_{wt}	– inertia of a wind turbine's rotor
i	– gear box (drive train) ratio [–]
K_s, B_s	– drive train stiffness [N·m] and respectively dumping [N·m·s]
η	– drive train efficiency [–]
Γ	– drive train torsional torque [N·m]

Induction generator

J_g	– generator's shaft inertia [kg·m ²]
-------	--

Γ_G	– generator's torque [N·m]
p	– number of pole pairs
V_S, V_R	– stator and respectively rotor RMS voltage [V]
i_S, i_R	– stator and respectively rotor current [A]
Φ_S, Φ_R	– stator and respectively rotor flux [Wb]
R_S, R_R	– stator and respectively rotor winding resistance [Ω]
L_S, L_R, L_m	– stator, rotor and respectively mutual winding inductance [H]
ω_S, ω_R	– stator (synchronous) and respectively rotor frequency [rad/s]
ω	– rotational speed in electrical rad/s
θ_S, θ_R	– stator and respectively rotor flux vector position [°]
σ	– leakage factor [–]

Modelling

s	– Laplace operator
j	$\sqrt{-1}$
$\dot{x}$	– time derivative of x [units of x / s]
x^*	– reference value for x variable [units of x]
$\bar{x}$	– value of a variable in a given static operating point [units of x]
$\Delta x = \bar{x} - x$	– variation around the static operating point $\bar{x}$ [units of x]
$\overline{\Delta x} = \Delta x / \bar{x}$	– normalized variation around the static operating point $\bar{x}$ [–]
$\sigma(x)$	– standard deviation of x
$S_{xx}(\omega)$	– spectral power density of x
$e(t)$	– white noise
$E\{x\}$	– expectation of x
T_w	– time constant of a low pass shaping filter [s]
γ	– torque parameter of a wind turbine [–]
J_l	– equivalent inertia rendered at the low speed shaft [kg·m ²]
J_h	– equivalent inertia rendered at the high speed shaft [kg·m ²]
J_T, J_G	– time constants for the wind turbine's linearized model [s]
x_d, x_q	– generator's x variable in (d,q) axis [units of x]
x_a, x_b, x_c	– generator's x variable in (a,b,c) 3-phase system [units of x]
T_G	– time constant describing the equivalent dynamics of the electromagnetic subsystem [s]

Acronyms and abbreviations

AS	– aerodynamic subsystem
BPS	– basic physical system

CS	– control subsystem
DFIG	– doubly-fed induction generator
DFT	– Discrete Fourier Transform
DT	– drive train
EFT	– effector (part of the HIL simulator)
EMS	– electromagnetic subsystem
EPS	– emulated physical system
EPSM	– model of the EPS
FFT	– Fast Fourier Transform
H/V AWT	– horizontal/vertical axis wind turbine
HFL	– high frequency loop
HIL	– hardware-in-the-loop
HILS	– hardware-in-the-loop simulation
HPF	– high-pass filter
HSS	– high speed shaft
IER	– interaction environment
IES	– interaction environment from the HIL simulator
IPS	– investigated physical system
LFL	– low frequency loop
LPF	– low-pass filter
LSS	– low speed shaft
OP	– operating point
OOP	– optimal operating point
ORC	– optimal regimes characteristic
PWM	– pulse width modulation
RTPS	– real time physical simulator
RTSS	– real time software simulator
SCIG	– squirrel cage induction generator
TSC	– tip speed controller
TSR	– tip speed ratio
(V/C S) WECS / WPS – (variable/constant speed) wind energy conversion system / wind power system	

INTRODUCTION

1.1 WIND ENERGY CONVERSION SYSTEMS (WECS) – TRENDS AND PERSPECTIVES

Nowadays, the energy domain faces a triple challenge: how to diminish the negative impact of the profile industry on the environment (climate, eco-equilibrium, etc.), how to face the energy demand's rapid growth (which is expected to double until 2030) and how to provide the electrical energy safely and optimally.

Long term consequences of the energy policy can already be seen. The electrical energy market has recorded structural changes: from oligopoly (reduced number of well-established producers) to a more and more pronounced atomicity (more and more independent producers of comparable competitive levels). Therefore, the structure of the energetic systems evolves to a decentralized production network, composed of many independent producers, of relatively low dimensions, which exploit a variety of energy sources. Among these, those from the renewable energy sources have rapidly grown up, being systematically politically supported.

Renewable energy sources (RES) tap naturally occurring energy flows, including sunlight, geothermal, wind and water movements. In particular, production of electrical energy from wind sources is consistent with the above mentioned trends. Wind has been intensively used along with the mankind's evolution; the wind energy conversion into electrical energy has been for the first time experimented in the XIX-th century. But large scale use of the renewable energies, among them the wind, has been alerted by the international oil crisis from 1972. Wind energy has already become a stable segment of the electrical energy market; it is expected that in the long term, renewable energy technologies have the potential to make a considerable contribution to the total world energy supply.

Like the other clean energy sources, the wind power systems have the advantage of the primary energy being free, abundant and inexhaustible (the wind potential has been estimated at $2.5\text{--}5\cdot 10^{15}$ kWh/year). When facing an energy crisis, wind energy can serve as a leading solution to security of supply, energy independence, rising demand and mitigation of climate change, all of these involving no geo-political risk and no additional infrastructure expenses (like those required by exploration, extraction, refining, etc.). Beneficial social impact can be statistically illustrated by the fact that 1 MW of installed power generates 15-19 work places. Reduced installation, operation and maintenance costs determine a relatively reduced price of the wind produced energy.

A synthetic image of the rapid growth of the total and installed power in 2002 on all continents, as well as prognosis until 2007, according to the German Institute of Wind Energy (DEWI), is presented in table 1.1 [KLUG 03].

	Total Installation End 2002 [MW]	Installed Power in 2002 [MW]	Prognosis until 2007 [MW]
America	5.088	495	13.938
Europe	23.832	6.165	58.632
Asia	2.687	424	7.467
Other continents	432	147	3.282
Worldwide total	32.039	7.231	83.319

Table 1.1 Total and installed power in 2002 and prognosis until 2007 [KLUG 03]

Technology of wind turbines has continuously improved since the 1970s, leading to 84% decrease of the wind generated energy in 2000 versus 1980, and this trend is also valuable today. Integration of wind power systems within energetic systems from the cost viewpoint needs *to increase their efficiency*, namely to reduce the installation, operation and maintenance costs, as well as to increase the power harvested from the wind. Recent studies show that the wind produced energy cost per kWh has already decreased below that of the nuclear energy unitary cost [PARF 05].

Regarding this matter, two main directions may be identified in the technological development of the wind power systems from the 1970s until today:

- increasing their rated power [QUAR 98] and
- increasing their flexibility by applying *new control paradigms* – e.g. *variable speed operation* [THRE 98].

According to [ACKE 00], by the end of 1989 the greatest technological advance was considered the 300 kW wind turbine having a 30 m diameter rotor, although megawatt turbines were already being tested. In the mid 1990s, many producers were already offering 600 kW class wind turbines. Five years later, 1.5 MW turbines having about 65 m diameter rotor were available. In 2002 and 2003 experiments on 3–4 MW prototypes have been started and nowadays one can find turbines of more than 4 MW. This evolution, together with prognosis until 2007, is illustrated in figure 1.1 (DEWI – [KLUG 03]).

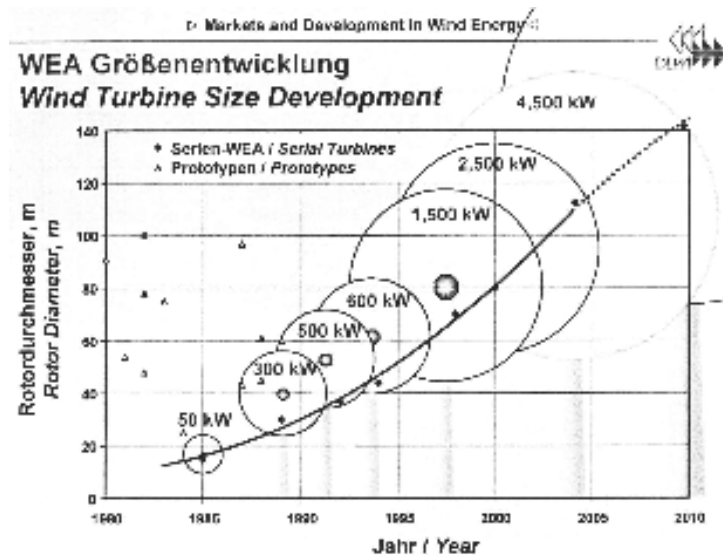


Fig. 1.1 Evolution of the rated power of WECS and prognosis until 2007 [KLUG 03]

Future wide scale use of WECS will probably depend mainly on the costs of the other options of producing electrical energy, as well as on the public opinion, and will not be necessarily influenced by the already mature development of the wind turbines technology. There are still some research directions whose exploration can generate technological advance for increasing the wind energy potential [ECCR 05a], [WWW1 06]; among these, the main can be resumed as follows:

- advanced rotor development by using new materials, in order to increase reliability;
- site-specific design;
- generator, drive train and power electronics efficiency improvements, in order to increase the quality of the provided power;
- systems and controls for growing the energetic efficiency and reducing the operation and maintenance costs.

The increasing in size/rated power of WECSs, the significant wind energy penetration in power systems and

the continuous competition with the other types of energy sources determine a variety of problems, pushing the technological advance of the WECS associated control systems. These systems have known a considerable growth in the last years, taking into account their positive impact on the wind turbines' efficiency; this latter may be synthetically expressed by two aspects: the provided energy quantity and its quality, respectively. Quantity can be grown either by increasing the reliability – a goal is now to double the lifetime from 10 to 20 years – or by implementing a suitable control, whereas quality requirements are grouped together into standards. Studies indicate that these are not trivial tasks, given the stochastic nature of wind; generally, the control strategies have to be designed to meet two seemingly conflicting goals — to increase energy capture, yet reduce turbine structural loading. Designing large wind turbines to be long lasting and fatigue-resistant at minimal cost is a difficult task.

Strong research teams focused on the wind energy conversion topics have grown within large laboratories worldwide: National Renewable Energy Laboratory (NREL) in the U.S.A., Wind Turbine Group at the University of Newcastle in Australia, Danish Wind Industry Association and RISØ Laboratory in Denmark, German Institute for Wind Energy (DEWI) and Delft University Wind Energy Research Institute (DUWIND) are some of the best known. Some of the most prestigious professional associations within area are the European Wind Energy Association (EWEA), the American Wind Energy Association (AWEA), the British Wind Energy Association (BWEA), etc.

1.2 BASIC CONCEPTS OF WECS

1.2.1 Principle of wind energy conversion

An air mass m moving with velocity v (wind) has a kinetic energy of $E_c = 1/2 \cdot mv^2$. Supposing that this energy would be fully captured by means of a turning device (**turbine rotor**), normally disposed on the wind speed direction, the total power provided to the device would be:

$$(1.1) \quad P_t = 0.5 \cdot \rho A v^3,$$

where ρ is the air density and A is the section area of the device.

In fact, the wind turbine harvests from the wind a mechanical power, P_{wt} , smaller than the total power, P_t , because of the nonzero wind speed behind the rotor. At its turn, this power is partially transferred to the turbine rotor and transformed into mechanical power, which is further transformed into electrical power by means of an **electrical generator** (figure 1.2).

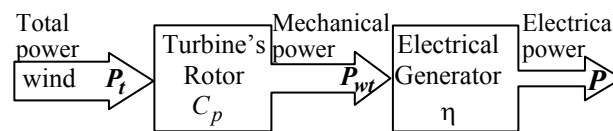


Fig. 1.2 Principle of wind energy conversion

The expression of P_{wt} is obtained according to Rankine–Froude theory of propellers in incompressible fluids, reconsidered by Betz in 1919 [BURT 01]:

$$(1.2) \quad P_{wt} = 0.5 \cdot \rho A v^3 \cdot C_p,$$

where:

$$(1.3) \quad C_p = \frac{P_{wt}}{P_t}$$

is called **power coefficient**, defines the rotor's aerodynamic efficiency and has the maximum theoretical value $C_{p_{Betz}} = 0.593$, which is also called **Betz limit** of the power coefficient [BURT 01].

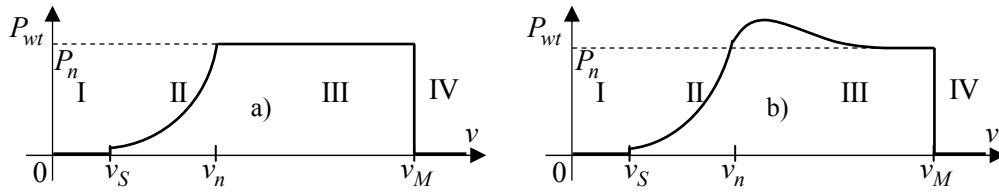


Fig. 1.3 Wind harvested power by a wind turbine versus the (average) wind speed: a) active and b) passive stall regulation

Depending on the wind speed, four zones can be identified on the static characteristic of a wind turbine (figure 1.3) [NICH 95]:

- I – for wind speeds smaller than the cut-in speed (v_S), the wind energy is not sufficient to move on the turbine (the provided power is zero);
- II – the *partial load zone* – speeds larger than the cut-in speed, but smaller than the rated one (v_n) – the extracted power is proportional to the wind speed cubed (zone also called *parabolic*, as to relation (1.2));
- III – the *full load zone* – speeds larger than the rated one (v_n) and smaller than the safe functioning limit, called cut-out speed (v_M) – the harvested power is limited at its rated value (P_n);
- IV – for wind speeds larger than the cut-out speed the provided power becomes zero.

The harvested power limiting (full load region, III on figure 1.3) can be performed in three ways: **pitch regulation**, **active stall regulation** and **passive stall regulation** [BURT 01]. In the first two cases, pitchable rotors within an active power loop for diminishing the aerodynamic efficiency in high winds are used, in order to maintain the harvested power within admissible values (figure 1.3.a)). The (passive) stall regulated turbines, use the (aerodynamic) stall effect – determined by the blade profile in high winds at relatively low rotational speeds – for limiting the power around the rated value (figure 1.3.b)); in this case the blades have fixed pitch.

The turbine's rotor drives (by means of a mechanical transmission, also called **drive train**) an electrical machine (generator), which transforms the mechanical power into electrical power at a non unitary efficiency, denoted by η , based upon the electromagnetic induction phenomenon [LEON 86].

1.2.2 Wind turbines

Wind turbines are realised in two basic configurations, namely **vertical axis wind turbines (VAWT)** and, respectively, **horizontal axis wind turbines (HAWT)**. These latter constitutes more than 95% of the concerned market; they make the object of our study.

type of turbine / functional feature	number of blades	rated speed	reliability	energetic efficiency
optimised for reliability, designed to support great mechanical efforts	≥ 3	low	high	low
energetically optimised, designed to avoid intense loads	1 or 2	large	low	high
optimised for control purposes	2 or 3	medium	results from the trade-off defined by the control goal	

Table 1.2 Basic trends in designing HAWT

Design of HAWT – based upon considering mechanical loads induced by wind – has been oriented according to three basic directions [THRE 98], as illustrated in table 1.2.

It is useful to give a functional taxonomy of the parts within a HAWT, from which the main are presented in figure 1.4; there are three such classes, as follows [BURT 01]:

1. parts of the energy conversion chain, organised into three subsystems:
 - aerodynamic subsystem, consisting in: rotor (composed of blades), turbine's hub (support for blades) and mechanism for varying the blade pitch;
 - drive train, composed of: low speed shaft – coupled with the turbine's hub, speed multiplier and high speed shaft – driving the electrical generator;
 - electric subsystem with: electric generator, elements for grid connection and local grid;
2. control elements: control of the wind harvested power, elements to ensure safe operation and sensors;
3. main auxiliary elements: supporting system, cooling system (for moving parts), braking system, elements for connection to the electrical grid, etc.

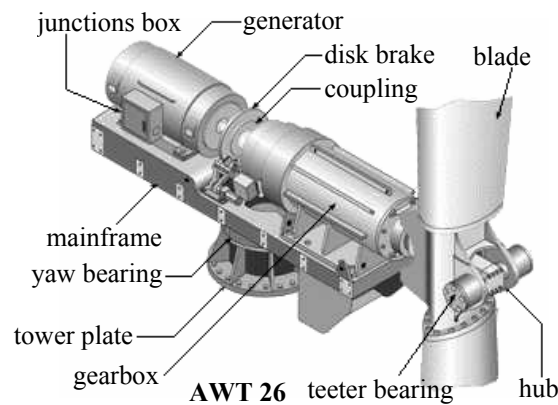


Fig. 1.4 Nacelle of a 2-bladed HAWT [LARW 98]

Operating modes of a WECS depend on the electrical subsystem's configuration. There are three main operating modes depending on the speed variation: **constant** speed, **semi-variable** speed and **variable** speed, which differ as detailed below.

Constant speed operation refers to a wind turbine driving a squirrel cage induction generator directly connected to the grid; the grid frequency (e.g. 50 Hz) imposes that the system turn at a constant speed, within slip limits (2%). This technological solution is cheap, but shafts' rigidity produces fatigue phenomena inside the drive train.

Semi-variable speed operation requires the growth of the generator's (wound) rotor electrical resistance, in order to increase the slip up to 10%. Additional connection systems are necessary for this (for example, collecting systems), which require high maintenance costs.

Variable speed operation corresponds to the situation when the turbine rotor's speed depends on the local wind speed and varies in a large domain ($\pm 50\%$ of the rated speed). Variable speed regime can be put into practice either by (electrically/hydraulically) controlling the blade pitch, or by (speed/torque) controlling the electrical generator. In the case of fixed pitch WECSs, variable speed operation requires the use of a power electronics system, whose main goals are:

- control and conditioning of the power transferred to the grid;
- wind harvested power's maximisation;
- alleviation of intense mechanical loads.

1.2.3 Wind energy conversion efficiency. Aspects of economic efficiency

When assessing the WECS generated energy cost, one habitually takes into account the gratuity of the primary energy. The main elements influencing this cost are: quantity of wind captured power, availability, operating and maintenance costs, producing and installation costs.

Increasing of the power captured from wind can be obtained by maximising the aerodynamic efficiency for a large range of wind speed variation, which is possible by variable speed operation [LEIT 91] (drive train and generator efficiencies are sufficiently high – between 0.7 and 0.9 – versus the aerodynamic one – having maximum around 0.5).

The **aerodynamic efficiency** is expressed through the power coefficient of the WECS, C_p (relation (1.3)). This latter depends on the so-called **tip speed ratio**, λ , defined as the ratio between the blade peripheral speed and the wind speed:

$$(1.4) \quad \lambda = \frac{\Omega_l \cdot R}{v},$$

where Ω_l is the low speed shaft's (rotor's) rotational speed and R is the blade length. The aerodynamic efficiency, $C_p(\lambda)$, of constant blade pitch turbines has a maximum for a well determined value of the tip speed, λ_{opt} , which is a constant constructive feature for a given wind turbine [BURT 01]. Because of the relatively high frequency random variations of the wind speed, to maintain the maximum value of C_p , denoted $C_{p_{max}} = C_{p_{opt}} = C_p(\lambda_{opt})$ without affecting the WECS reliability is now a challenge in the WECSs' control.

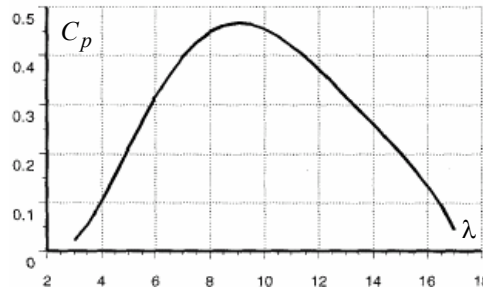


Fig. 1.5 Example of variation $C_p(\lambda)$ (2-bladed wind turbine, 100 kW)

The **availability** of a wind turbine is defined as being the ratio between the time duration under proper conditions and the total operation time; this notion is obviously related to the **reliability**. By increasing the reliability, consisting in reducing the mechanical efforts – possible by variable speed operation [LEIT 91], [THRE 98], [CARL 01], [VIHR 02] – total energy costs can be reduced by reducing the operation and maintenance costs and by increasing the availability. The necessity of reducing the operation costs of the wind turbines requires automatic and remote controlled functioning. An appropriate control strategy allows not only the improvement (maximisation) of the energetic conversion efficiency, but also the improvement of the system's safety and reliability. This is partially reflected in the reduction of the maintenance costs and also in the harvested energy growth (by increasing the number of functioning hours and the captured power from the wind).

As a conclusion, **variable speed** operation of WECS, along with a **suitable control**, make possible the produced energy cost decreasing to a minimum.

The electrical generator energetic efficiency can also be maximized by specific control of the electrical machine, obviously depending on the generation configuration [LEIT 91], while the mechanical transmission efficiency depends mainly on the technology used within.

1.3 CONTROL OF WECS

Taking into account the ideas from the previous paragraph, one can stress out the role and objectives of the WECS control [SALL 90], [LEIT 91], namely:

- starting on the WECS at the cut-in speed, v_S , and stopping it at the cut-out speed, v_M – figure 1.3;
- limiting the wind captured power for speeds larger than the rated one, v_n (full load zone – figure 1.3) – in the contrary case over-sizing of wind turbines would be necessary, in order to extract the whole available power, provided that large wind speeds are seldom encountered (Rayleigh distribution); this later approach is inefficient;
- maximising the wind harvested power in partial load zone (II from figure 1.3); the goal is to drive the rotor at λ_{opt} as long as constraints on speed and captured power are met;
- transferring the electrical power to the grid at an imposed level, irrespectively of the wind speed;
- alleviating the variable loads, in order to guarantee a certain level of resilience for the mechanical parts;
- guaranteeing a desired response to isolated wind gusts;
- meeting certain quality standards for the provided power (power factor, harmonics, flicker, etc.).

The control structure results from defining one or more of the above goals stated in relation with a certain mathematical model of WECS. The controller determines the desired global dynamic behaviour of the system, the total harmonic distortion of the output signal (electrical power) and reduces the disturbances' effect on its output.

There are two main types of control: one affects a pitchable rotor for power limitation in full load regime, and the other varies the torque/speed of the electrical generator for obtaining wide speed range in partial load regime. In the literature various types of controllers (for both of the previously stated control directions) are described, from the simplest (PID) to adaptive or optimal controllers, possibly requiring state observers [BOSS 00].

1.4 SCOPE AND OUTLINE OF THE WORK

The general scope of this work is to study and *to develop control laws for WECS operating at variable speed in the partial load regime*, using various approaches encountered in control systems theory, under given sets of modelling assumptions.

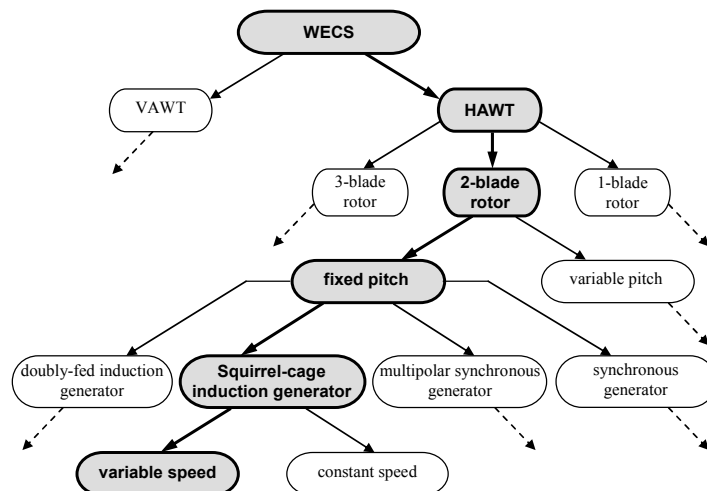


Fig. 1.6 A taxonomy of WECS – identification of the type to be further studied

The object of the control approaches to be presented in this work is a class of low/medium power WECS having *horizontal axis fixed pitch stall regulated 2-bladed* rotor. The mechanical transmission is considered to be a

single stage rigid/flexible speed multiplier. The generation subsystem has a highly reliable three-phased *squirrel-cage induction generator* (SCIG), connected to the electrical grid by means of an AC/AC *power electronics converter*. The WECS is operated at *variable speed* by specific (vector – torque) control of the SCIG; this implies that the AC/AC converter is equipped with corresponding control subsystems. A *higher control level* ensures the operation of the wind turbine in different regimes; the interest is focused here on the partial load regime. The study of the *strategies* embedded within these latter control systems represents the main objective of this work. Figure 1.6 identifies the approached type of WECS within a quasi-general taxonomy.

In this chapter has been presented a general view on the wind energy conversion and on WECSs evolution in the current political and economic context of the market energy; some of the very basic concepts about the wind turbine structures and operating principles and some general objectives concerning their control have also been outlined. The aim of the present work has been stated, along with the type of WECS being the object of the concerned control approaches.

The rest of the work is divided in eight chapters as follows.

The second chapter presents the state of the art in modelling and optimal control of the studied type of WECS in the partial load region and specifies more accurately and more technically the goal of the thesis. Some methodological and practical elements used for a variable speed WECS test rig construction, using hardware-in-the-loop technique, are described in the third chapter. The fourth and fifth chapters present nonlinear control approaches used for harvesting the maximum power available in the wind under different modelling assumptions, namely the maximum power point tracking and the sliding mode control. A novel optimal control structure derived from the frequency separation principle and consisting in two loops for separately processing the wind speed components is introduced in the sixth chapter, as an alternative to previously developed LQ control. Its applications for variable speed WECSs having rigid and flexible drive train are presented in the seventh and the eighth chapter respectively. The final chapter, the ninth, concludes this work by listing conclusion, contributions and future developments.

This work is accompanied by eight appendices, from A to H, containing technical details concerning the approaches developed in each of the first eight chapters.

To facilitate the lecture, an index of figures and an index of terms are placed at the end of this dissertation.

Chapter 2

MODELLING AND SIMULATION OF THE INDUCTION GENERATOR BASED WIND ENERGY CONVERSION SYSTEMS

2.1 GENERAL MODELLING ASSUMPTIONS

The class of variable speed WECSs chosen as object of control strategies to develop in this work has been stated in the previous chapter. The WECS configuration is assumed to conform to the following main specifications:

- two-bladed fixed pitch horizontal axis rotor,
- SCIG equipped with front-end AC/AC power electronics converter,
- connection to a local electrical grid,
- two versions of mechanical transmission: single (fixed) stage rigid and respectively flexible drive trains,
- vector torque control of the generator, ensuring wide range variable speed operation.

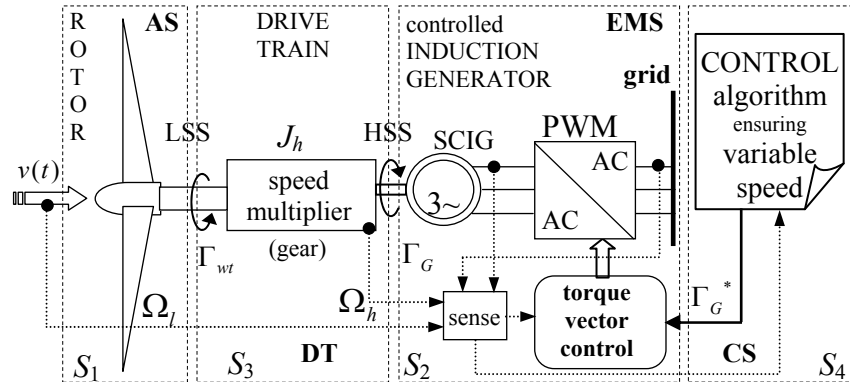


Fig. 2.1 The variable speed controlled WECS – systemic point of view

The structure of the system, visible in figure 2.1 contains three interacting main components, controlled by a fourth one (S_4): the aerodynamic subsystem (AS) – S_1 , the electromagnetic subsystem (EMS) – S_2 and the drive train (mechanical transmission, DT) – S_3 , which will be separately modelled. LSS and HSS denote low and respectively high speed shafts. For the considered class of WECS some generic (and also reasonable) modelling assumptions can be specified:

- the WECS is of low power (up to 10 kW) and its rotor has a teetered hub, so the rotor diameter is sufficiently small in order to neglect the tower effect and structural dynamics of the turbine,
- static and viscous friction are neglected,
- the power coefficient characteristic is fixed, any effects concerning the Reynolds number and air density variations are neglected,
- the nacelle is equipped with a vane, so the wind speed is always normal to the turbine's rotor,
- the system is functioning only in the partial load region (between the cut-in and the rated wind speed); the extreme operating regimes are not of interest in this work,

- the mechanical transmission has a constant efficiency for all speed range; the influence of the constructive features (e.g., vibrations, gear type, gear backlash, etc.) on its behaviour is considered parasitic and will be neglected,
- the influence of the generator's constructive features on its dynamics (e.g., higher harmonics, asymmetries, etc) is neglected and its parameters are constant,
- the WECS can turn at a widely adjustable speed range, whose gradient is bounded, depending on the system's inertia,
- the power converters have unitary efficiency, high order harmonics and their dynamics are neglected; the local electrical grid is ideal and of infinite power,
- the wind speed, HSS rotational speed and electrical power measures are available.

2.2 WIND MODELLING AND SIMULATION

From a systemic point of view, the wind speed represents the main exogenous signal applied to the WECS and determines its behaviour. Its erratic variation, highly dependent on the given wind site and on the atmospheric conditions, make the wind speed quite difficult to model.

Analysis of the wind speed has four main targets, as follows. Long term wind speed variations analysis for a given location is very useful for sitting a wind farm and predicting its output. Systemic analysis of WECS behaviour may require that wind speed dynamic be sufficiently known; moreover, some approaches include the model of the wind speed in the one of the wind turbine [EKEL 97]. Wind speed simulation, necessary for on-line testing the control techniques, claims that wind speed be synthesized according to some suitable models. Finally, the prediction of future values of the wind speed on a given horizon can improve the WECS control performance.

Wind nearby the Earth's surface is generally modelled by a spatial (3D) speed distribution. Considering that the turbine is equipped with a vane (or yawing equipment) and that changes in wind direction are sufficiently slow, then the turbine's rotor is maintained normal to the wind and WECS analysis requires only the longitudinal wind speed's synthesis/modelling. Since the analyzed (low power) WECS class has relatively small-length blades, the spatial wind speed variations along the rotor will be neglected. Thus, in the present work the wind speed will be modelled as a *scalar* (1D) variable. As the interest is here focused on the WECS behaviour in normal operating regimes, the developed models will not include extreme operating conditions like wind shears or gusts.

2.2.1 General wind speed model

Wind dynamics result from combining meteorological conditions with particular features of a given wind site. Thus, wind speed is modelled in literature as a nonstationary random process, yielded by superposing two components [NICH 02]:

$$(2.1) \quad v(t) = v_s(t) + v_t(t),$$

where $v_s(t)$ is the *low frequency component* (describing long term, low frequency variations) and $v_t(t)$ is the *turbulence component* (corresponding to fast, high frequency variations).

The same two components can be identified also in Van der Hoven's large band (six decades) model (figure 2.2). The spectral pause of around 0.5 mHz allows that the turbulence component be modelled as a zero average random process (there is few energy in the spectral range between two hours and ten minutes).

The *low frequency component* corresponds to the very slow wind speed variations and characterizes the wind

site from the energetic viewpoint. It can be modelled as a Rayleigh distribution [LEIT 91]:

$$v_s = a \cdot v \cdot e^{-1/2a\bar{v}^2},$$

where $\bar{v}$ is the wind speed's hourly average and a is a parameter depending on the wind speed's very long term average. The value of this component influences the turbulence amplitude, but its evolution is not crucial for short and medium term dynamic behaviour of WECS.

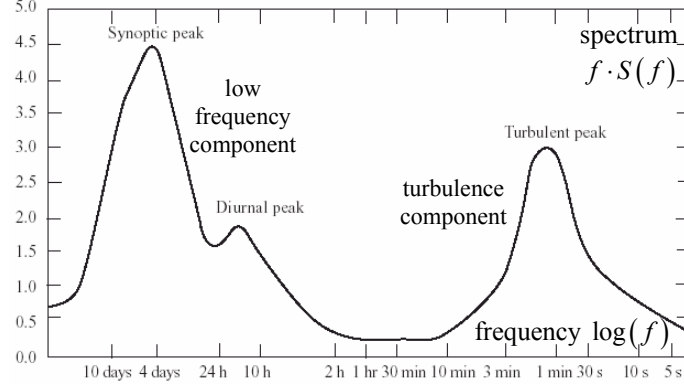


Fig. 2.2 Van der Hoven's spectral model of the wind speed [BURT 01]

Fast wind speed variations (typically occurring within ten minutes) are modelled by the *turbulence component*. This is mathematically described as a zero average normal distribution having a standard deviation, σ , depending on the current value of the hourly average, $v_s(t)$. The *turbulence intensity* is a measure for the global level of turbulence, depends on the ground surface roughness and is defined as:

$$(2.2) \quad I_t = \frac{\sigma}{v_s(t)}$$

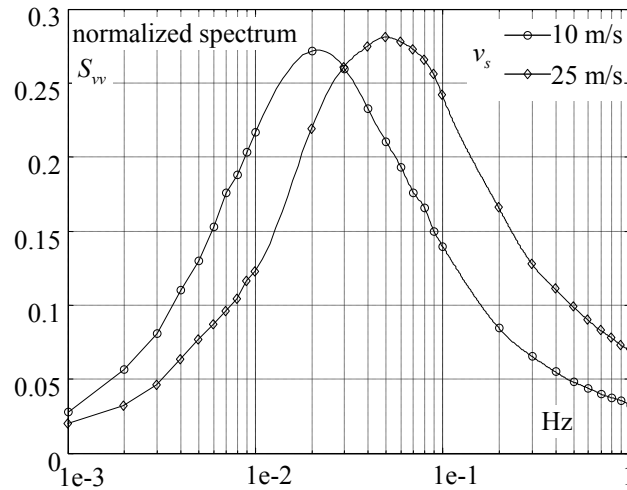


Fig. 2.3 Von Karman's spectra for smooth ground and various v_s [BURT 01]

Mathematical description of the turbulence's dynamical properties, $v_t(t)$, is performed by a variety of spectral models (Eurocode, IEC 1400, DS 472), derived from Kolmogorov fluid dynamics theory. Among these models, Von Karman's is very popular [BURT 01]; it provides the expression of the power spectral density of the wind speed:

$$(2.3) \quad S_{vv}(\omega) = \frac{0.475\sigma^2 L/v_s}{\left[1 + (\omega L/v_s)^2\right]^{5/6}},$$

where L is the turbulence length, specific to the wind site (surface roughness), and ω is the frequency.

Increasing the low frequency (average) wind speed, v_s , and the ground roughness determine the turbulence be increased, that is, a spectral deviation of $v_t(t)$ to large frequency (see figure 2.3); from this results the nonstationary character of this component.

The turbulence component, $v_t(t)$, is usually synthesized by feeding a suitable shaping filter, $H_t(j\omega)$, with a white noise. This procedure is based on the fundamental relation from the linear systems statistical dynamics [DAMP 95]:

$$(2.4) \quad S_{vv}(\omega) = S_{wn}(\omega) \cdot H_t(j\omega),$$

where $S_{wn}(\omega) = \text{constant}$ is the power spectral density of the white noise. Being a natural process, the frequency response of the shaping filter has the following form [WELF 97]:

$$(2.5) \quad H_t(j\omega) = \frac{K_F}{(1 + j\omega T_F)^{5/6}},$$

where parameters K_F and T_F depend on the low frequency wind speed: $T_F = L/v_s$.

This filter can be approximated by a two pole and one zero transfer function [NICH 02]. In the sequel two methods for obtaining sequences of nonstationary wind speed to be further used will be briefly illustrated.

In the first case, the wind speed generation scheme given in figure 2.4 is being used, where the adjustable shaping filter is described by the following expression:

$$(2.6) \quad H_t(s) = K_F \cdot \frac{m_1 T_F s + 1}{(T_F s + 1)(m_2 T_F s + 1)}, \quad m_1 > 0, \quad m_2 > 0$$

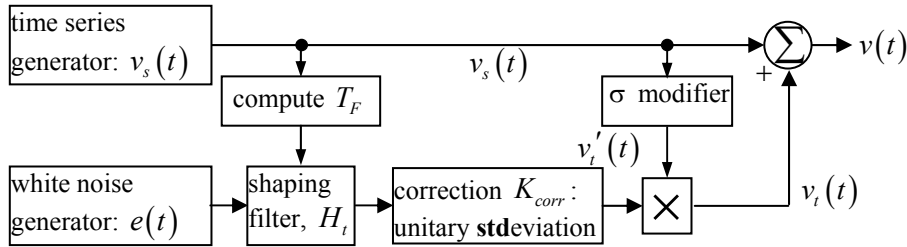


Fig. 2.4 Nonstationary wind speed generation – first approach

Supplementary, the coloured noise suffers a correction such that $v'_t(t)$ has a normalized standard deviation; finally, the turbulence component has a standard deviation imposed by the low frequency component. The time constant, T_F , the turbulence standard deviation, σ , and the filter's parameters can be computed using the turbulence intensity (as site's parameter) and relations provided by a standard (e.g. IEC) [BURT 01], [NICH 02].

A second approach in the wind speed generation employs a global shaping filter, which also includes the low frequency component's model, $H_s(s)$:

$$(2.7) \quad H_f(s) = \frac{\overbrace{K}^{H_s(s)}}{T_s s + 1} (T_0 s + 1) \cdot H_t(s)$$

Its parameters can be determined as follows. Van der Hoven's model provides a *stationary* spectral characteristic, $f \cdot S_{vv}(f)$, which can be parameterized as a transfer function, $G_{dB}(\omega)$, like the one in figure 2.5, for example. Such an operation leads to a shaping filter whose transfer function, $H_f(j\omega)$, meets relation (2.7); by

feeding this filter with a white noise, $e(t)$, one obtains a coloured noise, $v(t)$, whose spectral characteristic approximates $G_{dB}(\omega)$.

The *nonstationary* character of the wind speed (expressed also by figure 2.3) is modelled by modifying the time constant T_0 depending on the low frequency wind speed:

$$(2.8) \quad T_0 = F(v_s),$$

with $F(\cdot)$ being a bounded increasing function [NICH 02]. Figure 2.6 shows how T_0 variation determines the intensity and harmonics content of the turbulence component being changed. By identifying $H_f(j\omega)$ one obtains the reference value of T_0 corresponding to the asymptotic characteristic 1. If v_s grows (characteristic 2), then the shaping filter will output a turbulence component with a larger variance.

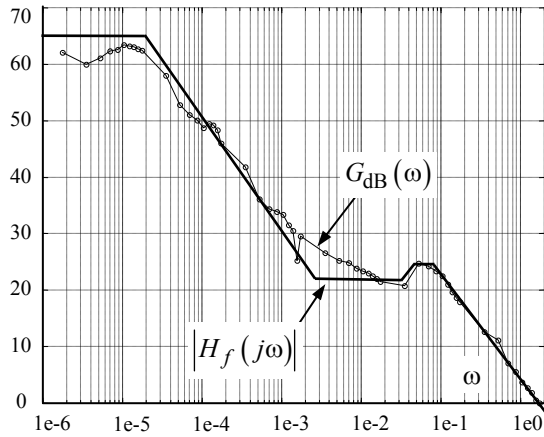


Fig. 2.5 Parameterization of the wind speed's spectral characteristic $v(t)$

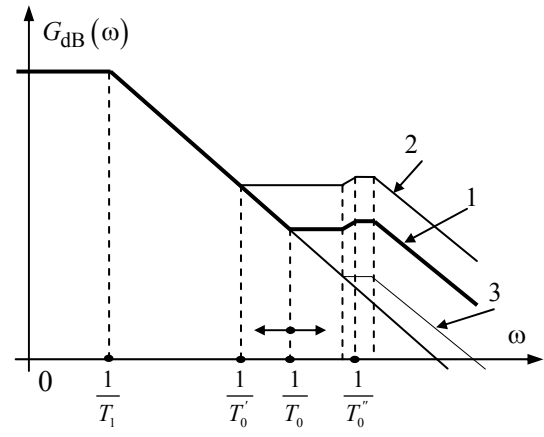


Fig. 2.6 Modifying the spectral characteristic of $v(t)$ by varying T_0

Considering that:

- the usual working wind speed range is quite narrow (4 m/s – 12 m/s), such that the turbulence intensity (relation (2.2)) can be taken as constant,
 - figure 2.6 suggests that T_0 is proportional to the average amplitude of the shaping filter output, therefore with the turbulence standard deviation, σ ,
- then function $F(\cdot)$ may be adopted as linear:

$$(2.9) \quad T_0 = F(v_s) = a \cdot v_s + b,$$

where a and b are deduced by fitting the experimental data collected on the studied wind site in a least squares sense. Concluding, the input-output description of the shaping filter has the form:

$$(2.10) \quad v(t) = K \cdot \frac{T_0}{T} \cdot e(t) + \frac{1}{T_s} \cdot (K \cdot e(t) - v(t)),$$

with T_0 described by relation (2.9).

Thus, the wind speed may be synthesized by using the block diagram from figure 2.7, where the Butterworth low-pass filter having a passing band of 0.01 Hz has been used for separating the low frequency component influencing the time constant T_0 . Value v_0 is a daily average of the wind speed and is taken as constant during the simulation horizon.

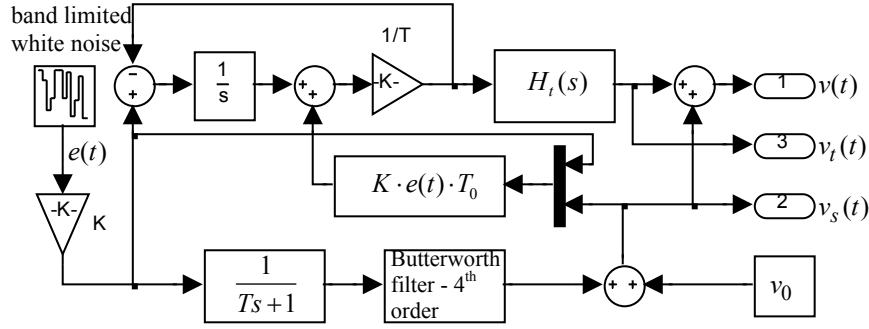


Fig. 2.7 Simulink diagram for wind speed synthesizing – second approach

Remarks:

• Diagram from figure 2.7 can represent the features of a given wind site by adjusting some parameters in the following sense:

- the power of the white noise generator, T and K , emulate the atmospheric conditions,
- parameters of $F(v_s(t))$ model the ground roughness,
- it has been assumed that wind blows mainly on a certain direction, for which the characteristics of ground are constant; therefore, the turbulence intensity, I_t , is also constant.
- Consequently, for the presented model, the turbulence band does not change, but only its amplitude, because only T_0 changes (figure 2.6).

Simulink simulation performed on the diagram from figure 2.7 instantiated with the values given in appendix B (see *nonstationary modelling* section) presents the wind speed evolution on a five hours horizon – figure 2.8a). One can notice the turbulence variance depending on the average wind speed. In figure 2.8b) the medium and long term wind speed component, v_s , and turbulence standard deviation are presented.

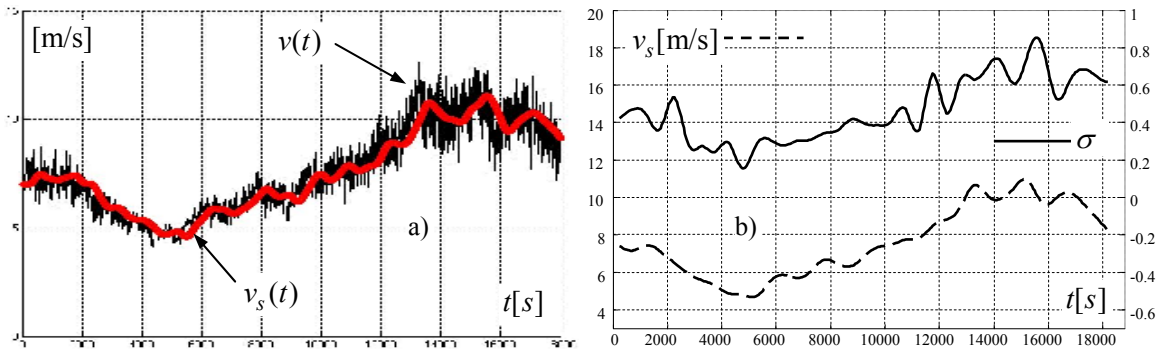


Fig. 2.8 Wind speed evolution (a) and variation of its parameters (b)

2.2.2 Simplified wind speed model

The turbulence model (2.5) may be simplified by adopting an integer (for example, unitary) order shaping filter. Moreover, the stationary component is obtained as the output of a first order filter also. This modelling simplification is justified by focusing on the dynamical aspects (relevant on short term), while neglecting the energetic ones (relevant on long term).

Thus, the wind speed can be synthesized by means of the diagram from figure 2.9, where the input signal is a zero average unitary variance Gaussian white noise. Value v_0 is a daily average of the wind speed and is constant during a simulation time span. Atmospheric conditions are modelled by k and v_0 , whereas the ground roughness by parameters of the two filters.

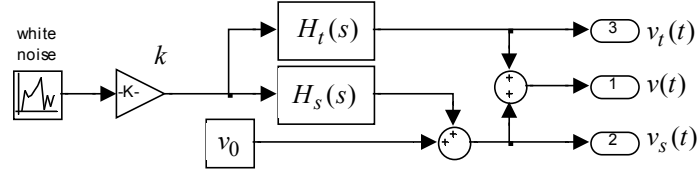


Fig. 2.9 Simplified Simulink diagram for wind speed synthesizing

Simulation performed on the diagram from figure 2.9, using $H_t(s) = \frac{k_t}{T_t s + 1}$ and $H_s(s) = \frac{k_s}{T_s s + 1}$, instantiated with the values given in appendix B (see *stationary modelling* section), presents the wind speed evolution on one hour horizon – figure 2.10a); a detail also including the low frequency component is presented in figure 2.10b).

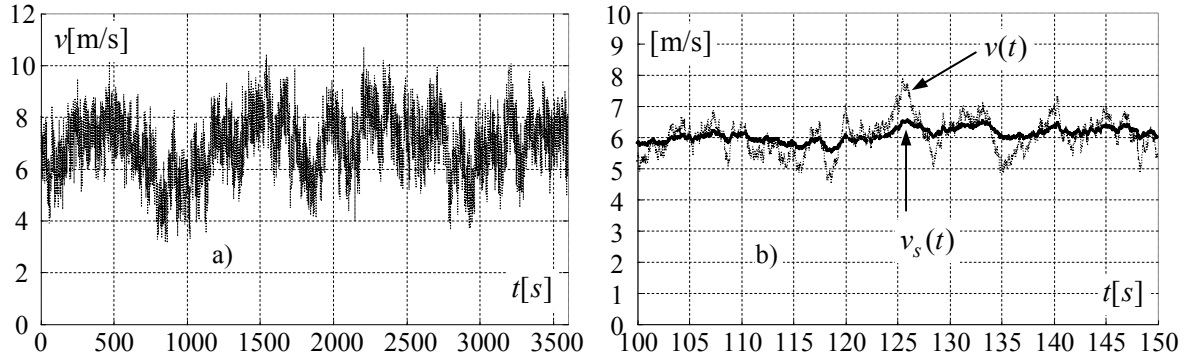


Fig. 2.10 Wind speed evolution

Sometimes the turbulence component must be separately synthesized, as required by the modelling approach to be used for dynamic optimization [EKEL 97]. Hence, a turbulence model may be that of figure 2.11, where $T_w = \frac{L_t}{v_s}$, with L_t being the turbulence length (which models the surface roughness), whereas the atmospheric conditions are modelled by the white noise average power (dispersion). This model may be used in analyzing by simulation the WECSs' dynamical regimes, supposing a constant low frequency component, v_s , in relation (2.1).

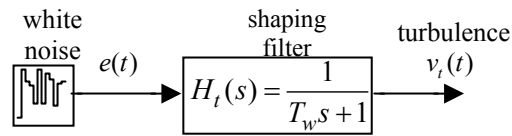


Fig. 2.11 Synthesis of the turbulence wind speed

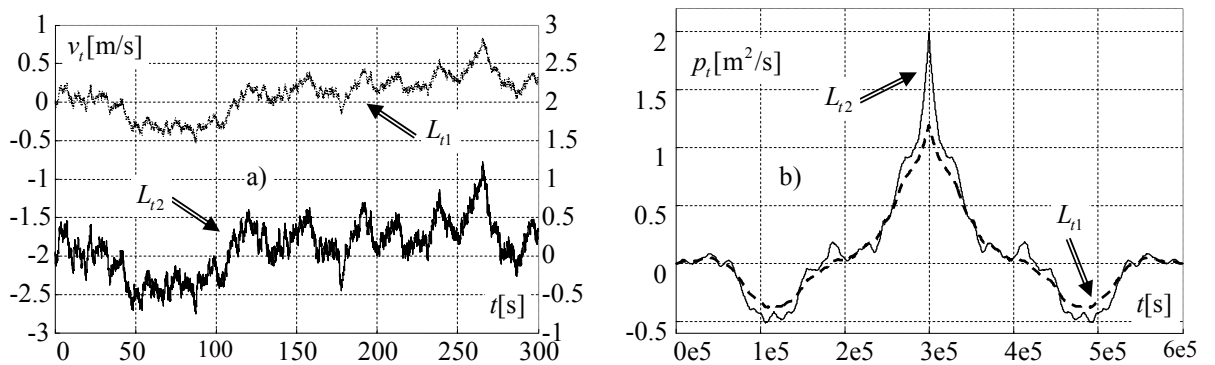


Fig. 2.12 Evolution (a) and autocorrelation (b) of the turbulence component

A five minutes evolution of the turbulence wind speed may be viewed in figure 2.12a), for constant low

frequency wind speed and for two values of the turbulence length, L_{t1} and L_{t2} , given in appendix B. The turbulence power, p_t , obtained by autocorrelation of v_t , is shown in figure 2.12b). One can remark that both turbulence dispersion (maximal value of p_t) and its spectrum too depend on L_t .

2.3 NONLINEAR MODELS OF WECS

This section aims at presenting some basic modelling aspects concerning the various functional parts of WECS. The result consists in a series of models capturing the main phenomena which govern the basic operation of these parts.

2.3.1 Aerodynamics modelling

In this work, the aerodynamic subsystem model describes (by **averaging**) the interaction of the turbine rotor with the air masses (wind); this subsystem is modelled by the mechanical torque provided by the rotor movement [WILK 90], [MILL 03]. Following the previously listed assumptions, for a fixed pitch (β) wind turbine, this torque depends on the low speed shaft rotational speed and on the wind speed:

$$(2.11) \quad \Gamma_{wt} = \Gamma_{wt}(\Omega_t, v) \Big|_{\beta=\text{constant}}$$

According to relation (1.2), one obtains:

$$(2.12) \quad \Gamma_{wt} = \frac{P_{wt}}{\Omega_t} = \frac{1}{2} \cdot \pi \cdot \rho \cdot v^2 \cdot R^3 \cdot C_\Gamma(\lambda),$$

where $C_\Gamma = \frac{C_p}{\lambda}$ is called **torque coefficient**.

More detailed aerodynamic models can be developed, emphasizing the rotational sampling, spatial filtering or induction lag [RODR 98], [VIHR 02], [MOLE 03], leading to a more complex expression of the developed aerodynamic torque, Γ_{wt} . For the chosen low power wind turbines, these effects – together with the structural dynamics – can be neglected, and simplified models are preferred [WILK 90].

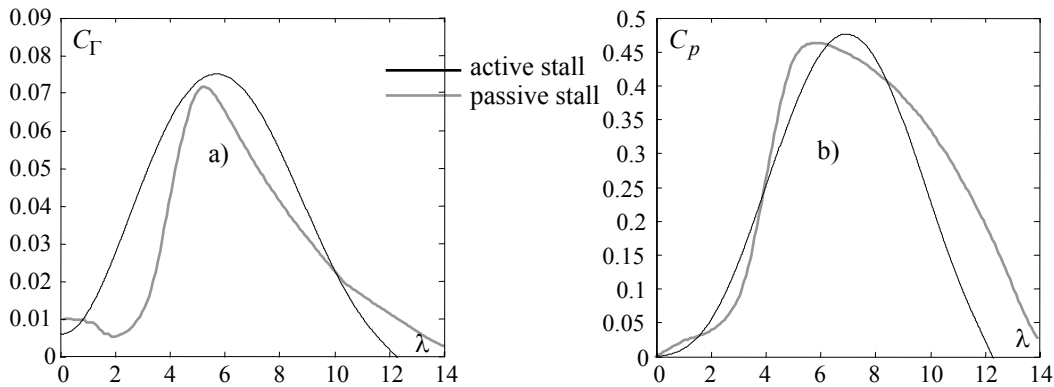


Fig. 2.13 Typical HAWT $C_\Gamma - \lambda$ a) and $C_p - \lambda$ b) curves

The torque coefficient can be described by a polynomial function of the tip speed ratio, λ (figure 2.13a) – [NICH 95], [MILL 03]):

$$(2.13) \quad C_\Gamma(\lambda) = a_6 \cdot \lambda^6 + a_5 \cdot \lambda^5 + a_4 \cdot \lambda^4 + a_3 \cdot \lambda^3 + a_2 \cdot \lambda^2 + a_1 \cdot \lambda + a_0$$

Parameters a_i , $i = 0 \dots 6$, are usually determined by fitting the look-up table representing an experimental torque characteristic in a least squares sense. Typical static C_T and C_p variations with respect to tip speed ratio for two bladed HAWT are given in figure 2.13. Different blade profiles imply different aerodynamic characteristic shapes; for example, in figure 2.13 are depicted $C_T - \lambda$ and $C_p - \lambda$ curves belonging to a passive stall rotor (light) and to an active stall rotor (dark).

The corresponding torque and power characteristics for the active stall rotor with respect to the LSS speed (obtained using relations (1.2) and (2.12)), parameterised by the wind speed, are shown in figure 2.14.

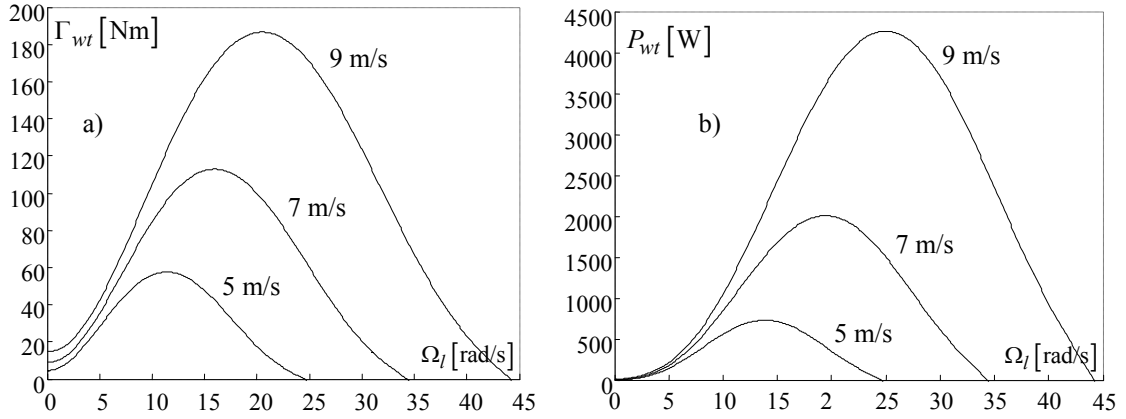


Fig. 2.14 Typical HAWT torque (a) and power (b) characteristics (LSS)

2.3.2 Electrical generator modelling

The electromagnetic subsystem essentially consists in a torque controlled squirrel-cage induction machine, which provides electromagnetic torque. In the adopted modelling assumptions, the SCIG model is expressed in (d, q) frame as [LEON 86]:

$$(2.14) \quad \Gamma_{em} = 3/2 \cdot p \cdot L_m \cdot (i_{Sq} \cdot i_{Rd} - i_{Rq} \cdot i_{Sd}),$$

p being the pole pairs number, L_m the stator-rotor mutual inductance, i_{Sd} , i_{Sq} , i_{Rd} and i_{Rq} are the stator, respectively rotor current's (d, q) components, obtained by integrating differential equations (2.15):

$$(2.15) \quad \begin{cases} \frac{di_{Sd}}{dt} = \frac{V_{Sd}}{L_S} - \frac{R_S}{L_S} \cdot i_{Sd} - \frac{L_m}{L_S} \cdot \frac{di_{Rd}}{dt} + \omega_S \cdot (i_{Sq} + \frac{L_m}{L_S} \cdot i_{Rq}) \\ \frac{di_{Sq}}{dt} = \frac{V_{Sq}}{L_S} - \frac{R_S}{L_S} \cdot i_{Sq} - \frac{L_m}{L_S} \cdot \frac{di_{Rq}}{dt} - \omega_S \cdot (i_{Sd} + \frac{L_m}{L_S} \cdot i_{Rd}) \\ \frac{di_{Rd}}{dt} = \frac{V_{Rd}}{L_R} - \frac{R_R}{L_R} \cdot i_{Rd} - \frac{L_m}{L_R} \cdot \frac{di_{Sd}}{dt} + (\omega_S - \omega) \cdot (i_{Rq} + \frac{L_m}{L_R} \cdot i_{Sq}) \\ \frac{di_{Rq}}{dt} = \frac{V_{Rq}}{L_R} - \frac{R_R}{L_R} \cdot i_{Rq} - \frac{L_m}{L_R} \cdot \frac{di_{Sq}}{dt} - (\omega_S - \omega) \cdot (i_{Rd} + \frac{L_m}{L_R} \cdot i_{Sd}) \end{cases},$$

where:

- $\omega = p \cdot \Omega_h$ is the speed in electrical radians per second (Ω_h is the generator's rotational speed), $\omega_S = d\theta_S/dt$ is the stator field pulsation, R_S , R_R are the stator and rotor resistances, L_S , L_R are the stator and rotor inductances;

- V_{Sd} , V_{Sq} , $V_{Rd} = V_{Rq} = 0$ are the stator, respectively rotor voltage's (d, q) components; also $\Phi_{Rd} = L_R \cdot i_{Rd}$, $\Phi_{Rq} = L_R \cdot i_{Rq}$ are the rotor flux components in (d, q) frame.

By simple calculi, the former equations lead to the following state equation:

$$\begin{bmatrix} \dot{i}_{Sd} \\ \dot{i}_{Sq} \\ \dot{i}_{Rd} \\ \dot{i}_{Rq} \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{\sigma L_S} & \omega_S + \frac{p\Omega L_m^2}{\sigma L_S L_R} & \frac{L_m R_R}{\sigma L_S L_R} & \frac{p\Omega L_m}{\sigma L_S} \\ -\left(\omega_S + \frac{p\Omega L_m^2}{\sigma L_S L_R}\right) & -\frac{R_S}{\sigma L_S} & -\frac{p\Omega L_m}{\sigma L_S} & \frac{L_m R_R}{\sigma L_S L_R} \\ \frac{L_m R_S}{\sigma L_S L_R} & -\frac{p\Omega L_m}{\sigma L_R} & -\frac{R_R}{\sigma L_R} & \omega_S - \frac{p\Omega}{\sigma} \\ \frac{p\Omega L_m}{\sigma L_R} & \frac{R_S L_m}{\sigma L_S L_R} & \frac{p\Omega}{\sigma} - \omega_S & -\frac{R_R}{\sigma L_R} \end{bmatrix} \begin{bmatrix} i_{Sd} \\ i_{Sq} \\ i_{Rd} \\ i_{Rq} \end{bmatrix} + \begin{bmatrix} \frac{1}{\sigma L_S} & 0 & \frac{-L_m}{\sigma L_S L_R} & 0 \\ 0 & \frac{1}{\sigma L_S} & 0 & \frac{-L_m}{\sigma L_S L_R} \\ \frac{-L_m}{\sigma L_S L_R} & 0 & \frac{1}{\sigma L_R} & 0 \\ 0 & \frac{-L_m}{\sigma L_S L_R} & 0 & \frac{1}{\sigma L_R} \end{bmatrix} \begin{bmatrix} V_{Sd} \\ V_{Sq} \\ V_{Rd} \\ V_{Rq} \end{bmatrix},$$

where $\sigma = 1 - \frac{L_m^2}{L_S L_R}$; (2.14) is the output equation and provides a torque characteristic as represented in figure 2.15.

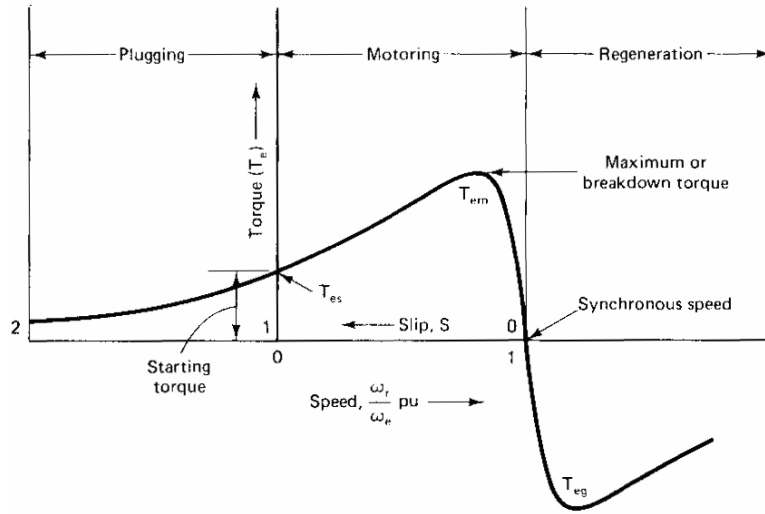


Fig. 2.15 Mechanical characteristic of the induction machine [BOSE 86]

2.3.3 Drive train modelling

The main element of the drive train (S_3 in figure 2.1), is the single-stage rigidly coupled speed multiplier, of (fixed) ratio i and efficiency η (figure 2.16). Subsystems S_1 and S_2 interact by means of subsystem S_3 ; this interaction is mathematically modelled by a movement equation [MUNT 97], rendered either at the low speed or at the high speed shaft.

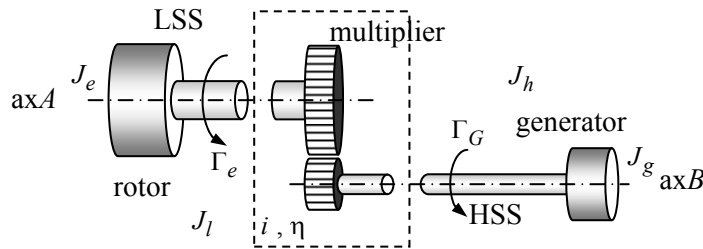


Fig. 2.16 Rigid drive train

Due to the speed multiplier, the generator experiments an i times reduced torque and an i times increased speed, $\Omega_h = i \cdot \Omega_l$; the system's equivalent inertia is reduced when rendered at the high speed shaft, J_h [MUNT 97]. Under the previously stated modelling assumptions (see §2.1), the WECS's dynamic may be expressed rendered at either the HSS or at the LSS in two equivalent forms [NICH 95], [WELF 97]:

$$(2.16) \quad J_h \cdot \frac{d\Omega_h}{dt} = \frac{\eta}{i} \cdot \Gamma_{wt}(\Omega_l, v) - \Gamma_G(\Omega_h, c),$$

$$(2.17) \quad J_l \cdot \frac{d\Omega_l}{dt} = \Gamma_{wt}(\Omega_l, v) - \frac{i}{\eta} \cdot \Gamma_G(\Omega_h, c),$$

where:

- $\Gamma_{wt}(\Omega_l, v)$ is the aerodynamic torque, parameterized by the wind speed, v ;
- $\Gamma_G(\Omega_h, c)$ is the electromagnetic torque, parameterized by a generically called “load variable”, denoted by c ;

$$(2.18) \quad J_h = (J_1 + J_{wt}) \cdot \frac{\eta}{i^2} + J_2 + J_g,$$

$$(2.19) \quad J_l = J_{wt} + J_1 + (J_g + J_2) \cdot \frac{i^2}{\eta},$$

where:

- J_1, J_2 are inertias of the multiplier's gears;
- J_{wt}, J_g are inertias of turbine's rotor and of electrical generator respectively;
- J_h, J_l are inertias rendered at HSS and LSS respectively.

As the drive train is rigid, the dynamical torque is given only by the rotational speed's variation. Figure 2.17a) contains a Simulink implementation of the movement equation rendered at the high speed shaft (relation (2.18)). This equation is usually referred to as being *the single mass WECS model*.

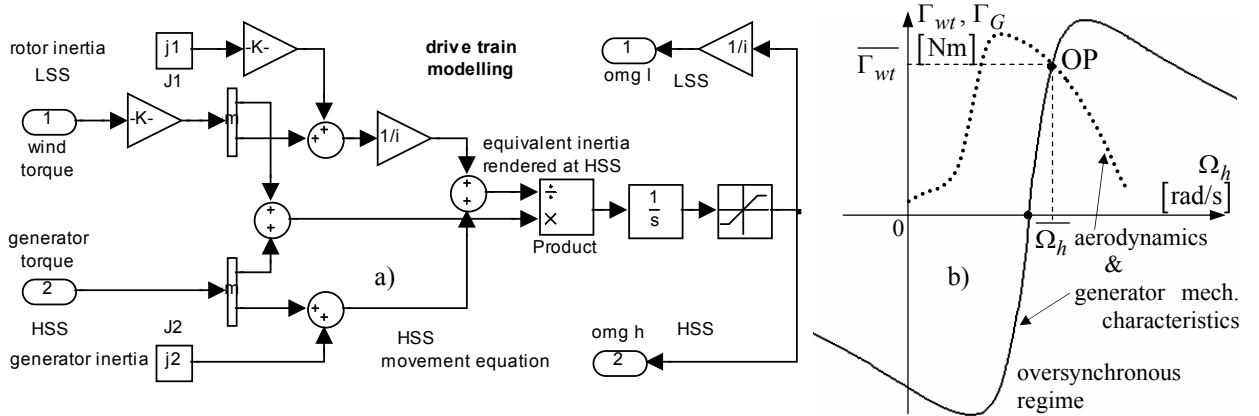
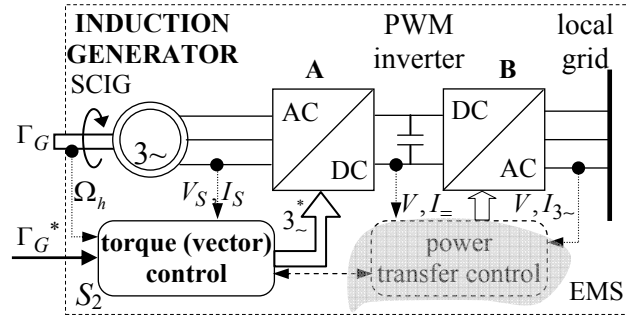


Fig. 2.17 a) Movement equation rendered at the high-speed shaft – Simulink implementation; b) steady-state regime of WECS

Figure 2.17b) presents the steady-state regime of the interaction between the turbine's rotor and the induction generator by means of the high speed shaft turning at Ω_h . The static operating point of WECS is thus determined as the cross-point of the rotor mechanical characteristic with that of the generator.

2.3.4 Generator control

The SCIG is controlled by means of a voltage source back-to-back inverter (figure 2.18). The machine side power converter (**A** in figure 2.18) allows that the high speed shaft torque be varied by controlling the generator torque, so it allows the variable speed regime of the turbine. The grid side converter (**B** in figure 2.18) is used for transferring the produced electrical power (by DC-link voltage regulation) to the mains, while controlling the voltage and the frequency of the output voltages. The two power converters are considered ideal (without power loss and dynamic) and are separately controlled. The control of inverter **B** is not of interest in this chapter; consequently, we will study only inverter **A**, used for operating the turbine at variable speed.

Fig. 2.18 Structure of the electromagnetic subsystem, S_2 /EMS

The torque control of the generator is realised by suitably controlling inverter A [PENA 00]. This latter is voltage vector controlled (indirect method), by computing the stator voltages' amplitude and frequency depending on the desired electromagnetic torque [BOSE 86]. The vector control compensates the induction generator's dynamic, as regards both the settling time and the dynamic performances also. This method basically relies on the alignment of the rotor flux, Φ_R , on the d axis of the (d,q) frame. If this alignment takes place ($\Phi_{Rq} \approx 0$), then relations (2.20) hold, meaning that Φ_{Rd} depends on i_{Sd} through a first order dynamic, and an estimation of the rotor flux frequency using Φ_{Rd} and i_{Sd} can be used.

$$(2.20) \quad \begin{cases} \Gamma_G = \frac{3}{2} \cdot p \cdot \frac{L_m}{L_R} \cdot i_{Sq} \cdot \Phi_{Rd} \\ \frac{L_r}{R_r} \cdot \frac{d\Phi_{Rd}}{dt} + \Phi_{Rd} = L_m \cdot i_{Sd} \\ \omega_S = \omega + \frac{L_m}{\Phi_{Rd}} \cdot \frac{R_r}{L_r} \cdot i_{Sq} \end{cases}$$

Using these equations in the SCIG model (2.15) one can develop the MIMO mathematical model of the field-oriented machine, having as input vector $[V_{Sd} \ V_{Sq}]^T$ and as state vector $[\Phi_{Rd} \ i_{Sq}]^T$ [LEON 86], [BRUN 00]. This model allows to separately controlling the two states and finally the generator's torque value using simple PI controllers and decoupling correction for attaining orthogonality between $V_{Sd} \rightarrow \Phi_{Rd}$ and $V_{Sq} \rightarrow i_{Sq}$ channels (see figure 2.19).

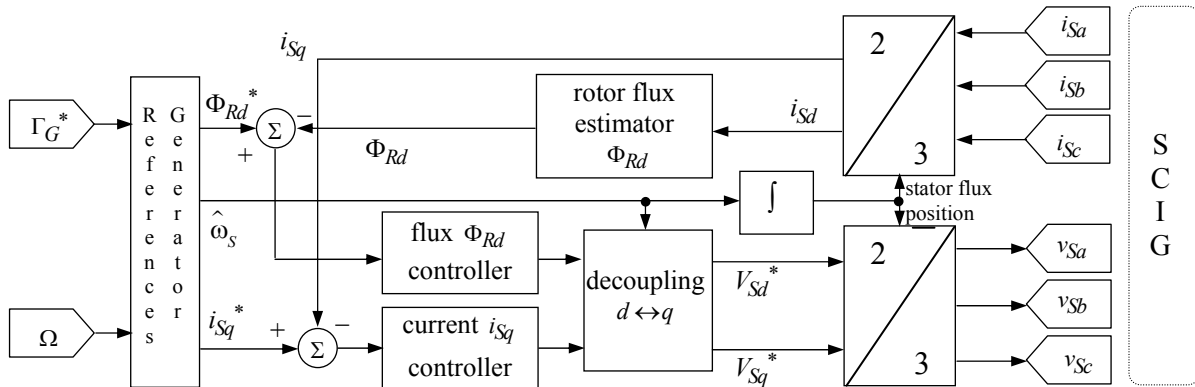


Fig. 2.19 SCIG vector control

Figure 2.19 contains a widely employed vector control structure for torque controlling a squirrel cage induction machine. This control scheme allows a very fast and accurate torque response of the generator, thus being suitable for wind turbine applications. Therefore, an I/O model of the controlled SCIG (EMS in our approach) – from the electromagnetic torque reference to its physical realisation – can be assimilated to a first order element,

with very fast dynamic. In short, a wise choice of the PI parameters in the vector control scheme allows a millisecond rated EMS time constant, T_G , being achieved, so the phenomena which govern the operation of subsystem S_2 happen much more rapidly versus the global WECS's dynamics. This allows to neglect this subsystem's dynamic in the total dynamics, when this is especially required.

2.4 LINEARIZED MODEL OF WECS

The aim of this paragraph is to present a linearized model of the mechanical subsystem of the studied type of WECS, containing the aerodynamic subsystem and the drive train. The control input is the electromagnetic torque, Γ_G , or its normalized variations. It is obvious that the electromagnetic subsystem, which provides Γ_G , has a much faster dynamic than that of the drive train, and thus can be neglected or considered as a first order dynamic in designing certain control laws. In this way, the WECS's model can be reduced to those of the above mentioned mechanical subsystems, whose linearization makes it possible to implement some linear control laws [EKEL 97], [NOVA 94].

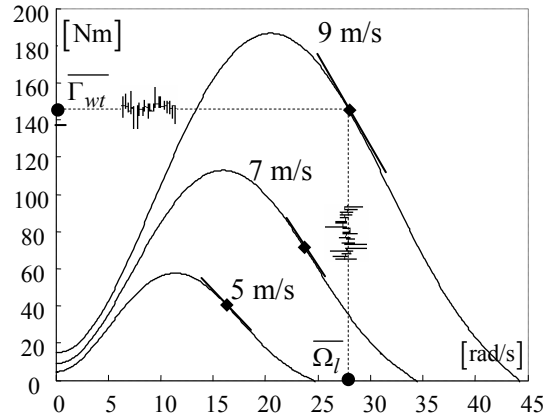


Fig. 2.20 Operating point position on rotor's mechanical characteristic

Let us consider a generic static operating point, $(\overline{\Omega_l}, \overline{\Gamma_{wt}})$, of the wind turbine in the partial load region under a wind speed denoted by $\bar{v}$; therefore, this point is situated on the turbine's mechanical characteristic as depicted in figure 2.20. In the sequel, for a generic functional variable x associated to this static point the following notation will be adopted:

$$\bar{x} = x|_{\text{static operating point}}; \Delta x = x - \bar{x}; \overline{\Delta x} = \frac{\Delta x}{x}$$

Starting from the nonlinear characteristic (2.12), one can obtain the linearized expression of the wind torque variations [EKEL 97]:

$$(2.21) \quad \overline{\Delta \Gamma_{wt}} = \gamma \cdot \overline{\Delta \Omega_l} + (2 - \gamma) \cdot \overline{\Delta v},$$

where:

$$(2.22) \quad \gamma = \gamma(\bar{\lambda}) = \frac{C_p'(\bar{\lambda}) \cdot \bar{\lambda} - C_p(\bar{\lambda})}{C_p(\bar{\lambda})}$$

is the **torque parameter**, which strongly depends on the operating point, and $C_p'(\lambda) = \frac{dC_p(\lambda)}{d\lambda}$. From relation (2.19)

one can deduce the dynamic of the system linearized around the chosen static operating point:

$$(2.23) \quad \frac{d}{dt}(\overline{\Delta\Omega_l}) = \frac{1}{J_T} \cdot [\gamma \cdot \overline{\Delta\Omega_l} + (2 - \gamma) \cdot \overline{\Delta v} - \overline{\Delta\Gamma_G}],$$

introducing the time constant:

$$(2.24) \quad J_T = \frac{\overline{\Omega_l} \cdot J_l}{\overline{\Gamma_{wt}}} = \frac{\overline{\Omega_h} \cdot J_h}{\overline{\Gamma_{wt}}}$$

The following notation is introduced:

$$(2.25) \quad \mathbf{x}(t) = \begin{bmatrix} \overline{\Delta\Omega_l(t)} \\ \overline{\Delta v(t)} \end{bmatrix} \quad - \text{ state vector; } \quad u(t) = \overline{\Delta\Gamma_G(t)} \quad - \text{ control input}$$

The turbulence wind speed, Δv , is synthesized like in §2.1.2 (figure 2.9), from a white noise, $e(t)$, by using a low-pass first order shaping filter with T_w as time constant [EKEL 97].

By neglecting the electromagnetic subsystem dynamic versus that of the drive train and supposing unitary efficiency of the latter, the linearized state space equation of the wind turbine can be written as follows:

$$(2.26) \quad \dot{\mathbf{x}}(t) = \underbrace{\begin{bmatrix} \frac{\gamma}{J_T} & \frac{2-\gamma}{J_T} \\ 0 & -\frac{1}{T_w} \end{bmatrix}}_{\mathbf{A}} \cdot \mathbf{x}(t) + \underbrace{\begin{bmatrix} -\frac{1}{J_T} \\ 0 \end{bmatrix}}_{\mathbf{B}} \cdot u(t) + \underbrace{\begin{bmatrix} 0 \\ \frac{1}{T_w} \end{bmatrix}}_{\mathbf{L}} \cdot e(t)$$

The output equation results from defining a measure variable, $z(t)$, as output variable. This is here the normalized variation of the tip speed ratio:

$$(2.27) \quad z(t) = \overline{\Delta\lambda(t)}$$

Because $\overline{\Delta\lambda(t)} = \overline{\Delta\Omega_l(t)} - \overline{\Delta v(t)}$ [MUNT 02], the output equation rewrites:

$$(2.28) \quad \overline{\Delta\lambda(t)} = \underbrace{\begin{bmatrix} 1 & -1 \end{bmatrix}}_{\mathbf{C}} \cdot \mathbf{x}(t)$$

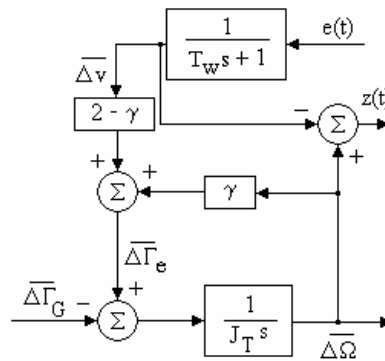


Fig. 2.21 Linearized model with respect to low rotational speed and wind speed – rigid drive train

The linearized in variations model is then:

$$(2.29) \quad \begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A} \cdot \mathbf{x}(t) + \mathbf{B} \cdot u(t) + \mathbf{L} \cdot e(t) \\ z(t) = \mathbf{C} \cdot \mathbf{x}(t) \end{cases}$$

and it corresponds to the block diagram in figure 2.21.

Remarks:

- A complete description of how the above linearized model has been obtained can be found in [MUNT 03] and also in appendix G.
- The above model has as state variables the normalized variation of the low speed shaft rotational speed around its steady-state value and the normalized variation of the wind speed (that is, the turbulence) around its low frequency value.
- It can be shown that the matrix pair $(\mathbf{A}, \mathbf{B})$ is not controllable [MUNT 02], but it is stabilizable.

2.5 STATE-OF-THE-ART IN WECS OPTIMAL CONTROL

Control of variable speed fixed pitch WECS in the partial load region generally aims at regulating the power harvested from wind by modifying the electrical generator's speed; in particular, the control goal can be to capture the maximum power available in the wind. For each wind speed, there is a certain rotational speed at which the power curve of a given wind turbine has a maximum (the C_p reaches its maximum value). All these maxima compose what is known in the literature as the *optimal regimes characteristic, ORC* (see figure 2.22) [NICH 95].

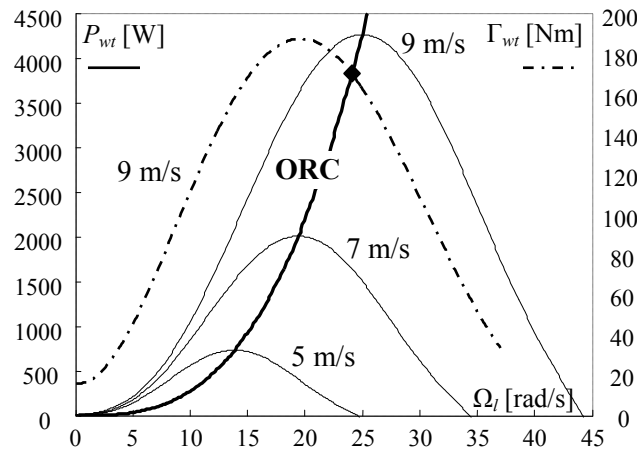


Fig. 2.22 Optimal (static) regimes characteristic, ORC

By keeping the static operating point of the turbine around the ORC one ensures an optimal steady-state regime, that is, the captured power is the maximal one available in the wind. This is equivalent with maintaining the tip speed ratio at its optimal value [CONN 93] and can be achieved by operating the turbine at variable speed, corresponding to the wind speed.

Because of the turbine's quite important inertia, the wind speed variations cannot be precisely enough tracked but with inadmissibly intense mechanical loads. Therefore, optimizing the dynamical regimes becomes necessary; the most important control methods aiming at this, split into two classes upon the type of model used, will be reviewed in the sequel.

In the concerned literature, one can find multiple methods employed in variable speed WECS controllers developing, not only for the type of WECS concerned in this work, but for various other types (including permanent magnet or multipolar synchronous generators, doubly-fed induction generators, etc.). This multitude of control approaches have emerged because of the erratic nature of the wind and the life service reduction due to mechanical stress [CARL 01], nonlinear variant behaviour of the WECS, poor reliability of some (essential) measurement information, unknown parameters/features, etc. Basically, the control approaches encountered in the WECS control field are varying upon some assumptions concerning the known models/parameters, the measurable variables, the

control method employed and the version of WECS model used.

2.5.1 Optimal control methods using the nonlinear model

"Maximum Power Point Tracking" (MPPT)

This technique is encountered in the literature under its acronym, MPPT. Its goal is to operate the WECS around the maximum power (within safety limits), using information from the static power characteristic (relation (1.2)) and a minimum of information from the system. The power characteristic of the turbine rotor is completely unknown, but general features of WECS (such as rated power, number of blades, total shaft inertia, etc) are considered known. The high speed shaft rotational speed, Ω_h , and the active power of the generator, P , are the only available measurements from the system.

Essentially, the approach is based on the computation of the power and rotational speed gradients, employed further in a hill climbing – like method. This information is used to determine $\partial P / \partial \Omega_h$ value, its sign implying the static operating point (OP) position on the power curve in relation to this curve's maximum (zero corresponding to the power maximum). An on-off control logic (XOR based), aiming at keeping $\partial P / \partial \Omega_h$ at small values, updates the speed reference of the generator vector control block with constant variations $\pm \Delta \Omega_h$ [SCHI 00], [BHOW 98], [DATT 03]. Since the OP excursions around the optimal operating point (OOP) are quite large under turbulent winds, variants of this method employing wind speed estimation or adaptive control input can be used, depending on the closeness of OP to OOP and on its trend.

Even it is robust subject to WECS's parametric uncertainties and does not need much and often unavailable information, this method has the main inconvenient of using some variables' gradient estimations in dynamic conditions. The control system from figure 2.1 is instantiated for this case as figure 2.23a) presents.

Fuzzy logic control

Maximizing the harvested power from the wind (in the same modelling assumptions) is aimed at in this case too, and the control law (premises' evaluation according to the control rules) is an *extension of the* MPPT method in the sense that the rules base is an extension of the MPPT control logic. The rules base is therefore built for keeping the operating point around the optimal one (at a small value of $\partial P / \partial \Omega_h$). Value $\Delta \Omega_h$ is variable for a certain wind speed and depends on the distance between the optimal and the current operating point and on the speed variation of the latter [SIMO 97], [ABOK 04], [ZHAN 04]. In this way small variations of OP around OOP are obtained in steady-state operation. The dynamic response is also improved; the fuzzy controller is more flexible than a MPPT one. The most important drawback of this method is the context dependence (the wind site's features, the turbine's type, etc.), requiring quite consistent a priori knowledge. The corresponding control system (figure 2.1) is instantiated for this case as in figure 2.23b).

Sliding mode control (SMC)

The sliding mode or variable structure control (SMC/VSC) is a vibrational control method, suitable to nonlinear systems; the controller is a variable structure system which switches with high frequency between several control laws. In particular, its output can be an ON/OFF signal. As to well-known results from the variable structure systems' theory [UTKI 71], the controller implements a nonlinear control (switching) law, in order to drive and maintain the system's state trajectory on a desired (switching) hypersurface. Its robustness to disturbances and parametric uncertainties makes unnecessary a precise knowledge of the system; also, the VSC can be implemented

by the power electronics already existing in the system. But for the applications using the electromagnetic torque as control input the mechanical stress increases due to the chattering.

There is a certain difficulty about the VSC design, concerning the definition of a sliding surface with guaranteed properties of attractiveness and stability [LEVI 96], [YOUN 99]. VSC has been used on various configurations of WECSs, for regulating the generated power, as required by a general purpose user [LONG 99], [BATT 00b], [BATT 04], or for power efficiency and torsional dynamics optimisation [BATT 00a]. Flexibility of the sliding mode approach can be raised by adopting combined switching surfaces, in order to allow multi-criteria optimization (i.e., captured power maximization and electromagnetic torque variations' minimization).

Briefly, in the most general case the sliding surface depends explicitly on the system state, control input and time: $\sigma \equiv \sigma(\mathbf{x}(t), u(t), t)$; by adopting some simplifying assumptions (i.e., by neglecting the blades' dynamics and the generator's response time), the movement equation of the high speed shaft (2.16) can be re-written:

$$(2.30) \quad \underbrace{\dot{\Omega}_h(t)}_{\mathbf{x}(t)} = \underbrace{\frac{\Gamma_{wt}(\Omega_l(t), v(t))}{J_h \cdot i}}_{f(\mathbf{x}, t)} + \underbrace{\left(-\frac{1}{J_h}\right)}_{b(\mathbf{x}, t)} \cdot \underbrace{\Gamma_G(\Omega_h, t)}_{u(\mathbf{x}, t)},$$

which is the nonlinear state model in a form suitable to use for the sliding mode design:

$$(2.31) \quad \dot{\mathbf{x}}(t) = f(\mathbf{x}, t) + b(\mathbf{x}, t) \cdot u(\mathbf{x}, t)$$

The control input is obtained as a switching surface feedback, having the general form (see figure 2.23c)) [LEVI 96]:

$$(2.32) \quad \Gamma_G^* = u(\mathbf{x}, t) = u_{eq}(\mathbf{x}, t) + u_N(\mathbf{x}, t),$$

as in figure 2.23c), where the first component is called **equivalent control input**, $u_{eq}(\mathbf{x}, t)$, and satisfies the *tracking condition*

$\frac{d\sigma(\mathbf{x}(t), u(t), t)}{dt} = 0$ and the second component, $u_N(\mathbf{x}, t)$, is a **dynamical** one and results from the *stability condition*

imposed to the closed loop system. Stability is proved by finding a (energy) Lyapunov function, i.e., positive definite with negative first derivative; typically, this is a quadratic form of the switching surface.

This method is effective and intrinsically robust, requiring relatively few information about the system and being insensitive to parametric variations. The chattering [LEVI 96], specific to VSC, is the main drawback in this case; it negatively influences the mechanical subsystem, by inducing supplementary stress, and might excite the unmodelled dynamics (e.g., the oscillating modes of the blades or those of the flexible drive train), thus producing destructive oscillations.

Direct imposing of optimal operating point (OOP) position

From a static point of view, improving/maximizing energy capture below the rated power (in partial load region) can be ensured by forcing the turbine rotor to operate at maximum power, P_{opt} , corresponding to the instantaneous wind speed. This means that the operating point is in its optimal position (OOP). Equivalently, this means to impose the electromagnetic torque which equals the wind torque corresponding to the maximum power available (denoted by Γ_{opt}). As the maximum power operating point corresponds to the wind rotor turning at optimal tip speed ratio, λ_{opt} , relations (1.2) and (2.12) give that:

$$(2.33) \quad P_{opt} = \Gamma_{opt} \cdot \Omega_l = k \cdot \Omega_l^3,$$

where $k = \frac{0.5\pi\rho R^5 C_p}{\lambda_{opt}^3}$.

Figure 2.23d) (upper part) shows that the generator's torque reference is obtained using a rotational speed measure and relation (2.33). Also, if a power reference is preferred, a PI control is employed for modifying the SCIG mechanical characteristic and obtaining the torque reference, as depicted in the lower part of figure 2.23d).

As the WECS control structure allows the wind speed to be tracked within admissible limits of mechanical loads, this method can be used as depends only on slow wind speed variations, because it employs a static optimisation. For turbulent winds filtering of the variables is necessary, along with using compliant PI parameters, to ensure sufficiently slow closed loop dynamics. This method is strongly sensitive to parametric variations.

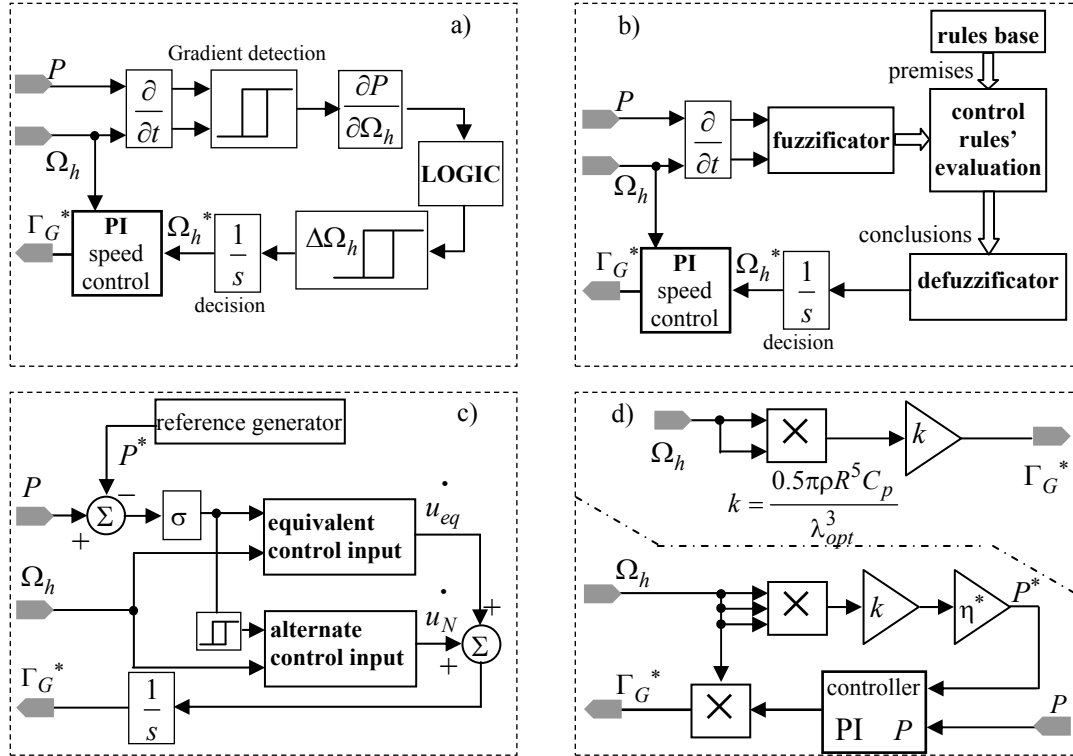


Fig. 2.23 Nonlinear control approaches for WECS: a) MPPT, b) fuzzy, c) SMC, d) OOP controllers

2.5.2 Optimal control methods using the linearized model

Steady-state optimization of WECS

The control goal is formulated as maintaining the tip speed ratio at its optimal value, λ_{opt} . For this, a rotational speed tracking system is conceived [MILL 97], [BROE 99], whose reference $\Omega_{h_{opt}}(t)$ depends on the instantaneous wind speed, $v(t)$, and is computed from relation (1.4):

$$(2.34) \quad \Omega_{h_{opt}}(t) = i \cdot \Omega_{l_{opt}}(t) = i \cdot \frac{\lambda_{opt}}{R} \cdot v(t)$$

The tracking system is based upon a PI classical controller, designed as follows. The cross-point of the mechanical characteristic and the ORC is identified; this point is placed on the falling zone of the torque characteristic (see figure 2.22). The turbine's model (2.16) is then linearized in a neighbourhood of this point, allowing that the parameters of a PI (linear) controller to be designed (e.g., using a pole placement procedure for the closed loop system). The instance of the corresponding WECS control structure is presented in figure 2.24a). One

can derive the following remarks:

- WECS's large inertia generally does not allow the wind speed to be tracked within admissible limits of mechanical loads, but only in steady-state operation (slow wind speed variations);
- fast wind speed variations can lead to abruptly decreasing the available power, even to modifying the power balance in the system, such that the induction machine works as a motor, whereas the turbine becomes a fan [LEIT 90];
- the linearized system's parameters depend on the wind speed; therefore, choosing a PI control is even more suitable, provided its robustness to parametric variations.

Linear quadratic (LQ) dynamic optimization

The optimal control can be implemented (as in previous paragraphs) by tracking the optimal rotational speed corresponding to a given wind speed. This type of control strategy induces variations of the electromagnetic torque, so supplementary mechanical stress, which reduces the lifetime of the drive train mechanical parts. In this way, the turbine reliability is also decreased by involving supplementary maintenance costs and reducing the turbine availability.

The mechanical fatigue of the drive train can be reduced by imposing the electromagnetic torque variations, $\Delta\Gamma_G(t)$, to be minimized [NOVA 94], [EKEL 97]. Ekelund [EKEL 97] used an optimization criterion complying with the minimization of the generator torque variations, which are responsible for the mechanical fatigue of the drive train. Thus, maximizing the harvested energy and minimizing the torque variations are **two antagonistic demands**, which can be expressed by a combined optimization criterion:

$$(2.35) \quad I = E \left\{ \alpha \cdot [\lambda(t) - \lambda_{opt}]^2 \right\} + E \left\{ \Delta\Gamma_G^2(t) \right\} \rightarrow \min ,$$

with $E\{\cdot\}$ being the statistical average symbol. The optimization problem is, therefore, defined as being *Gaussian (stochastic) linear quadratic* [ATHA 66], using the model described in §2.4.

Operation around optimality is ensured by minimizing only the first component from (2.35), but allowing important torque variations (second term of the previous criterion). The positive coefficient α is introduced to adjust the trade-off between the two above mentioned demands.

The optimal control input is obtained as state feedback, as shown in figure 2.24b) [LEVI 96]:

$$(2.36) \quad u(t) = -\mathbf{K} \cdot \mathbf{x}(t)$$

The gain vector $\mathbf{K}$ results from solving a stochastic linear quadratic optimization problem (expressed by criterion (2.35)), defined on the linearized model (2.29) of the WECS, where the state vector $\mathbf{x}$ is given by relation (2.25).

Parameters of the dynamical system depend on the operating point's position on the turbine mechanical characteristic, which in turn depends on the average wind speed. Therefore, an adaptive control structure has been proposed as solution for the optimization problem, in order to switch the gain vector, $\mathbf{K}$, depending on the wind speed [EKEL 97]. Moreover, the system states are not completely available to measure, thus requiring a Kalman filter for state reconstruction.

Introducing coefficient α confers *flexibility* to the control law in the following sense. If the wind turbulence is not significant, then the accent may fall on the energetic efficiency of the WECS, therefore α will take a large value. If, on the contrary, the wind turbulence is important, then, through a small value of α , the accent will fall on reducing the mechanical stress and increasing the life service of the WECS.

Variants of this control law can be found in the concerned literature. In [BIAN 05] a systematic gain scheduling procedure for linear parameter varying systems applied to variable speed WECSs is developed. The LQ control law desensitising with respect to parametric variations may be obtained using a significantly complicated (and difficult to implement) additional control structure.

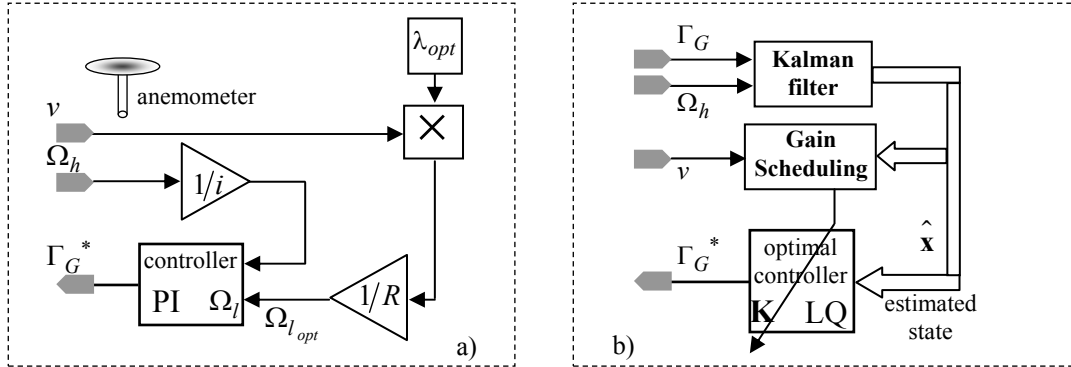


Fig. 2.24 Linear control approaches for WECS: a) steady state optimization, b) LQG optimization

2.5.3 A reliability viewpoint

From previous assertions one can conclude that WECS energetic optimisation by variable speed operation could potentially require important control efforts, especially in high turbulent winds. The associated large mechanical loads have negative influence on the WECS reliability and service lifetime, by decreasing the availability of the system. In return, this will mean supplementary maintenance and operation costs, therefore a reduced economic efficiency. In order to avoid these bad consequences one can naturally think of limiting the amplitude of the drive train's loading cycles, which corresponds to moving to the right the breakdown point on Wöhler's fatigue diagram – figure 2.25 [SUTH 95], [SUTH 99].

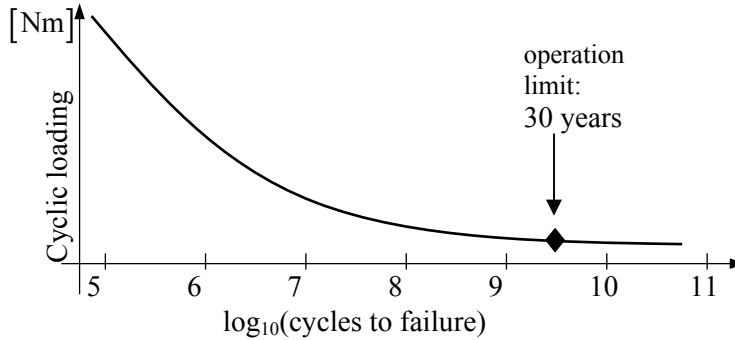


Fig. 2.25 Wöhler's diagram

For the WECS described in appendix A, let us make a comparison between the case of the variable speed operation using steady-state optimisation (i.e. the controller from figure 2.24a)) and the case of constant speed operation (without control, SCIG is connected directly to the grid). The PI controller has been designed to reduce the time constant of the system by 10 times in the worst case (for the cut-in speed).

The performance difference between the two cases can be analyzed on figure 2.26a). Given that the optimal tip speed is known, $\lambda_{opt} = 7$, one can note that the controlled WECS operates much closer to the optimal regime.

However there are some variations of the tip speed from λ_{opt} , as the turbulence varies significantly faster than the rotor speed. Figure 2.26b) shows the difference between the electromagnetic torques in the two cases. It is noticeable that the fatigue loads are much larger in the case of variable speed operation. The spectral distributions in the two cases are depicted in figures 2.26c) and 2.26d), showing that large high frequency harmonics are induced by

the variable speed operation. For concluding, in the presented variable speed operation, a relatively low performance in tracking λ_{opt} has been realised with large generator torque (control input) variations.

The drive train design includes an analysis of the fatigue loads, for example time-at-level technique which is an averaging macro-approach [SUTH 95]. This basically implies a “time-at-level” histogram being built, by counting the total time the gearbox will be subjected to a given magnitude of torque. An analysis of figures 2.26b), 2.26c) and 2.26d) shows that, if tracing “time-at-level” histograms for both constant and variable speed cases, they would significantly differ. This means that an endurance limit assumed by the drive train design in the constant speed operation can be over passed if the same mechanical subsystem is operated at variable speed.

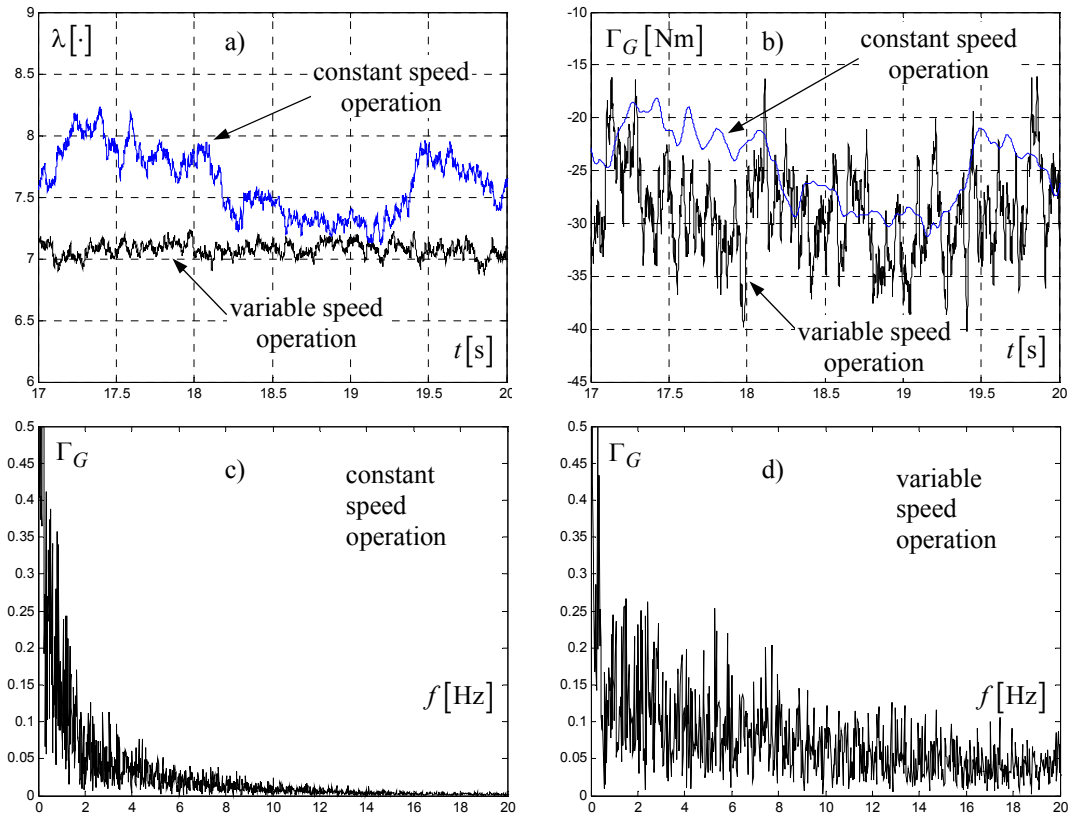


Fig. 2.26 Comparison between constant speed and variable speed operation regimes

As conclusion, given the particularities of the WECS operation (related to remote operation, turbine availability and finally to economical reasons), it is crucial that the energetic optimisation obtained by variable speed operation be done with as small as possible torque variations, for minimizing the implication on the service lifetime of the turbine.

2.6 PHYSICAL SIMULATORS FOR WECS

The justifying reasons for building such simulators result naturally from the need of real time validation/testing of WECS control laws. In the case of variable speed WECS, the direct (field) application of different control laws is difficult and not recommended, because of the wind speed randomness, impossible to influence, and of the quite significant costs.

The scaled-down real time electromechanical simulators have thus become necessary, since they allow that

the dynamical characteristics of given wind turbines to be reproduced and tested under controlled working (laboratory) environment, that is, for various wind regimes, irrespectively from the actual meteorological context. Thus, repeatable, realistic, deterministic and cost-effective experiments, as well as rapid prototyping of WECS control laws, are some key features of the WECS physical simulators. The possibility of changing the analyzed/simulated WECS, the wind site features and wind conditions, confers great flexibility to such simulators.

In the concerned literature, the preliminary experimental validation is always performed on wind turbine simulators [NUNE 93], [BATT 96], [BARR 97], [RODR 98], [DIOP 00], [RABE 02], [STEU 04]. The physical WECS simulators embed models of the wind speed corresponding to known wind sites, models and physical elements of a known variable speed wind turbine, as well as the associated control structures, thus greatly facilitating the real time experimentation of a wind turbine sitting, variable speed operation or grid interfacing. A further transfer of the control law to the real applications takes place by software implementation and the success depends on the simulator's accuracy of reproducing the static and dynamic characteristics of the real wind turbine, in a specified wind site.

These simulators are presently designed using the **hardware-in-the-loop simulation** (HILS) concept, which generally consists in closed loop connecting physical and software parts, for reproducing under controlled conditions the dynamical behaviour of an industrial process. Because of the fast development of software and real time information processing devices, the technological base of the HIL systems has grown more than its conceptualisation. In spite of their recognized necessity and extensive use, the design of such real time simulation structures unfortunately suffers from a methodological lack.

2.7 CONCLUSION. TECHNICAL JUSTIFICATION OF THE WORK

It is widely recognized the gap between the development of the advanced control algorithms and their effective use in most of the engineering practice domains. In particular, a general point of view in WECS control is impossible to be sustained, given the diversity and the specificity of the control approaches encountered in the concerned literature. As a matter of fact, none of the presented techniques has become classical such to be widely used by system integrators of fixed pitch variable speed wind turbines. Their drawbacks, together with some inherent difficulties resulted from the erratic nature of the wind, prevent from easily implementing these techniques into practice.

A synthetic comparative evaluation of the studied control approaches is realized using five criteria with five assessment degrees, as table 2.1 shows.

Studied approach \ Evaluation criterion	Realism of the modelling assumptions	Efficiency	Supplementary mechanical stress	Simplicity	Flexibility
MPPT	good	average	weak	very good	very weak
Fuzzy logic	weak	good	average	weak	average
SMC	good	very good	weak	average	very good
Direct imposing of OOP	weak	average	average	good	weak
Steady-state optimisation	weak	weak	weak	very good	weak
LQG	average	very good	good	average	good

Table 2.1 Synthetic assessment of the WECS control methods encountered in the literature

The use of one or another from the above control methods depends on the envisaged control goal and the available information about system parameters and feedback. Thus, the employed method will be more sophisticated as the control goal is more complex and feedback information is scarce. Ideally, the chosen method would allow the best trade-off between various contradictory demands, which can be roughly reduced to good efficiency under a given (restricted) set of assumptions, meanwhile ensuring reasonable (supplementary) mechanical stress.

One can note from table 2.1 that the fuzzy logic control could apparently ensure a satisfactory performance level, but in fact the resulting controllers are context dependent, needing information from a quasi omniscient user. The method of direct imposing of OOP is very sensitive to parametric and exogenous variations. The steady-state optimisation practically does not allow to alleviating the supplementary mechanical stress induced by the control. Moreover, as an energetic criterion cannot be defined, none of these three methods allows varying the turbine's efficiency in capturing wind power. This brief analysis allows removing these three methods from any potential set of promising future developments.

The approach reported in this work will exploit the advantages of the other three methods remained (MPPT, SMC and LQG), because their drawbacks can be alleviated in a certain degree. Thus, the MPPT method has the huge advantage of employing very poor parametric and feedback information in the controller construction. Sliding mode control method is very robust to parametric uncertainties and suitable for nonlinear systems. LQG control allows the alleviation of mechanical stress, by imposing a trade-off between captured power from the wind and wind turbines' reliability.

The main idea will be to use the benefits of a global (multipurpose) dynamic optimization approach, concerning the wind power systems. Versions of the above control techniques consistent with this approach, by using the detailed modelling elements from §2.1 to §2.4, will be presented and assessed by Matlab/Simulink simulations and real time experiments. These latter have been possible in laboratory conditions under controlled environment, using dedicated electromechanical simulators, built upon the HILS concept within a new methodological design framework.

Chapter 3

HARDWARE-IN-THE-LOOP SIMULATION (HILS) OF WIND ENERGY CONVERSION SYSTEMS

The hardware-in-the-loop simulation (HILS) generally consists in closed loop connecting physical and software parts, in order to reproduce in laboratory conditions the dynamical behaviour of an industrial process. The software part derives from modelling the analyzed system, whereas the physical part is taken as it is from the real system to simulate.

This chapter aims at presenting the HILS principles and at proposing an original systematic design methodology. Then, it is detailed how this design procedure can be applied to build a development platform based on a real time simulator of variable speed asynchronous generator based low power WECS. The structure and performance of this platform are presented. The possibilities of this platform – among which the most important for our purpose is the real time validation of different control laws of the provided electric power – are described next, along with the most significant experimental results.

3.1 INTRODUCTION. NECESSITY AND GOAL

The HILS concept, strictly related to the real time simulation, seems, in this author's opinion, the most appropriate to support the effective construction of physical simulators. It essentially consists in closed loop connecting physical and software parts, aiming at reproducing the dynamical behaviour of an industrial process in a controllable environment. HILS has been originally introduced for developing and testing control structures for mechanical equipments [HANS 93] and has proved its efficiency in low cost and rapid prototyping.

The use of hardware-in-the-loop (HIL) simulators to control law validation is justified in the following situations: either the controlled plant is not available or the cost required to realise it is very high, or experiments involve important risks for the global operation, or the controlled process nature does not allow deterministic tests in its natural environment. In this context, the HILS concept may be useful for a wide range of applications. For example, in [HANS 96] and [KIFF 96] HILS applications in the automobile industry are reported, which use the Matlab/SimulinkTM software on a dSPACE development kit.

The electromechanical applications are another field where HILS may be used, from which the renewable energy conversion is currently a rich investigation area, particularly suitable to using this kind of simulators. Because of the fast development of software and real time information processing devices, the technological base of the HILS systems has grown more than its conceptualisation. In spite of their recognized necessity and extensive use, the design of such real time simulation structures suffers from a methodological lack. In [RODR 98], [VIHR 02] and [STEU 04] implementations of HIL simulators for the wind energy conversion are presented, but without explicitly stating a design methodology. When approaching the same domain, in [DIOP 00] and [BOUS 03] certain methodological elements have been given, which still are very context dependent. Some aspects regarding the hardware design of an experimental rig with doubly-fed induction generator for wind turbines are discussed in

[RABE 02], using a hardware structure similar to the one detailed in the present approach.

The approach presented in this work starts from the terminology introduced by [NICH 98] and partially used in [DIOP 99a], [DIOP 00], [NICH 02]. These articles have as common idea the splitting of the system into two interacting parts, one of them being emulated by software control of a hardware element. The associated mathematical model is also split in two, allowing to establish a basic HILS design methodology. This approach is difficult to apply in controlling the interaction between the two subsystems, generating an uneasy design/implementation of the associated control loops. Therefore, the approach proposed here envisages the mathematical model being split into three parts for managing the above mentioned interaction. A generalization to HIL simulation of any industrial process (no matter its nature) is also aimed at. Briefly, in this chapter we shall show how the problem of designing/building a development platform for real time control applications for WECS may be solved, by proposing an original systematic general design procedure of HILS structures. The capabilities of the resulted platform are illustrated by the most significant experimental results.

This chapter is organised as follows. The next section is dedicated to detailed presentation of the HILS concept and of the proposed design methodology for a generic industrial system. The requirements imposed to the development platform for the chosen class of WECS are presented in the third section. The fourth and the fifth section concern the steps of building and testing the two important parts of the real time experimental platform from the viewpoint of the proposed HILS design procedure: the real time physical simulator (RTPS) and the investigated physical system (IPS) respectively. Specific building aspects are skipped, as considered classical and well known. Some significant experimental results to illustrate the separate behaviour of each part are provided at the end of each of these two latter sections, whereas the sixth section concerns illustration of the global operation and overall performance of the development platform, for both constant and variable speed regimes. The final section, the seventh one, is dedicated to conclusion and perspectives.

3.2 HILS CONCEPT. METHODOLOGY OF DESIGNING HIL STRUCTURES

Use of the HILS concept naturally matches the need of real time validating the control laws for various physical systems, under laboratory conditions. Let a *basic physical system* (BPS) be considered, for which a generic control problem is formulated. The associated mathematical model may write as:

$$(3.1) \quad \begin{cases} \dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}, \mathbf{u}) \\ \mathbf{y} = \mathbf{G}(\mathbf{x}, \mathbf{u}) \end{cases},$$

where $\mathbf{u}$, $\mathbf{x}$ and $\mathbf{y}$ are respectively the input, state and output vectors, $\mathbf{F}$ and $\mathbf{G}$ being generally nonlinear vector fields.

A HIL simulator is required to generally allow a cost-effective and safe reproduction of the BPS dynamic behaviour, for purposes of as realistic as possible closed loop deterministic experiments in laboratory conditions.

The basic idea used in HILS structures generally supposes that the BPS can be naturally divided into two subsystems which interact one with each other, namely a first subsystem – e.g. a primary mover – and a second subsystem, undertaking the control action. The first subsystem is such that the closed loop experiments are very expensive (and deterministic experiments are almost impossible). Therefore, it will be this subsystem the one whose behaviour must be replaced by a physical simulator and it will be further called *emulated physical system* (EPS). The second subsystem will exist in the HIL simulator exactly as it is in the BPS, thus allowing laboratory experiments under realistic enough conditions. Being the object of a R&D effort, it will be further called *investigated physical system* (IPS).

EPS and IPS provide outputs of the same nature and interact by means of a so-called **interaction environment**, IER (figure 3.1a)). Generally, at this level a power transfer takes place. Thus, from a systemic point of view, outputs of the EPS and IPS are inputs (**cause** variables) for the IER, whereas the output (**effect** variable) of the IER derives from a differential equation describing an energy conservation law.

In the sequel, the structure of the HILS system will be detailed. IPS remains the same as in the BPS, as its study represents one of the main purposes of the HIL simulator construction. The IER is replaced by a more suitable (from a simplicity/cost-effectiveness point of view) interaction environment, denoted by IES (interaction environment from the HIL simulator). The EPS will be replaced by a so called **real time physical simulator** (RTPS – see figure 3.1b)), embedding also the differences between IER and IES. The above elements must be chosen such that the resulted HIL simulator to approximate the BPS dynamics.

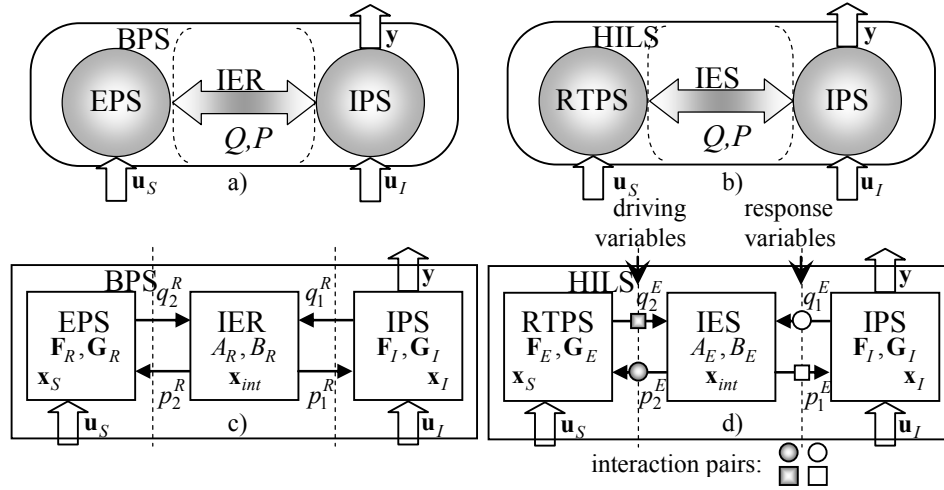


Fig. 3.1 Interaction regarded comparatively inside the BPS and HIL simulator

Let us consider that EPS and IPS have different inputs such that the total input vector is $\mathbf{u} = [\mathbf{u}_S \quad \mathbf{u}_I]^T$. Consider also that the total output vector is the IPS's output vector, $\mathbf{y}$. The above separation allows writing that $\mathbf{x} = [\mathbf{x}_S \quad \mathbf{x}_I \quad \mathbf{x}_{int}]^T$, where $\mathbf{x}_S$, $\mathbf{x}_I$ and $\mathbf{x}_{int}$ are respectively the state vectors of EPS, IPS and IER.

Let Q and P be the classes of input (cause) and respectively output (effect) variables in/from the interaction environment: $Q = \{q_1^R, q_1^E, q_2^R, q_2^E\}$ and $P = \{p_1^R, p_1^E, p_2^R, p_2^E\}$, where index 1 belongs to variables related to IPS, index 2 belongs to variables related to EPS/RTPS, exponent R corresponds to EPS/IPS in the real physical system, BPS, and exponent E corresponds to RTPS/IPS in the HILS system (figure 3.1c)). Products of type $q_i \cdot p_j$ have always power dimensions.

In the BPS, the interaction EPS–IPS takes place at the level of IER (figure 3.1a)) and equivalently determines the nature of the two sets of variables (for example, the interaction between two rotating systems is represented by the couple torque – rotational speed). The same kind of interaction (RTPS–IPS) must therefore exist inside the HILS system. From the point of view of HILS design methodology, a so called **interaction pair** is chosen, which is composed of a variable q_i^E of class Q and a variable p_j^E of class P , where $i \neq j$ (figure 3.1d)). This means that an interaction pair is always composed of a variable related to the RTPS and the other one related to the IPS. So, the interaction between RTPS and IPS must be controlled such that HILS system approximate BPS; this is realised by controlling (imposing) the variable of the RTPS's side, based upon an estimation (measure) of the other one, of the IPS's side. The controlled variable is further called **driving variable** and the other one, **response variable**.

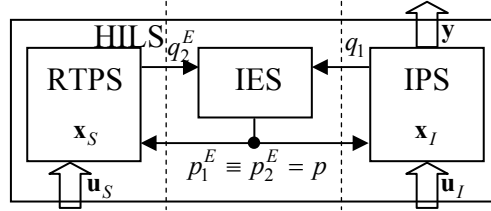


Fig. 3.2 Block structure of the HILS

Remarks:

1) As the RTPS must provide the driving variable, it must replicate a combined model EPS–IER. If the driving variable is chosen as being a cause, then the RTPS will contain an inverse model; if the driving variable is an effect, then the RTPS will contain a direct model.

2) Because IPS is taken in HIL simulator as it is in the BPS, it results that $p_1^R = p_1^E$. Also, $q_1^R = q_1^E$, which will be uniquely referred to as q_1 .

3) The IES is chosen to be constructively as simple as possible, such that the effect variable is the same for both IPS and RTPS, so $p_1^E \equiv p_2^E$. The same idea applies for IER, $p_1^R \equiv p_2^R = p_1^E$, as it has the same nature as IES; these variables will be uniquely referred to as p . Moreover, any superior order dynamic in the combined model EPS–IER is transferred to the RTPS, such that the IER/IES's dynamics to result of first order.

Provided the above separation, model (3.1) of BPS can be rewritten as:

$$(3.2) \quad \left\{ \begin{array}{l} \dot{\mathbf{x}}_R = \mathbf{F}_R(\mathbf{x}_R, [\mathbf{u}_S \quad p]^T) \\ q_2^R = \mathbf{G}_R(\mathbf{x}_R, [\mathbf{u}_S \quad p]^T) \end{array} \right\}_{\text{EPS}}, \quad \left\{ \begin{array}{l} \dot{p} = A_R \cdot q_2^R - B_R \cdot q_1 \end{array} \right\}_{\text{IER}}, \quad \left\{ \begin{array}{l} \dot{\mathbf{x}}_I = \mathbf{F}_I(\mathbf{x}_I, [\mathbf{u}_I \quad p]^T) \\ [q_1 \quad y]^T = \mathbf{G}_I(\mathbf{x}_I, [\mathbf{u}_I \quad p]^T) \end{array} \right\}_{\text{IPS}}$$

where $\mathbf{F}_R$, $\mathbf{G}_R$, $\mathbf{F}_I$, $\mathbf{G}_I$ are generally nonlinear vector fields and $p \equiv \mathbf{x}_{int}$ because the IER's dynamics are of first order; A_R and B_R are scalars describing the EPS-IPS interaction dynamics.

Correspondingly, the HILS dynamics may be described by:

$$(3.3) \quad \left\{ \begin{array}{l} \dot{\mathbf{x}}_E = \mathbf{F}_E(\mathbf{x}_E, [\mathbf{u}_S \quad p]^T) \\ q_2^E = \mathbf{G}_E(\mathbf{x}_E, [\mathbf{u}_S \quad p]^T) \end{array} \right\}_{\text{RTPS}}, \quad \left\{ \begin{array}{l} \dot{p} = A_E \cdot q_2^E - B_E \cdot q_1 \end{array} \right\}_{\text{IES}}, \quad \left\{ \begin{array}{l} \dot{\mathbf{x}}_I = \mathbf{F}_I(\mathbf{x}_I, [\mathbf{u}_I \quad p]^T) \\ [q_1 \quad y]^T = \mathbf{G}_I(\mathbf{x}_I, [\mathbf{u}_I \quad p]^T) \end{array} \right\}_{\text{IPS}}$$

where $\mathbf{x}_E$ is the RTPS state vector and $\mathbf{F}_E$, $\mathbf{G}_E$ are generally nonlinear vector fields; A_E and B_E are scalars describing the RTPS-IPS interaction dynamics.

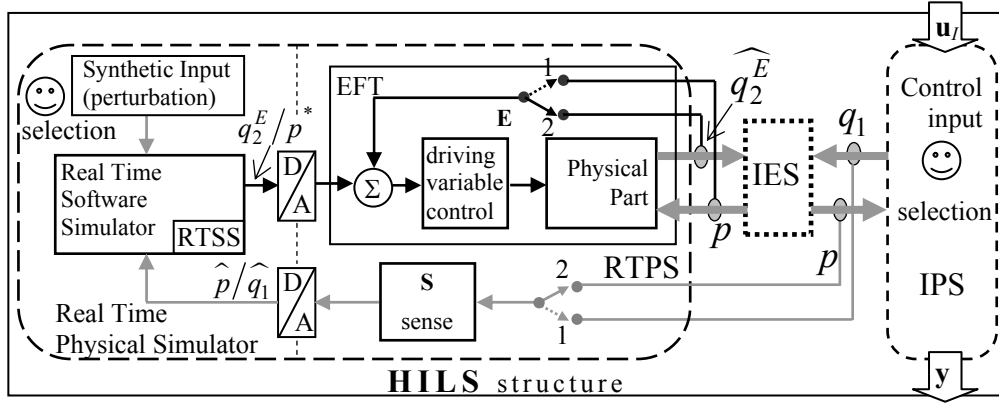


Fig. 3.3 General architecture of HILS systems, presenting the structure of the RTPS

The HILS system, which must reproduce the dynamical behaviour of the BPS, will have the structure shown in figure 3.3. One can note that the RTPS is composed of a software part (*real time software simulator* – RTSS) and a hardware part which has been called *effector* (EFT). Using a measure of the response variable, the value of the driving variable is computed based on the model of the EPS (see relation (3.2)), contained in the RTSS. The driving variable is rendered at physical level by means of the EFT, which contains a physical subsystem depending of the nature of interaction between the EPS and the IPS. The EFT is in fact a tracking loop for the driving variable, whose steady-state value can therefore be found as the output of the EFT.

In figure 3.3 one can note that the response variable is affected by the transducer dynamic (described by vector field $\mathbf{S}$) and the driving variable by the effector dynamic (described by vector field $\mathbf{E}$). Therefore, these variables have slightly modified instantaneous values, which have been generically denoted by $\hat{\bullet}$.

The RTPS replaces EPS if three conditions (called *reproducibility conditions*) are met:

- 1) computation inside the RTSS must be sufficiently faster than the dynamic of the EPS (real time condition),
- 2) the EFT's dynamic must be faster than that of the EPS (the tracking loop be sufficiently fast) and
- 3) the passing band of the transducers must be sufficiently large.

Under these conditions the interaction described by the pair $q_i, p_j, i \neq j$, is sufficiently accurately reproduced, values $\hat{\bullet}$ equal the original ones, so HILS system emulates BPS.

The problem is now how to choose the generic driving and response variables. Two situations may happen:

Case 1: the variable chosen as driving variable is an output/state of the IES, therefore an *effect* variable (of P class), the model implemented in the RTSS is strictly causal and can be easily realised; the corresponding HILS structure can be obtained by setting the switches on position 1 in figure 3.3.

Case 2: the variable chosen as driving variable is an input of the IES, therefore a *cause* variable (of Q class), the model implemented in the RTSS is non causal; the corresponding HILS structure can be obtained by setting the switches on position 2 in figure 3.3.

For example, a pair of interaction variables for a hydraulic system may be pressure-flow. If the pressure (cause) is chosen as driving variable, then the model used in the RTSS will be causal (direct); if, on the contrary, one chooses the flow, then the resulted model is non causal (inverse). Each of the two situations has disadvantages. Thus, in the first case the EFT's dynamic is quite slow, whereas getting the second case into practice is difficult because temporal derivatives must be computed, that increases the measurement noise. In the sequel, the model implemented into the RTSS (containing the model of the EPS and a representation of the difference between IER and IES) will be referred to as EPSM.

In conclusion, a general design methodology of HIL structures may consist in several steps, as follows.

1) *Design of the modelling structure of the basic physical system (BPS), according to the stated control problem*

At this step one must deduce the BPS's mathematical model, by identifying its subsystems and the input, state and output variables.

2) *Delimitation of the IPS and of the EPS in the structural diagram of the BPS and choice of the interaction variables*

This step is guided by the requirements imposed to the HIL structures, concerning the investigated physical system (IPS), which is taken as it is from the BPS. It is this system that represents the starting point, since its real environment must be "transposed" in laboratory conditions. The EPS results by taking the IPS out from the BPS and the interaction nature of these two subsystems completely determines the choice of the interaction pair, as well as the IER's frontiers.

3) *Configuration of the RTPS*

There are two operations to perform at this step, namely: to establish the physical part of the EFT, which must be directly coupled to IPS and, respectively, to choose the driving and response variables.

4) *Development of the detailed model of the EPS, which will be implemented in the RTSS (EPSM)*

This step depends on choosing the driving variable and on how the RTSS is realized. The EPSM can be either implemented in direct form, if the possibility / the wish exists that the driving variable be naturally defined as output variable (effect), or in inverse form, if taking a cause as driving variable.

5) *Putting into practice the real time software simulator (RTSS)*

This is achieved by using the EPSM, deduced in step 4). A difficult problem is to simultaneously ensure the real time operation of the RTSS and its immunity to disturbances, even more provided that this model describes a fast dynamic and that the driving way adopted in the RTPS involves the non causality of the EPSM.

6) *Design of the tracking system contained in the physical part of the RTPS (EFT)*

The difficulty of designing a control law for this loop is in general due to the non linearity of the process and to the fast variations of its dynamic parameters. Therefore, one must guarantee that the EFT's settling time is much smaller than the EPS's one.

7) *Building of the IPS, which is strongly context dependent.*

3.3 DEVELOPMENT PLATFORM'S STRUCTURE FOR THE CHOSEN CLASS OF WECS TO SIMULATE

The wind power converters structure significantly differs from a case to another (e.g., the generator scheme called Scherbius cascade [LUBO 03] vs. the one using a permanent magnet synchronous generator), so a test rig (in a certain hardware structure) can simulate only a category/class of such converters. This section aims at establishing the WECS type to simulate and at stating the requirements imposed to the variable speed WECS physical simulator.

Characterizing the class of WECS to simulate

The WECS considered in this chapter has the main features as listed in §1.4; the only difference lies in the EMS, as the generation subsystem contains here a doubly-fed induction generator (DFIG). In this case, the variable speed regime of the wind turbine is allowed by using back-to-back power electronics (PWM) converters in the rotor circuit [LUBO 03]. Also, a rigid single step speed multiplier (drive train) is used as mechanical transmission.

Two kinds of control systems are used for the converted power transfer to the electrical grid: the torque/speed control of the induction generator and the control of the parameters of the electric power fed to the grid. An upper level of control for global WECS management should also be considered.

From the point of view of the HILS methodology, the above described system is the BPS. A general control problem can be defined for this system, concerning the electromechanical power of the generation system (e.g., the maximisation of the captured power from the wind).

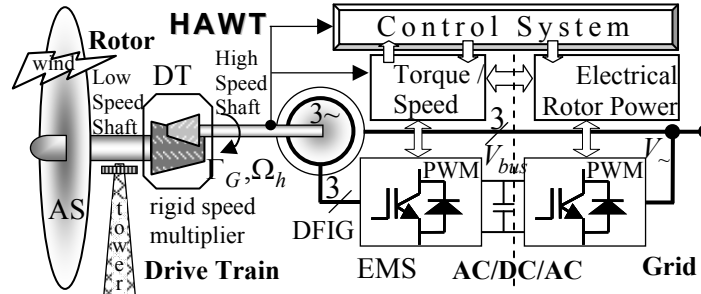


Fig. 3.4 Topology of the wind energy system (BPS) to simulate

Requirements imposed to the WECS test rig

A 1:1 (same power) simulator for the above described variable speed WECS, allowing reproducible experiments, must be built. It must reproduce the behaviour of different wind turbines belonging to the above described WECS class when conditions about the wind sites and the wind/weather vary, in different operating regimes and under various control inputs.

As the physical system is fixed, the simulator must have the ability of changing the scale factors in order to allow different wind turbines being simulated. The parameters of the wind turbines and of the wind site must also be easily changed for obtaining a flexible test rig. As its final scope is to experiment various control laws in variable speed regimes, the test rig must allow these control laws being interchanged and the manipulation of the parameters and of the experimental results through an user interface.

The energy conversion process is dealt with by means of the generator control, thus the IPS will contain the electrical part of the WECS (EMS – taken as it is in the original system). The WECS simulator must render the experiments insensitive to weather conditions, allowing the wind site's features easily changing. For flexibility and economical reasons, the aerodynamic parts and transmission behaviour must also be emulated, so included in the RTPS.

The choice of the driving (and consequently the response) variable(s) considerably affects both the hardware and the software parts of the test rig. Therefore, one must clearly establish the driving variable before starting building the platform. In the present work the choice is made as stated in the second case from §3.2, that is, the driving variable will be a *cause*, namely the *high speed shaft torque*.

3.4 BUILDING THE RTPS

This section aims at illustrating the using of the main methodological steps – as stated in §3.2 – to the construction of a physical simulator for a variable speed WECS having the main characteristics stated in §3.3.

3.4.1 Modelling of the BPS. Identification of the interaction variables

In figure 3.4 one can identify the main functional parts of the BPS:

- aerodynamic subsystem (turbine rotor), which captures the wind energy and turns on the LSS;

• mechanical transmission subsystem (speed multiplier), which transfers the power to the electrical generator by means of the HSS;

- electromechanical subsystem, consisting of the electrical generator;
- power electronics, allowing the rotor to be coupled to the local utility grid;
- utility grid and connection elements;
- control subsystem, allowing that various operating regimes be imposed.

It is proposed that the considered BPS (figure 3.4) be structured from the HILS point of view as follows:

- the EPS consists of the aerodynamic subsystem (mainly the turbine rotor) and the low speed shaft;
- the IPS is made of the DFIG and the PWM inverters;
- the IER is represented by the high speed shaft, allowing the interaction EPS-IPS.

As the EPS-IPS interaction is realized at high speed shaft level, the interaction variables have a mechanical nature, namely the mechanical torque (Q class) and the high speed shaft rotational speed (P class). In the sequel, models of the above identified parts are presented and variables introduced in relation (3.2) will be instantiated in the particular case of the considered WECS.

For the aerodynamic subsystem, the average model employing the rotor aerodynamic performance is used, yielding the wind (aerodynamic) torque provided by the turbine rotor (§2.3.1, [CARD 04]):

$$(3.4) \quad \Gamma_{wt}(\Omega_L, v) = 0.5 \cdot \pi \cdot \rho \cdot v^2 \cdot R^3 \cdot C_T(\lambda) + \Gamma_{ts} - \Gamma_{vf} - \Gamma_s,$$

where v is the wind speed, $C_T(\lambda)$ is the torque coefficient, Γ_{ts} is the torque generated by the tower shadow effect, Γ_{vf} is the viscous friction torque and Γ_s is the static friction torque.

As in §2.3.3, the turbine rotor interacts with the electrical generator by means of the drive train; if considering the movement equation of the high speed shaft, one can write:

$$(3.5) \quad \dot{\Omega}_h = \frac{1}{J_h} \cdot \Gamma_h - \frac{1}{J_h} \Gamma_G(\Omega_h),$$

where the involved parameters have been previously defined and $\Gamma_h = \eta \cdot \Gamma_{wt}/i$ is the wind torque rendered at the HSS. Consequently, the high speed shaft is confounded with the IER and its dynamics are given by relation (3.5).

Comparing with IER's equations from relation (3.2), one can note that $A_R = B_R = \frac{1}{J_h}$. Concerning EPS's

equations from relation (3.2), it is also easy to note that $\mathbf{u}_S \equiv v$, $\mathbf{x}_R \equiv q_2^R \equiv \Gamma_h$, $p \equiv \Omega_h$.

IPS is composed of the DFIG and the PWM inverter (figure 3.4). It is described by relations (3.6), where the first seven equations describe the dynamic operation of the DFIG, whereas the last three equations correspond to the average model of the PWM inverter [BOSE 86]. In both cases, classical generic notations are used, namely: V , I and Φ representing respectively the voltages, currents and flux, R and L correspond to resistance and inductance respectively, indices d and q refer to variables in the (d,q) system and Γ_G is the generator electromagnetic torque. For the DFIG indices 1 and 2 refer respectively to stator and rotor, L_m' is the coupling inductance, $\sigma = 1 - L_m'^2 / (L_1 \cdot L_2)$ is the leakage factor, ω represents pulsation and p is the pole pair number. For the PWM inverter, V_0 , C and R are respectively the voltage, the capacity and losses of the DC-link, L_s and R_s represent respectively the inductance and resistance of the DFIG stator, V_m is the maximal voltage and β is the commutation function [LEON 01].

$$(3.6) \quad \left\{ \begin{array}{l} V_{2d} = R_2 I_{2d} + \sigma L_2 \frac{dI_{2d}}{dt} - \omega_2 \sigma L_2 I_{2q} + \frac{L_m'}{L_1} \frac{d\Phi_{1d}}{dt} - \left(\omega_2 \frac{L_m'}{L_1} \Phi_{1q} \right) \\ V_{2q} = R_2 I_{2q} + \sigma L_2 \frac{dI_{2q}}{dt} + \omega_2 \sigma L_2 I_{2d} + \omega_2 \frac{L_m'}{L_1} \Phi_{1d} + \left(\frac{L_m'}{L_1} \frac{d\Phi_{1q}}{dt} \right) \\ V_{1d} = 0 = R_1 I_{1d} + \frac{d\Phi_{1d}}{dt} - \omega_1 \Phi_{1q} \\ V_{1q} = R_1 I_{1q} + \omega_1 \Phi_{1d} + \frac{d\Phi_{1q}}{dt} \\ \Phi_{1d} = L_m' I_{2d} + L_1 I_{1d} \\ \Phi_{1q} = L_m' I_{2q} + L_1 I_{1q} \cong 0 \\ \Gamma_G = -p \frac{L_m'}{L_1} \Phi_{1d} I_{2q} + p \frac{L_m'}{L_1} \Phi_{1q} I_{2d} \cong p \Phi_{1d} I_{1q} \\ L_s \frac{dI_{PWMd}}{dt} = V_m - R_s I_{PWMd} + L_s \omega I_{PWMq} - \frac{V_0}{2} \beta_d \\ L_s \frac{dI_{PWMq}}{dt} = -R_s I_{PWMq} - L_s \omega I_{PWMd} - \frac{V_0}{2} \beta_q \\ C \frac{dV_0}{dt} = \frac{3}{2} [I_{PWMd} \cdot \beta_d + I_{PWMq} \cdot \beta_q] - \frac{V_0}{R} \end{array} \right\} \quad \begin{array}{l} \text{DFIG (a)} \\ \text{PWM (b)} \end{array}$$

Comparing the equations of IPS in relation (3.2), one can remark that $\mathbf{u}_I \equiv [V_d \ V_q \ \beta_d \ \beta_q]^T$, $\mathbf{x}_I \equiv [\Phi_{1d} \ \Phi_{1q} \ I_{2d} \ I_{2q} \ V_0 \ I_{PWMd} \ I_{PWMq}]^T$, $q_1 \equiv \Gamma_G$. Concerning the outputs, $\mathbf{y}$, these may be appropriately chosen as combinations of states.

Therefore, the BPS model is obtained by coupling equations (3.4), (3.5) and (3.6), and consequently the total input and state vectors of BPS are respectively:

$$\left\{ \begin{array}{l} \mathbf{u} = [v \ V_d \ V_q \ \beta_d \ \beta_q]^T \\ \mathbf{x} = [\Phi_{1d} \ \Phi_{1q} \ I_{2d} \ I_{2q} \ V_0 \ I_{PWMd} \ I_{PWMq} \ \Omega_h]^T \end{array} \right.$$

In conclusion, in the approached case the investigated physical system (IPS) is composed of electrical elements belonging to the energy conversion chain, the emulated physical system (EPS) is formed by the aerodynamics and the low speed shaft, and the interaction EPS-IPS is realized at the high speed shaft level, which is the IER. The EPS's input is a computer synthesized wind speed, and the IPS's inputs are provided by a control system.

3.4.2 Configuration of the physical part of the RTPS. Determination of the EPSM

The physical part of the effector (EFT) is here implemented by a torque/speed controlled permanent magnet DC motor (DCM with parameters given in appendix C), rigidly coupled to the DFIG shaft in the IPS by means of a speed reduction gear. This motor must reproduce the mechanical characteristics of the high speed shaft of the wind power system.

Case 1: choosing the driving variable as being an effect variable

In this case, the high speed shaft's rotational speed, Ω_h , is chosen as driving variable; consequently, the response variable will be the generator torque, Γ_G (usually estimated based upon generator main variables).

Essentially, one must impose to the IES (which is the mechanical shaft supporting the DCM and DFIG), a rotational speed having a dynamic corresponding to that of the high speed shaft. So, in this case the EFT is a rotational speed control loop. The relations used for obtaining the IES's speed reference are selected from relations (3.2):

$$\begin{cases} \dot{\mathbf{x}}_R = \mathbf{F}_R(\mathbf{x}_R, [\mathbf{u}_S \quad p]^T) \\ \dot{p} = A_R \cdot \mathbf{G}_R(\mathbf{x}_R, [\mathbf{u}_S \quad p]^T) - B_R \cdot q_1 \end{cases}$$

Taking into account that in our case $\mathbf{u}_S \equiv v$, $\mathbf{x}_R \equiv q_2^R \equiv \Gamma_h$ and $p \equiv \Omega_h$ (see §3.4.1), one obtains the rotational speed reference:

$$\Omega_h^* = \frac{1}{J_h \cdot s} \cdot (\Gamma_h(v, \Omega_l) - \Gamma_G),$$

where the term $\Gamma_h(v, \Omega_l)$ derives essentially from relation (3.4). This choice corresponds to a causal (direct) EPSM, but to a relatively slow dynamic of the EFT and a measure of the DFIG electromagnetic torque affected by estimation errors.

A HIL implementation of a similar system, having made the above described choice, is reported in [MUNT 97], [DIOP 99b], [CUTU 05].

Case 2: choosing the driving variable as being a cause variable

In this case, the HILS high speed shaft's mechanical torque, denoted by Γ_E , is chosen as driving variable, the response variable will then be the high speed shaft rotational speed, Ω_h (measured by means of an encoder); therefore, EFT is a torque control loop. Such a choice ensures a very fast dynamic of the EFT and the torque (current) control of the DC motor. Consequently to choosing the driving variable as being a cause variable, the resulted EPSM (to be implemented by the RTSS) is non causal.

As to the general approach, the driving variable, $\Gamma_E \equiv q_2^E$, must emulate the evolution of $\Gamma_h \equiv q_2^R$, such that to obtain the same dynamical evolution of the interaction variable, p . From equating the state equations of p variable in set (3.2) of BPS and in set (3.3) of HILS system results that $A_R \cdot q_2^R - B_R \cdot q_1 = A_E \cdot q_2^E - B_E \cdot q_1$ and further:

$$q_2^E = \frac{A_R}{A_E} \cdot q_2^R + \frac{B_E - B_R}{A_E} \cdot q_1,$$

where q_1 is finally obtained from IER's equation in BPS:

$$(3.7) \quad q_2^E = \frac{A_R B_E}{A_E B_R} \cdot q_2^R - \frac{B_E}{A_E} \left(\frac{1}{B_R} - \frac{1}{B_E} \right) \cdot \dot{p}$$

Relation (3.7) shows the dependence of the driving variable, q_2^E , of the response one, p , whose derivative must be computed/estimated. In the simulator, $A_E = B_E = \frac{1}{J_E}$, where $J_E = J_g + J_{DCM}$, with J_{DCM} representing the DC machine inertia. Finally, taking into account the above identification of the model elements, the value to impose as reference to the tracking loop inside the EFT results as:

$$(3.8) \quad \Gamma_E = \Gamma_h - \left(\frac{J_{wt} \cdot \eta}{i^2} - J_{DCM} \right) \cdot \frac{d(\Omega_h)}{dt} = \frac{\eta \cdot \Gamma_{wt}}{i} - \left(\frac{J_{wt} \cdot \eta}{i^2} - J_{DCM} \right) \cdot \dot{\Omega}_h,$$

where relation (3.4), using a synthesized wind speed, v , must be implemented in the model for the wind torque

computation, Γ_{wt} . Therefore, the EPSM is composed of relations (3.4) and (3.8).

Remark:

In the general case of a 1:n simulator, with $n = P_n/P_s$, P_n being the rated power of the real system and P_s being the rated power of the simulator, the simulator inertia results from the movement equation as:

$$J_s = \frac{J}{n} \cdot \left(\frac{\Omega_n}{\Omega_s} \right)^2,$$

with J , Ω_n and Ω_s being the system inertia and rated speed and the simulator rated speed, respectively.

In the sequel in this chapter, the implementation of the EPSM in the RTSS and the building of the EFT within RTPS correspond to the second case.

3.4.3 Building the RTSS. Design of the tracking system within the effector

The role of RTSS (software part of the RTPS) is to provide a wind speed sequence – using a pseudo-random model or a deterministic one [NICH 02] – to implement the EPSM and to compute the imposed value of the driving variable, fed as a reference to the EFT. The RTSS is a component of a software application running on a floating point digital signal processor (DSP), that is a PowerPC 750 of the DS1005 board [*** 03]. The other component of the program is dedicated to implementing the PWM control algorithms of the IPS's elements, which will be detailed in §3.5.

The program on DS 1005 runs two tasks (figure 3.5b):

- a *principal (interruption) task*, which has the highest priority, in charge with real time operations, related to RTSS: reading the analogical inputs from transducers, running the EPSM and providing the output reference of EFT;
- a *background task*, which updates the DSP memory used for the modified variables by means of an user interface.

The simulation diagrams corresponding to the two tasks have been built in Matlab/Simulink™ and implemented by means of the *Real Time Interface* toolbox (dSPACE RTI for target processor DS1005). The bidirectional information flux between the physical and the software part is supported by the data acquisition interface of the DSP. The user supervising interface has been realized through a ControlDesk™ panel for monitoring the interest variables.

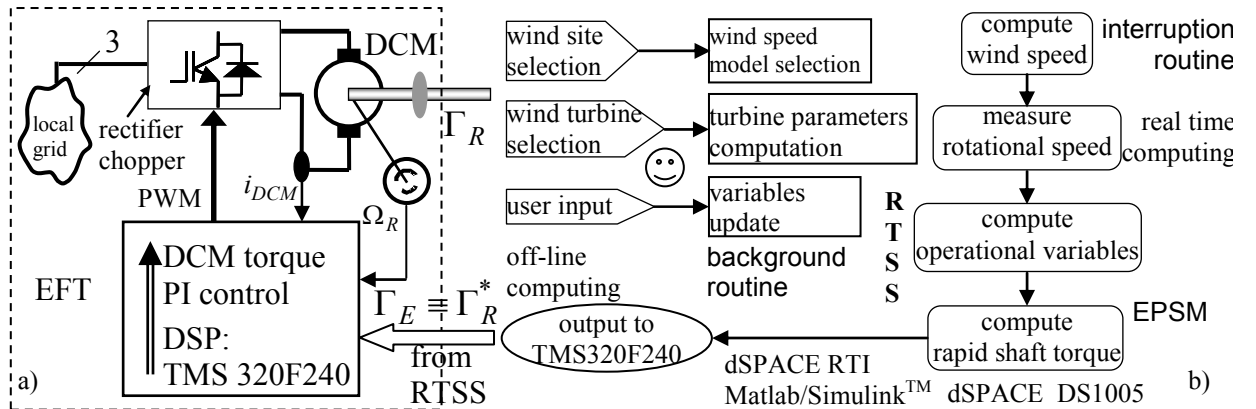


Fig. 3.5 RTPS's hardware a) and software b) components

The physical realization of the driving variable, Γ_E , is carried out using the DC machine; based upon its proportionality with the induced current [LEON 01], a current tracking loop is employed. It is composed of a current

transducer, a numerical PI regulator supported by a fixed point digital signal processor, TMS320F240, and an actuator composed of a PWM IGBT chopper (4 quadrants) connected with a diode rectifier (figure 3.5a)).

The parameters needed by the control algorithm are provided by a computer via the RS232 protocol, by means of a TestPoint™ user interface. Thus it is also allowed to visualize the torque reference, Γ_E , computed on the DS1005 board and provided to the TMS320F240 DSP via an analogical input.

3.4.4 Experimental results to validate the RTPS operation

This section will present the performance of the effector in different conditions. The parameters of the wind turbine used for the experimental setup can be found in appendix A.

In figure 3.6a) one can see the step response of the current loop within the EFT, when the DCM current reference step covers the entire domain. The rising time of the response is very short, as expected, around 4 ms. As the time constant of the EPS is generally large (for low power wind turbines it can be around 0.1 s), the torque tracking loop speed is high enough for ensuring the second reproducibility condition (see §3.2).

In figure 3.6b) one can remark the dynamical behaviour of the turbine rotor for a pseudo-random wind speed sequence having an average value of 7 m/s and medium turbulence intensity of $I=0.17$, this latter obtained by using the von Karman spectrum in the IEC standard.

The upper part of figure 3.6b) shows that the rotational speed of the low speed shaft is maintained almost constant by the IPS. The induction generator speed evolves within a restraint domain in oversynchronous regime and presents some variations due to a sufficiently high slip.

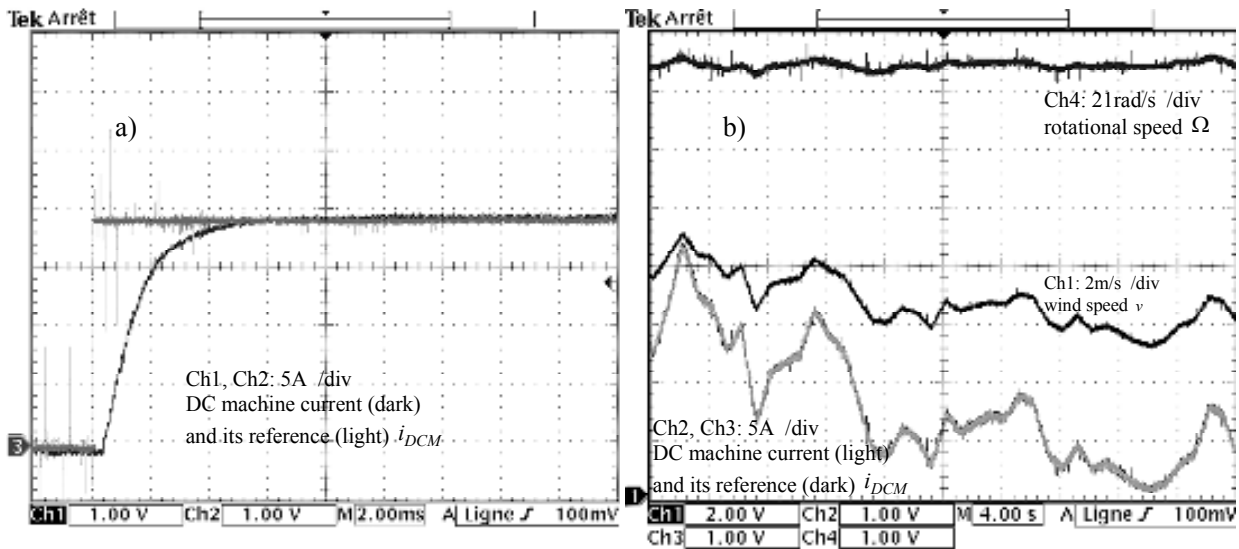


Fig. 3.6 RTPS operation

The current evolution corresponding to high speed shaft mechanical torque is given in the lower part of figure 3.6b). One can note the perfect tracking of the high speed shaft torque (current) reference, obtained using the computer synthesized wind speed, measured rotational speed and the EPSM.

3.5 BUILDING THE IPS. ELECTRICAL GENERATOR CONTROL

The IPS in the HIL simulator is the same as in WECS. Here, its construction is oriented to the control loops realizing the transfer of the DFIG power to the electrical grid. As this transfer is performed in two stages, two control subsystems are to be implemented, one for controlling the generator and one for transferring the DC-link

power to the grid. Each of these structures acts on the correspondent voltage source (PWM) inverter (see figure 3.4).

3.5.1 Control of the wind turbine

The variable speed operation of WECS having rigidly coupled drive train can be generally achieved by controlling either the speed or the torque of the turbine high speed shaft. In order to obtain a smoother behaviour – so less mechanical fatigue – of the drive train, the DFIG is vector controlled. Here a vector control structure is employed. It is obtained using a stator field oriented (d,q) model for the wound rotor induction machine; under some assumptions [BOSE 86] this model can be derived from relations (3.6a). The control structure is based on the separate control of the electromagnetic torque (motion control) and rotor flux (flux alignment onto d axis) [LUBO 03], [CARD 04]. PID controllers are used for this purpose, which can be tuned using the modulus and symmetrical optimum criteria [ASTR 95b]. As the DFIG rotor is supplied by a voltage source inverter, the control law is affected by some decoupling and compensation terms [RABE 02].

The speed control adds another outer loop governed by a third PID controller, designed using the symmetrical optimum criterion. Being considered classical and well known [BOSE 86] [LEON 01], this control structure of the DFIG torque/ speed is not given here.

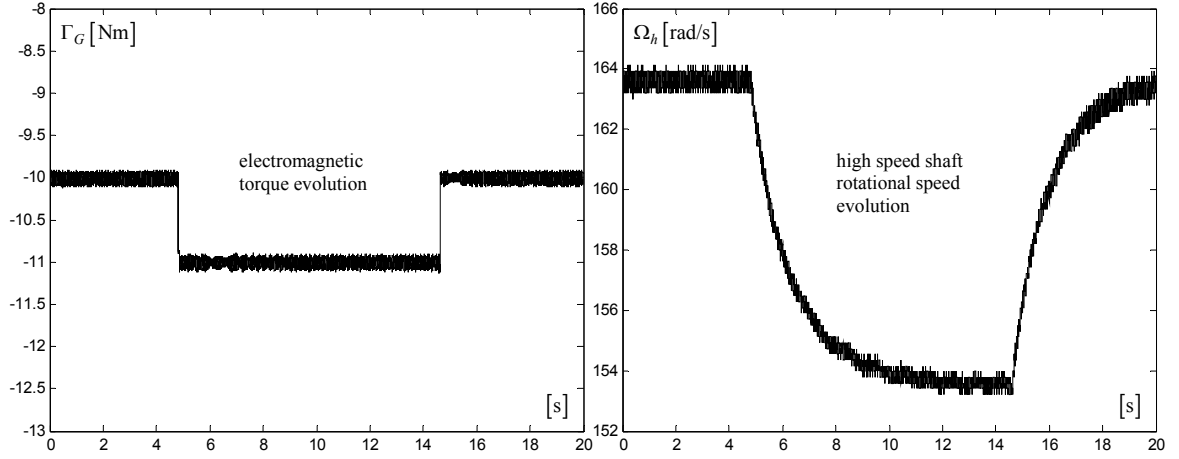
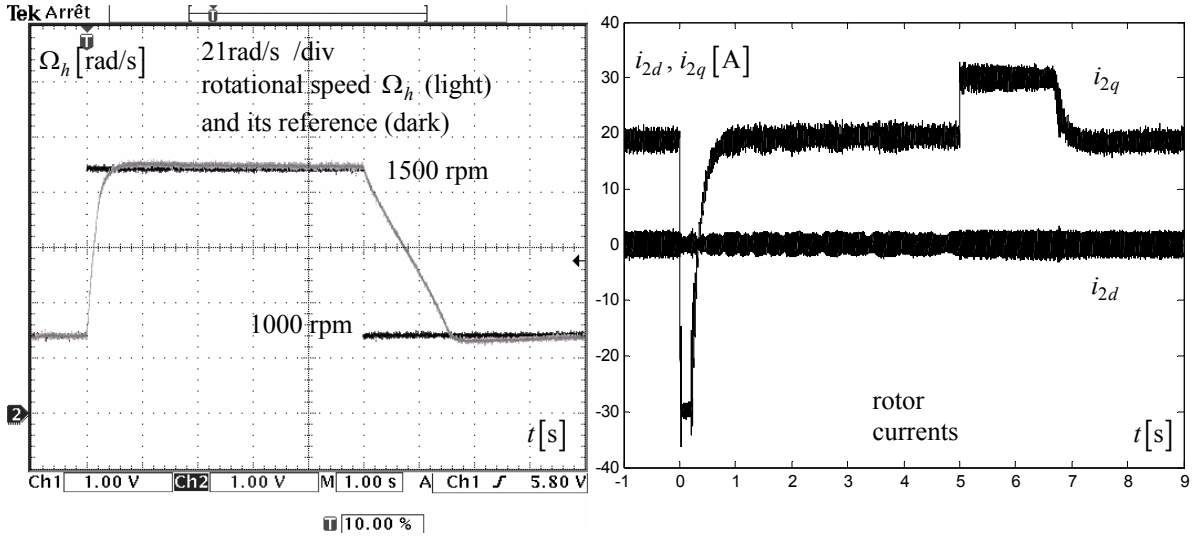


Fig. 3.7 Torque control of the WECS ($v=7$ m/s)

Figure 3.7 (ControlDesk/Matlab captures) shows the behaviour of the torque controlled WECS for 20 seconds time horizon when the wind speed is constant at 7 m/s, for step changes in the electromagnetic torque reference. One can see an instantaneous (ms sized) torque response of the DFIG (left side). The evolution of the rotational speed (high speed shaft) is presented on the right side. The dynamic response of the system is very slow because of the turbine rotor inertia and depends on the operating point.

In figure 3.8 one can see the WECS's response to step rotational speed reference, under constant wind speed, of 8 m/s. The left side shows differences between tracking the rising edge and respectively the falling edge of the reference, mainly due to the torque limitations, as visible on the right side of the figure in the evolution of i_{2q} (rotor current, proportional with the electromagnetic torque). Current i_{2d} is zeroed, and so the rotor flux has a constant value depending on i_{1d} .

Figure 3.8 shows also that the DFIG motoring regimes are allowed, which is useful for starting the turbine when the wind speed is not sufficiently high. In conclusion, the harvested power is partially converted – depending upon the turbine driving regime – at the DFIG rotor level, being further retrieved within the DC-link (figure 3.4).

Fig. 3.8 Speed control of the WECS ($v=8$ m/s)

3.5.2 Transfer of the generator rotor power to the grid

A second stage for transferring the DFIG rotor's power to the grid is realized using another inverter (grid-side) acting as an interface, as shown in figure 3.4. This is performed by feeding tri-phased currents into the mains, while controlling the DC-link voltage at a constant value, V_{bus} . The control structure is synthesized using the (d,q) model of the tri-phased electrical system and the DC-link modelling (derived from relations (3.6b)), having an outer voltage control loop and two current control loops for q and d current components [PENA 96], [POLL 03].

These loops employ anti-windup PI controllers, tuned using modulus optimum criterion. The inner loops output the grid voltage references in the (d,q) frame, to be firstly transformed into a tri-phased system, then applied to the inverter. A phase locked loop for obtaining the mains electrical angle is used for synchronising the rotor voltage system angle with the grid one [KAUR 97], [RABE 02]. The reference of the voltage controller is constant, at 350 V, and its output feeds the i_q current loop. The i_d reference is zero, as the reactive power control is not of interest here.

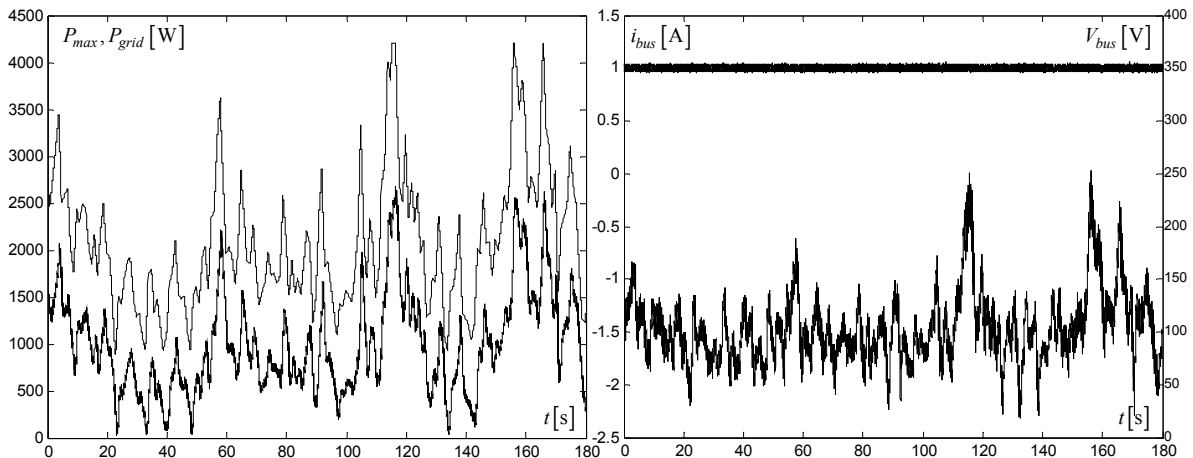


Fig. 3.9 Grid-side inverter control

In the left side of figure 3.9, one can see the evolution of the power that can be maximally harvested, P_{max} , corresponding to a wind speed sequence having an average of 7 m/s and medium turbulence intensity of $I=0.17$ (obtained by using the von Karman spectrum in the IEC standard – see figure 2.4 from §2.2.1). Below this curve the

power fed to the grid, P_{grid} , is plotted, exhibiting a total efficiency of about 40%. The right side of figure 3.9 shows the DC-link voltage control efficiency, under the same wind conditions. The variations of the DC-link current, i_{bus} , feeding the grid-side inverter, are also presented.

3.6 GLOBAL CONTROL OF THE SIMULATED WECS. OPERATING REGIMES

3.6.1 Diagram of the HIL simulator

As a conclusion to the developed approach, here below is given the complete functional diagram of the WECS real time simulator, designed according to the HILS methodology (figure 3.10). One can remark that the conversion chain, represented in figure 3.4, is fully replicated by the HILS structure.

In IPS (right side of figure 3.10), the control structures realizing the DFIG rotor power transfer to the grid, previously exposed in §3.5.1 and §3.5.2, have been built in Matlab/Simulink™ (on computer PC1) and implemented by means of the *Real Time Interface* toolbox (dSPACE RTI for target processor DS1005). This software component includes also an operating mode controller, responsible for the global behaviour of the WECS. The resulted code runs on the DS1005 Power PC processor together with the RTSS. The bidirectional information flux – containing sensor information (A/D), PWM outputs, binary configuring signals for the power system, D/A outputs for visualizing rapid signal variations – is supported by a complex I/O system of the DSP. The interest variables are monitored by means of a ControlDesk™ panel.

The left side of figure 3.10 contains the structure of the RTPS, previously described in §3.4, monitored by means of the TestPoint software on computer PC2. One must note that the RTPS-IPS interaction happens only at the physical level, by means of the DFIG shaft.

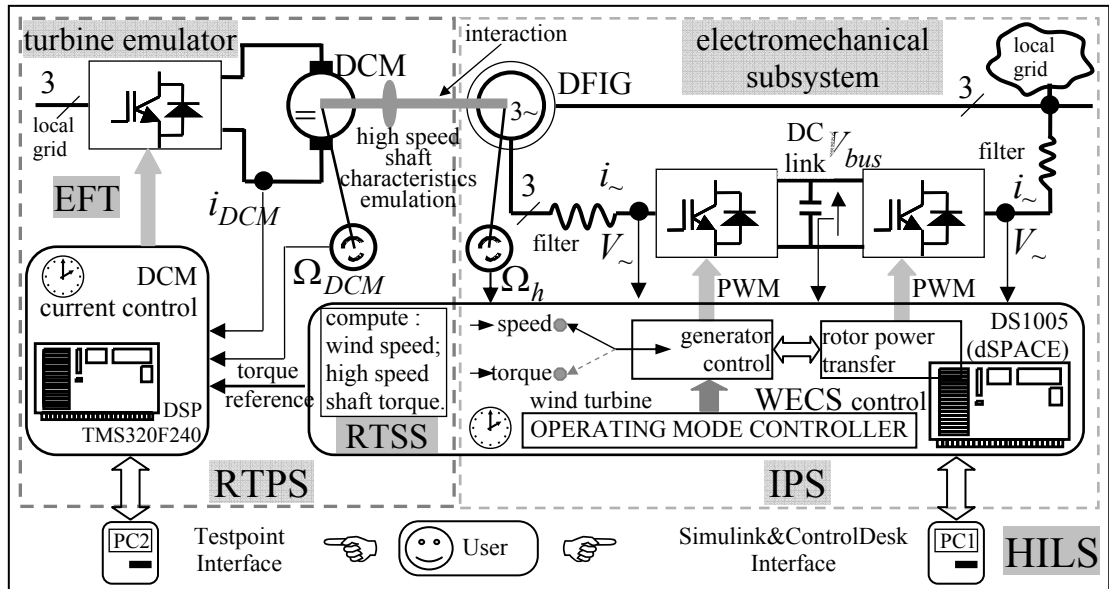


Fig. 3.10 Functional diagram of the WECS real time simulator, as to the HILS methodology

3.6.2 Simulation of fixed speed operating regime

In figure 3.11 a direct connection between the DFIG and the grid is emulated, such that the HILS reproduces the fixed speed operation of WECS under a random wind speed sequence (figure 3.11a)), as imposed by the DFIG (figure 3.11d)). One can note the non optimal evolution of the tip speed, λ , (figure 3.11b)), of the generator torque,

Γ_G (figure 3.11c)), of the power coefficient, C_p , expressing the aerodynamic efficiency high deviations from the optimal value (figure 3.11e)), and of the electrical power delivered to the grid, P_{grid} (figure 3.11f)).

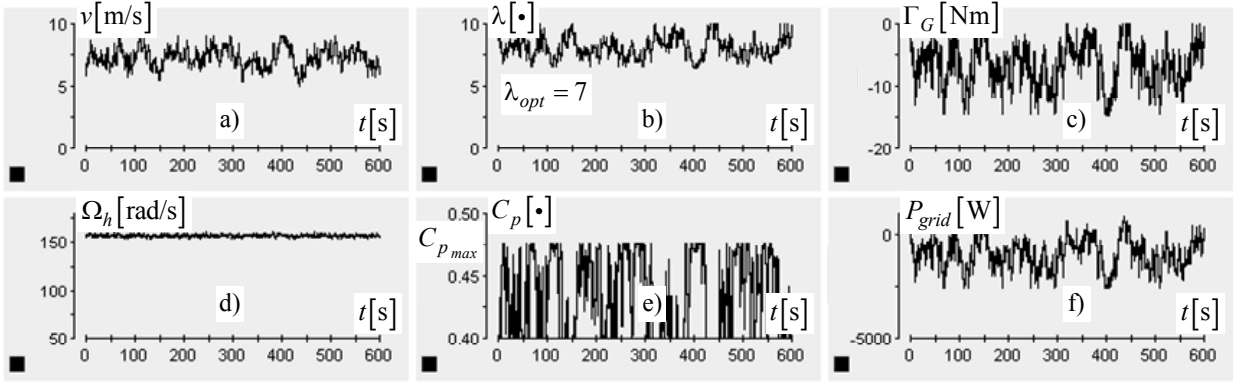


Fig. 3.11 HILS global functioning, *fixed speed* – ControlDesk™ captures

3.6.3 Variable speed operation

Figure 3.12 illustrates the variable speed operation of the considered WECS. In this case, the IPS is torque controlled (figure 3.12c)), in order to track the energetic optimum (which is equivalent to tracking the optimal tip speed – figure 3.12b)), the maximal power coefficient – figures 3.12e) and 3.12h), and to harvesting wind power around the optimal regimes characteristic, ORC – figure 3.12i). The random wind speed sequence used here (figure 3.12a)) has the same spectral properties as the one in figure 3.11a). The high speed shaft's rotational speed varies in a large domain (figure 3.12d)).

One can remark the evolution of the power captured from wind (figure 3.12g)) and of the power provided to the grid, P_{grid} (figure 3.12f)); the difference between the two results from a non unitary global efficiency of the system.

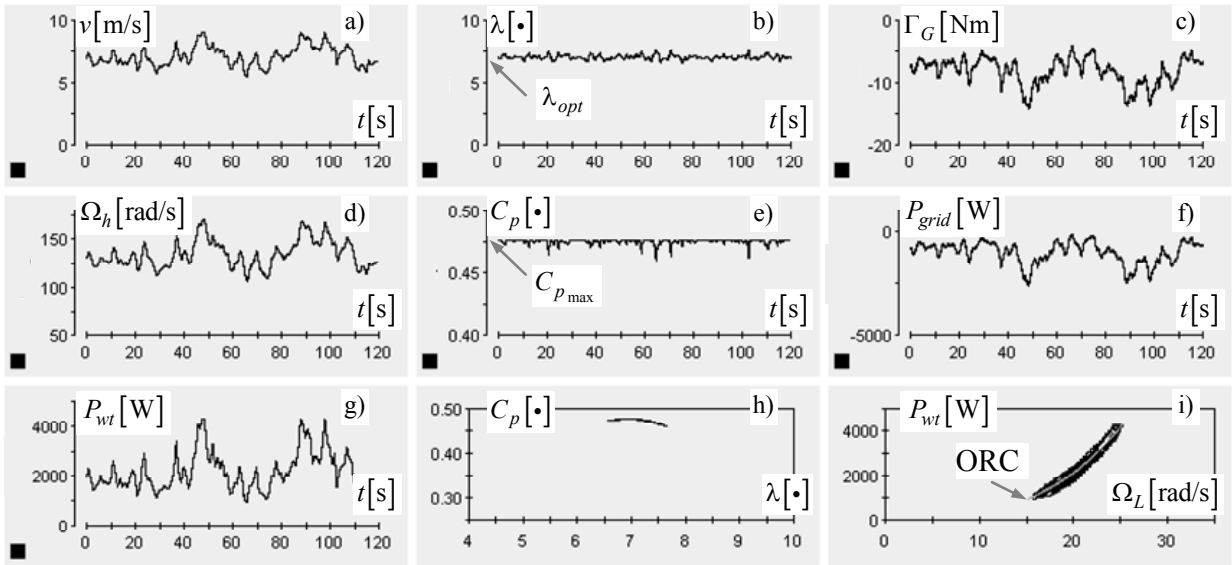


Fig. 3.12 HILS global functioning, *variable speed* – ControlDesk™ captures

The tip speed and the power coefficient present large deviations from their optimal values, λ_{opt} and $C_{p_{max}}$ respectively, in the fixed speed case versus the variable speed case (figures 3.11b) and 3.12b) versus figures 3.11e) and 3.12e) respectively). The IPS is controlled in sliding mode; more details on this issue can be found in the eighth chapter of this work and also in [MUNT 06].

3.7 CONCLUSION

The approach exposed in this chapter concerns the building methodology and practical aspects, as well as the description of functions and capabilities of a development platform dedicated to the real time simulation of WECSs. Its construction is based upon using the HILS principle, which generally consists in closed loop connecting hardware and software components, in order to reproduce the dynamic behaviour of an industrial process in a laboratory controlled environment. The insertion of the physical elements contributes to a better reproduction of the real phenomena and to the reduction of the information processing time within the simulator. The HILS structure consists of a real time physical simulator (RTPS) which interacts with an investigated physical subsystem (IPS). As a general remark, the physical simulator replaces a usually expensive part of the system operating in a stochastic environment, whereas the IPS exists in the HIL simulator exactly as it is in the real system also. The interaction between the two is controlled by the software part of the simulator, which encloses a model of the simulated physical subsystem.

The development platform for the class of WECS considered here is designed using a general systematic method, whose steps require a thorough modelling approach. Thus, the RTPS has been identified as the turbine's aerodynamic subsystem (rotor), with the IPS being the controlled electrical generator (in this case, a DFIG based generation structure has been chosen). Some control aspects concerning the transfer of the electrical power to the grid have also been presented.

The result is a flexible experimental rig that allows experiments being carried out independently from wind and meteorological conditions. As it uses synthetic wind speed, such simulator can be used at wind turbine performance analysis and sitting, at wind turbine testing in various functioning (or failure) regimes, at validating various control strategies of the turbine generator and at studying the transfer of the provided electric power to the grid.

Some experimental results illustrating the simulator's main parts operation, as well as the global operation in different regimes have been presented. Thus, real time simulations have been carried out for both fixed and variable speed operation, the latter for validating the performance of a torque control law aiming at maximizing the energetic efficiency under reasonable control effort (as detailed in the eight chapter of this work). Results show a perfectly realistic behaviour of the simulator versus the original system, provided the adopted modelling assumptions.

Future work shall aim at extending the capabilities of the development platform for implementing various wind speed models, types of rotors (for example, variable pitch or vertical axis wind turbines – VAWT) and drive trains (for example, flexible or multiple ratio) and also different control laws ensuring variable speed operation.

Chapter 4

MAXIMUM POWER POINT TRACKING (MPPT) – A MINIMAL KNOWLEDGE APPROACH

The control problem associated to the variable speed WECS class established in chapter 1, working in the partial load region, consisting in the energetic conversion maximization, is approached here under the assumption that the wind turbine model and its parameters are poorly known.

Using a new approach derived from the optimum seeking methods category, generically called **Maximum Power Point Tracking (MPPT)**, the control solution proposed in this chapter aims at driving the average position of the operating point near to optimality. Instead of inducing sinusoidal search signals [ARIY 03], here the wind turbulence is used as search disturbance. The average rotational speed of the HSS is slowly adjusted using the fast Fourier transform (FFT) processing of some available measures from the system as an estimate of the operating point's position/distance to optimality. Numerical simulations are used to validate the control law based on this estimation.

4.1 Problem statement and literature review

As stated in chapter 2, for a low power horizontal axis variable speed WECS working in the partial region, one can associate a control problem for maximizing the energy captured from the wind. Consider that the aerodynamics and drive train models are not fully available and only some constructive parameters are known. Also, only the HSS's variables, generator's variables and the wind speed can be measured.

The stated problem (captured energy maximisation) can be solved by employing linear (and quite elaborated) methods for obtaining the control law, like those cited in chapter 2. Their performances on real systems depend on the accuracy of the system parameters employed in the control law, on the intrinsic nonlinearities and parametric variations, so that the nonlinear methods are often used. These methods usually employ the simple and reliable on-off control law for desensitising the controlled system with respect to the WECS parameters and to the unmodelled dynamics.

A very reliable and robust control method is the so-called "Maximum Power Point Tracking" (MPPT) [HILL 94], [WANG 99], [SCHI 00], [SCHI 01], [TSOU 03], which covers in fact an entire class of extremum search algorithms. Basically, the approach employs these algorithms (i.e., hill climbing method) [DATT 03], [WANG 04], [TAN 04] for dynamically driving the operating point to the ORC, by using some searching (probing) signal in order to obtain gradient estimations of some (few) measurable variables.

Given that the WECS parameters (i.e., the optimal tip speed and maximum of the aerodynamic efficiency) are unknown, the MPPT algorithms generally aim at maintaining the optimal operating point by zeroing the value $\partial P_{wt} / \partial \Omega_l$, where P_{wt} is the total wind power and Ω_l is the LSS rotational speed. Therefore, the control input, representing the wind turbine speed reference, depends on the operating point position and on its moving trend, expressed by the sign of $\partial P_{wt} / \partial \Omega_l$ (see figure 4.1 and table 4.1).

Since the turbine rotor's power is not measurable, an estimation of its value, obtained based on the active power measure is used for operating point localisation, leading to a somehow static approach. Also, for obtaining the LSS rotational speed, a measurement of the generator speed is used.

$\frac{d\Omega_l}{dt} \backslash \frac{dP_{wt}}{dt}$	< 0	> 0
< 0	$\Omega_l \nearrow$ case I	$\Omega_l \searrow$ case II
> 0	$\Omega_l \searrow$ case III	$\Omega_l \nearrow$ case IV

Table 4.1 MPPT control logic

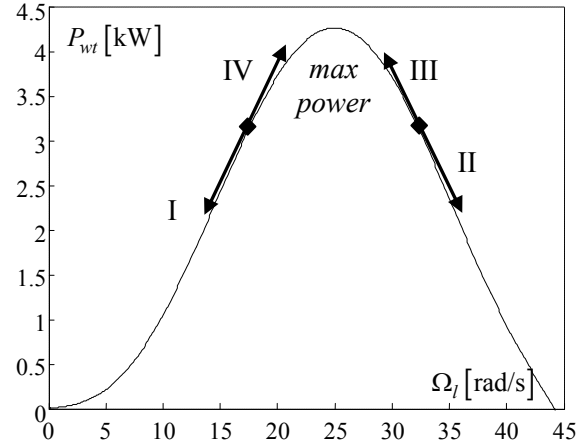


Fig. 4.1 Power static characteristic of a wind turbine

Essentially, the principle of the MPPT algorithm (as stated in most of the related papers) is:

- #k-th step:
 - measure rotational speed $\Omega_k \sim \Omega_l$, electrical power $P_k \sim P_{wt}$ and the wind speed $v_k = v$,
 - depending on the wind speed, set the rotational speed variation step (equivalent to the searching speed), $\Delta\Omega_0$,
 - estimate the power and speed gradients and deduce their signs: $A = \text{sign}((P_k - P_{k-1})/(t_k - t_{k-1}))$ and $B = \text{sign}((\Omega_k - \Omega_{k-1})/(t_k - t_{k-1}))$,
 - deduce the rotational speed variation sign as $\text{sign}(C) = \overline{A \oplus B}$ (see table 4.1), and obtain the speed variation value at step k: $\Delta\Omega_k = \text{sign}(C) \cdot \Delta\Omega_0$,
 - obtain the control input (the HSS's rotational speed reference) by integration, as $\Omega_k^* = \Omega_k + \Delta\Omega_k$; $\Omega_h^* = i \cdot \Omega_k^*$,
- rewind for $k \leftarrow k + 1$.

In this approach, based on the operating point position on the power characteristic, the rotational speed is controlled in the sense of approaching the maximum power available. The search of the power maximum, combined with the wind speed variations and high turbine inertia, has some drawbacks, from which the main are: significant estimation errors and important high frequency power fluctuations with negative influence on the system overall reliability.

The cancellation of the first mentioned drawback has been obtained using heuristic methods needing wind speed estimation, combined with power coefficient characteristic identification [SPEE 94], [BHOW 98], [FARR 00]. As for the second drawback, one can use some extensions of the MPPT algorithms, obtained by employing fuzzy control techniques [HILL 96], [SIMO 97], [CHEN 00], [ABOK 04], leading to extended and more flexible controllers, which are, however, quite context dependent. The rules base is built to maintain the operating point at a low value of $\partial P_{wt} / \partial \Omega_l$ and represent an extension of the control logic presented in table 4.1. The step variation of the rotational speed, $\Delta\Omega_0$, is variable and depends on the operating point distance from the optimal operating point and on its movement direction and speed.

The **extremum seeking control** (ESC) method relies upon finding the extremum of some unimodal hard-to-model dynamics by exciting the plant with some sinusoidal probing signals [ASTR 95a], [KRST 00], [ARIY 03]. The basic functional diagram of this control method is given in figure 4.2 [KRST 00]. This figure shows that the controller performs a modulation/demodulation operation and that its output has a harmonic component called the *probe signal*. It usually contains a washout filter (for separating the high frequency components of the plant's output), a demodulator, a low pass filter and an integrator for obtaining the average component of the control input, and a summation with the probing signal.

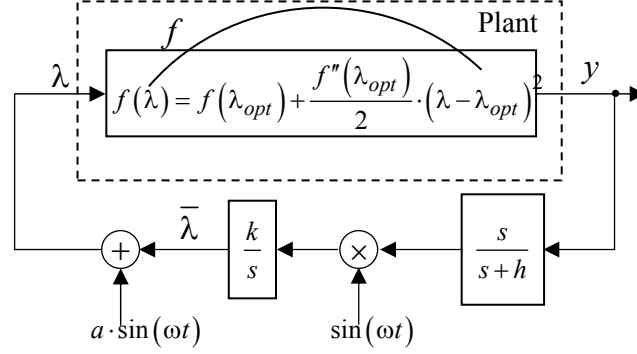


Fig. 4.2 Explaining the ESC principle [ARIY 03]

Let us consider that the plant contains a dynamic described by a generic unimodal function denoted by $f(\lambda)$, having a maximum at λ_{opt} . In this approach, the argument of function f has two components: an average one, $\bar{\lambda}$, and a harmonic probing component, of amplitude a (figure 4.2). Consider then the Taylor series of this function around its maximum, $f(\lambda_{opt})$, with $\tilde{\lambda} = \lambda_{opt} - \bar{\lambda}$ denoting the optimum search error. Given that the integrator constant k and the excitation amplitude a are positive and that $f''(\lambda_{opt})$ is negative, based on the above described diagram one can deduce that the search error gradient is negative [ARIY 03]:

$$(4.1) \quad \dot{\tilde{\lambda}} = \frac{k \cdot a^2 \cdot f''(\lambda_{opt})}{4} \cdot \tilde{\lambda},$$

and, therefore, the searching process is convergent.

Remark:

The excitation frequency, ω , must be sufficiently large to ensure stability of the closed loop system; the washout filter parameter, h , depends on this frequency [ARIY 03].

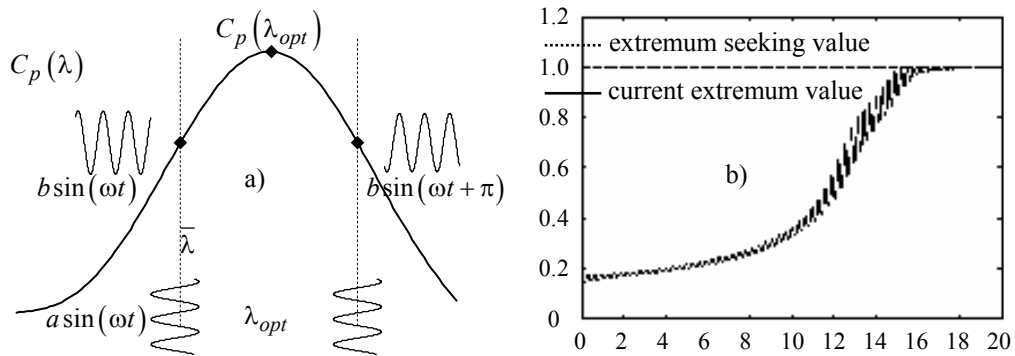


Fig. 4.3 Explaining the maximum search idea

Consider now the case of a wind turbine having an aerodynamic efficiency described by the power coefficient, C_p , as in figure 4.3, and consider a ω frequency sinusoidal variation of the tip speed and a sufficiently

small amplitude a . Depending on the position of the operating point on the slope of the aerodynamic efficiency curve, the $C_p(\lambda)$ variation will be sinusoidal, in phase with the λ variation for the ascending part and with a phase lag of π for the descending part (the intermodulation components for small a are neglected). Simple calculi give that the integrator input, $d\bar{\lambda}/dt$, will toggle its sign as the operating point (OP) moves from a side to the other of the C_p curve's optimum (see figure 4.3a)), and, assuming equal slopes of the $C_p - \lambda$ curve, its value – and consequently the search direction – varies as in relation (4.2):

$$(4.2) \quad d\bar{\lambda}/dt = \pm k \cdot b \cdot \sin^2(\omega t)$$

Therefore, the OP will move to the optimal position and the speed of convergence depends proportionally on k , a and $1/\omega$ factors [ARIY 03].

How do we use this principle for the application of WECS control? ***Instead of feeding the system with sinusoidal probing signal, we aim at using an already existing perturbation: the wind speed turbulences.*** In this case, the modulation process is naturally achieved by means of (nonharmonic) high frequency wind variations.

In this chapter is presented a new method for driving the operating point to the energetic maximum; this movement results from an extremum seeking operation using the wind turbulence as a search excitation (probing) signal. The obtained method is employed in a new form of the MPPT algorithm. The chapter is organized as follows. The next section presents supplementary details added to the main modelling assumptions about the WECS subjected to control. The proposed control solution is detailed in the third section, some simulation results are discussed in the fourth section and the fifth section concludes this chapter.

4.2 Modelling assumptions

The method approached in this chapter is intended to be applied to various types of variable speed WECS, from kW to 600 kW class and having different aerodynamic, transmission and generation configurations. However, the particular variable speed WECS used here as case study belongs to the class of systems presented in chapter 2.

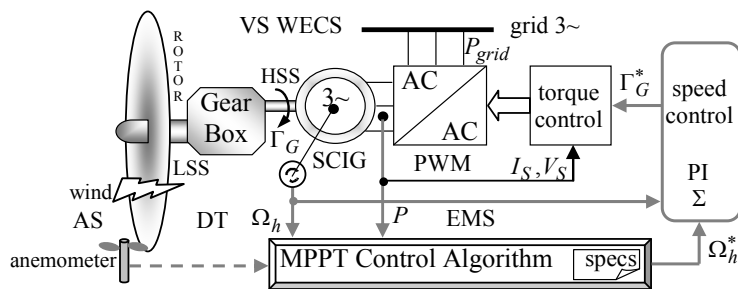


Fig. 4.4 The controlled WECS

Apart from the elements already presented in §2.1 – §2.3, the approached system presents a higher level control loop superposed on the generator torque control: the HSS rotational speed control (figure 4.4). This allows the direct control of the tip speed ratio, as required by the principle exposed in figure 4.2. Operating an induction machine by using vector control is a wide developed and well known technique [BOSE 86], [LEON 01], which supposes the employing of a PI controller in conjunction with the torque generator control (§2.3.4). As the torque gradients must not exceed certain limits imposed by reliability requirements, the speed PI controller parameters are designed for narrow frequency band of the speed loop; supplementary, the speed reference gradient is also limited. Elements concerning the speed control of the WECS are given in appendix D.

The general modelling frame (from chapter 2) concerning the modelling assumptions stands also for this chapter. Supplementary assumptions are listed below:

- the WECS can turn at an adjustable speed, whose gradient is bounded, depending on the system inertia,
- measures of the wind speed, rotational speed and electrical power are available,
- the turbulence in the wind is significant,
- concerning the known parameters of the system, only the blade length, R , the transmission step, i , an estimation of the turbine rotor's inertia and the SCIG parameters are available; the aerodynamic efficiency characteristic is totally unknown (and so are the maximum of C_p and λ_{opt}), but is supposed to be unimodal,
- a reliable measure of the captured power can be obtained using the electrical power, $P = \eta \cdot P_{wt}$, since the power conversion efficiency, η , is considered constant in the concerned rotational speed range,
- a measure of $C_p(t)$ is necessary (see figures 4.2 and 4.3),
- as the control input concerns only the average value of the tip speed (the high frequency probing signal is generated “naturally” from the turbulence wind speed), then the rotational speed is practically instantaneously obtained from its reference (in any case, faster than the variations of the low frequency wind speed component, v_s).

Using the previous assumptions and remarks in the modelling frame exposed in §2.1 – §2.3, the model of the variable speed WECS can be sketched as in figure 4.5.

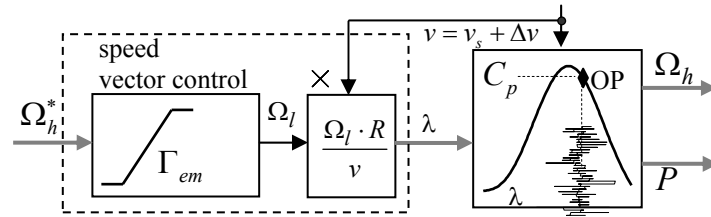


Fig. 4.5 The WECS model used for MPPT

4.3 Available information processing. The proposed control algorithm

4.3.1 Feedback information processing

The stated scope of the control can be achieved by changing the tip speed ratio. As in chapter 2, the tip speed can be expressed in variations:

$$(4.3) \quad \Delta\lambda = \frac{R}{v} \cdot \Delta\Omega - \frac{\lambda}{v} \cdot \Delta v,$$

therefore a variation of the tip speed depends on the rotational speed change, but also on the wind change. This means that a variation of rotational speed will not be able to ensure by itself a targeted variation of the tip speed, since the wind speed is not controllable. One can consider that the wind turbulences together with rotational speed variations around a steady-state value induce some tip speed variations around its average value and consequently some ΔC_p variations, which are non harmonic, but have a bounded spectrum.

The tip speed ratio, $\lambda(t)$, can be computed using measures of the wind speed and rotational speed, as to its definition relation ((1.4) in chapter 1). Under the previously stated modelling assumptions, the power coefficient can be estimated from the electric power, $P(t)$, and wind speed using the following relation:

$$(4.4) \quad C_p(t) = P(t) / (0.5\pi \cdot \rho \cdot \eta \cdot R^2 \cdot v(t)^3),$$

with η being the non unitary efficiency of the mechanical to electrical power conversion.

In the sequel, normalized variations of these two signals, in relation to their maximum values, will be used. Supposing now a Fourier decomposition of $\lambda(t)$ and $C_p(t)$ signals; obviously, each $\lambda(t)$ harmonic component will generate a response which is a part of $C_p(t)$. The method exposed in the previous section can be expanded to this new situation by taking the components of the Fourier decomposition and then by composing/averaging their effects. This idea leads to two approaches for obtaining OP position on the C_p curve, which is in fact the objective of the demodulation:

a) using the discrete Fourier transform (DFT) for extracting the phase of each harmonic component for $\lambda(t)$ and $C_p(t)$ signals and then compute the phase lag of each component. An average of these values should give the angle – denoted further by $\theta(t)$ – containing the OP average position information. Values of $\theta(t)$ will get closer to 0 if the OP is on the left (rising) slope of the C_p curve or closer to π if the OP is on the right (falling) one;

b) demodulation can be done also by using a convolution between $\lambda(t)$ and $C_p(t)$ signals, as the product of its harmonic components (DFT obtained) is equivalent with a convolution operation in time domain [OPEN 97].

The control method exposed in the sequel will use the first approach in obtaining the OP position information. So, instead of computing the *instantaneous* gradients – which is not an obvious task in dynamic conditions – the method used here is based upon deducing the *average phase shift*, denoted by θ , between the power coefficient and the tip speed, by computing the DFTs of the two signals on an appropriately chosen time window. Thus, zone 1) from figure 4.6 will be characterized by $\theta < \pi/2$ and zone 2) by $\theta \geq \pi/2$.

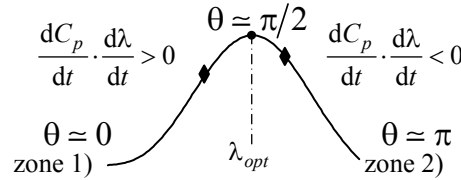


Fig. 4.6 Feedback on the operating point position

Remarks:

- As in the extremum seeking theory, the control is implemented using an integrator fed by the OP position information, which gives the direction of search (the evolution of the average tip speed ratio); the search step is the integration coefficient.

- The C_p curve is somehow flat, so the OP will change the slope in a continuous way; this action is not well illustrated by the binary information signal ($\theta(t)$ angle) concerning the OP position. So, around the C_p maximum, the $\theta(t)$ signal will be processed using a continuous function instead of a relay as in relation (4.2). Even if the C_p curve is in general nonsymmetric, the shape of the continuous function employed in the processing of $\theta(t)$ signal will be symmetric, because the C_p shape is unknown. Therefore, a slight static error of the average tip speed versus its optimal value is expected.

- The variations of the variables determining the system behaviour depend primarily on the turbulence wind speed evolution; the concerned measured information can be updated at each sampling period, further denoted by T_S , depending mainly on the turbine dynamics. This implies that the average position signal, $\theta(t)$, is to be computed, using fast Fourier transform (FFT), within a time window of width $T_C = 2^n \cdot T_S$, with n natural, resulted

from a trade-off between suitably tracking the signals' variations (imposed by the wind variations) and complying with the system inertia. Hence, it is obviously clear that a given system will not be ever made to track an unlimitedly turbulent wind.

4.3.2 The control algorithm

The control law logic is based on the following idea. The objective is that the average position of the OP must be maintained around the top of the aerodynamic efficiency curve, $C_p - \lambda$, in a certain neighbourhood around its maximum. The control input intends to move slowly (comparing with the turbine's dynamics) the average OP to the top of the curve, by regulating the average value of the tip speed computed on a relatively large time window. Therefore, we expect some large deviations of the instantaneous tip speed around its optimal value, λ_{opt} , only the average value of the tip speed will remain close to the λ_{opt} .

The control structure, presented in figure 4.7 has two main parts, namely an information processing block and a rotational speed reference generator. Essentially, for an OP position on the positive slope of the C_p curve the integrator will process a positive value, giving an increased tip speed reference. On the contrary, for an OP position on the negative slope of the C_p curve, the tip speed reference diminishes. This can be achieved by integrating a nonlinear function of average phase information, $\text{sgn}(\theta - \pi/2)$.

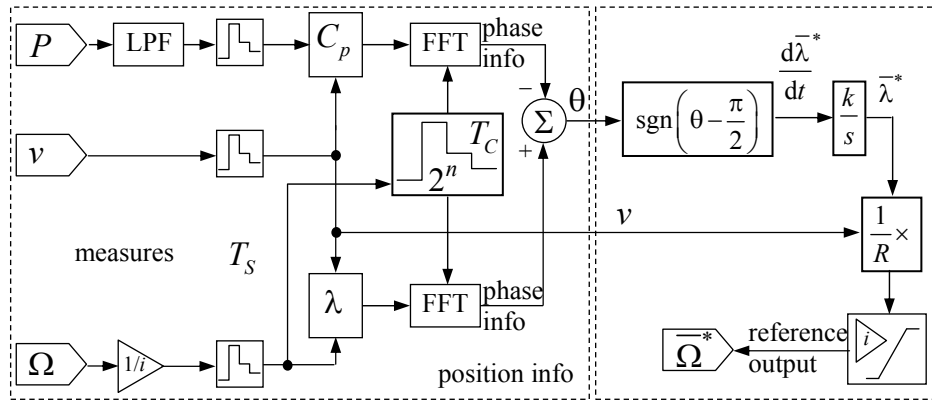


Fig. 4.7 The adopted MPPT control structure

On the left side of diagram from figure 4.7, $C_p(t)$ and $\lambda(t)$ normalized signals are obtained (in the modelling assumptions) using the electrical power and rotational and wind speed measurements (as to relations (1.2) and (1.4)). These signals – passed through a Blackman window for avoiding the Gibbs effect – are feeding a FFT algorithm for obtaining their phase spectrum and the corresponding average position signal, $\theta(t)$, as stated in the previous section. For information consistency, a sufficiently large window (in relation to the turbulence dynamics) must be chosen.

As the OP position changes continuously around OOP (the slope of the aerodynamic efficiency is continuous), in the second part of the control scheme a preliminary processing of $\theta(t)$ around the optimal OP is necessary and can be made as figure 4.8 suggests. The result of this operation, applied to the integrator, produces a tip speed reference, renewed every T_C seconds after the computation of the phase shift, θ . The control structure output is the rotational speed reference, obtained from the tip speed reference by using relation (1.4), plus low pass filtering and rate limiting operations (for technical reasons concerning the generator's control).

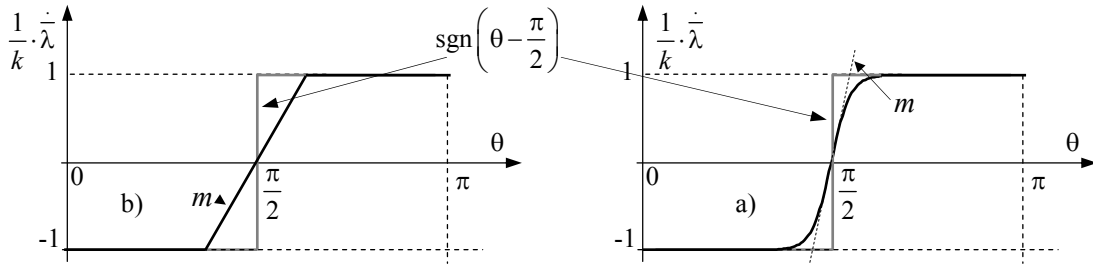


Fig. 4.8 Feedback on the operating point position: a) linear approximation and b) hyperbolic tangent approximation of the sign function

Once the computing time T_C is established, for reasons concerning the turbulence dynamics, the key parameter is the **integrator coefficient** k , imposed by the T_C value and the desired speed of the maximum search. One can consider that a relatively good performance of this control structure is represented by a sufficiently small standard deviation of the tip speed around its average value. So, the k coefficient can be chosen such that the variable speed turbine compensates the tip speed standard deviation in the computing time T_C . The slope m also influences the system response. Some specifications of the above presented control structure are in appendix D.

4.4 Numerical simulation results

The numerical simulations have been performed on a low power high speed horizontal axis WECS whose parameters are given in appendix A. The turbine has variable speed capability, being equipped with a speed controller based on a vector control structure. The tests concern only the partial load region for medium wind turbulence and no wind gusts.

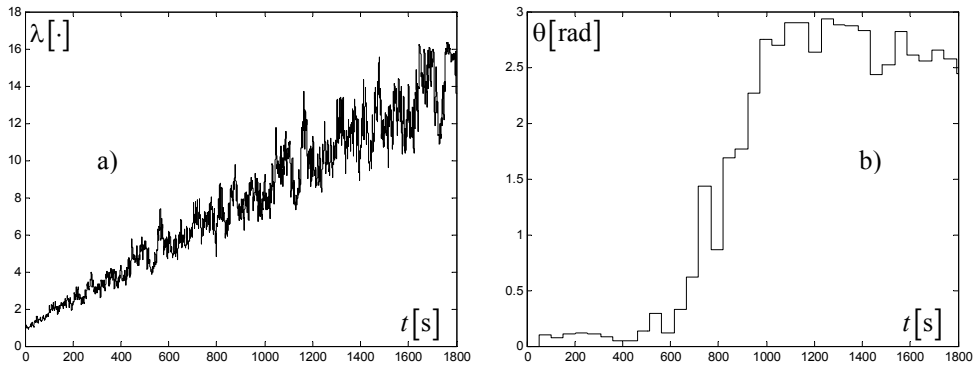


Fig. 4.9 Information preprocessing: a) the considered tip speed variation, b) the corresponding position signal, θ

Figure 4.9 presents the change in the θ angle as the tip speed increases. In order to obtain this result, the rotational speed is imposed to vary in ramp between 20 rad/s and 250 rad/s, while the wind speed has an average component of 8 m/s and an indispensable turbulence component with medium intensity and constant statistical parameters. The tip speed evolution over a half an hour is presented in figure 4.9a). For the results above, $T_s = 0.2$ s and FFT is performed on a 256 element sequence. The OP position on the C_p curve is considered to be at the left side of the maximum efficiency point (ascending part) if $\theta < \pi/2$ and at the right side if $\theta > \pi/2$ (figure 4.9b)).

In the sequel are presented primary simulation results concerning the control solution proposed in §4.3. The simulations have been done for 50 minutes for a wind sequence having the average speed of about 8 m/s and a

medium turbulence intensity of $I=0.15$ (figure 4.10a)), obtained using the von Karman spectrum in the IEC standard.

Concerning the control, the sampling period is $T_s=0.1$ s and FFT is made on a 256 element sequence, yielding a computing time of about 25 seconds. For the following three figures, the controller gain has been chosen as $k=0.02$, which should compensate a tip speed deviation of 0.5 in the chosen computing time.

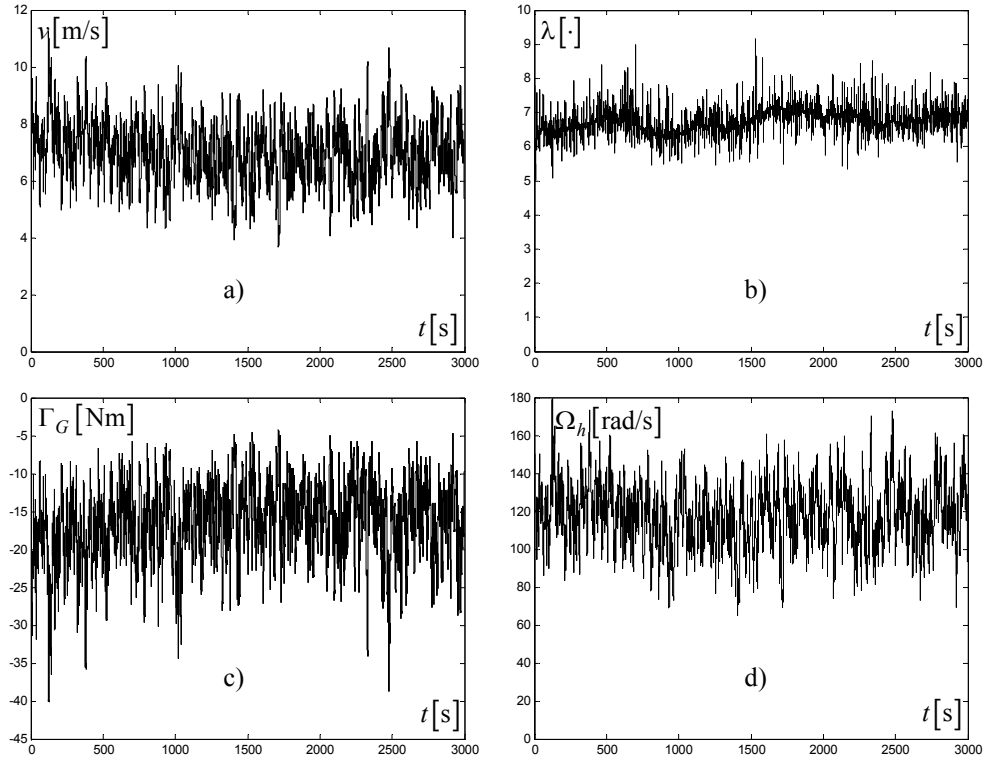


Fig. 4.10 Time evolutions of the operating variables

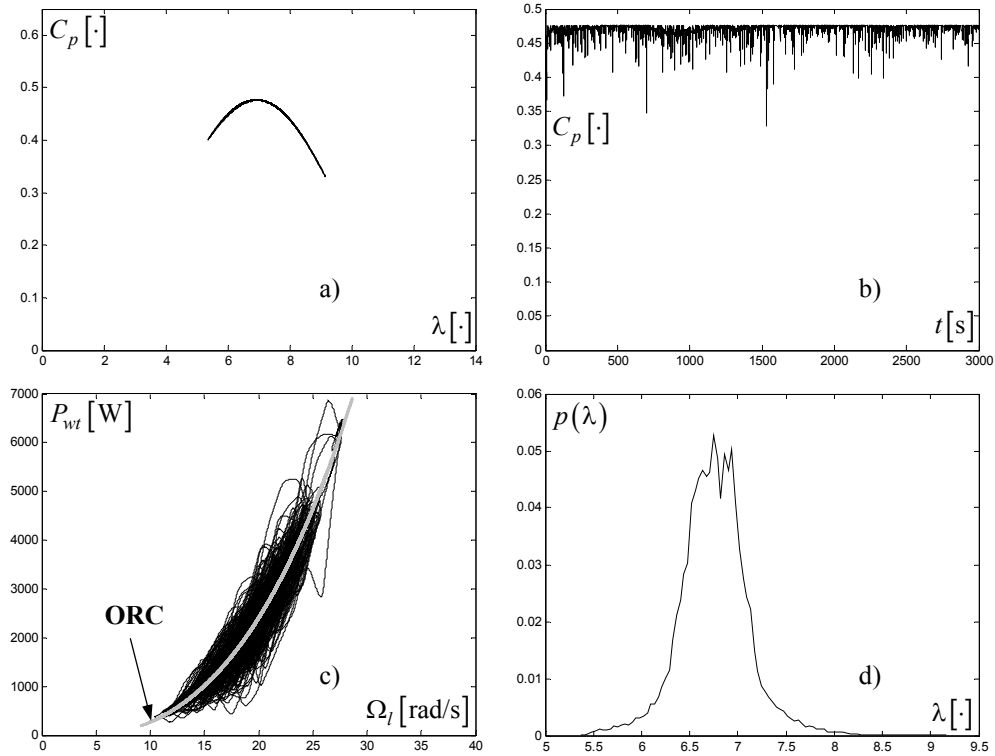


Fig. 4.11 Performance of the control law in terms of achieved energetic efficiency

In figure 4.10b) one can see that the effectiveness of the proposed control in maintaining the tip speed around its optimal value is quite poor, allowing large deviations from it. The variable speed regime is described by figures 4.10c) and d). One could expect some quite reasonable high frequency mechanical efforts on the turbine shaft, since the generator torque variations due to the slow change of the operating point are minimal and it is not expected to increase when increasing the searching speed, k .

Figure 4.11 describes the performance of the control law. In a) is given the evolution of the aerodynamic efficiency on the top of the $C_p - \lambda$ curve, while in b) one can found the corresponding time evolution; in c) is given the operating point distribution around ORC (in speed-power plane); in d) is depicted the probability density function of the tip speed ratio for which result an average value of 6.75 and a standard deviation of 0.36.

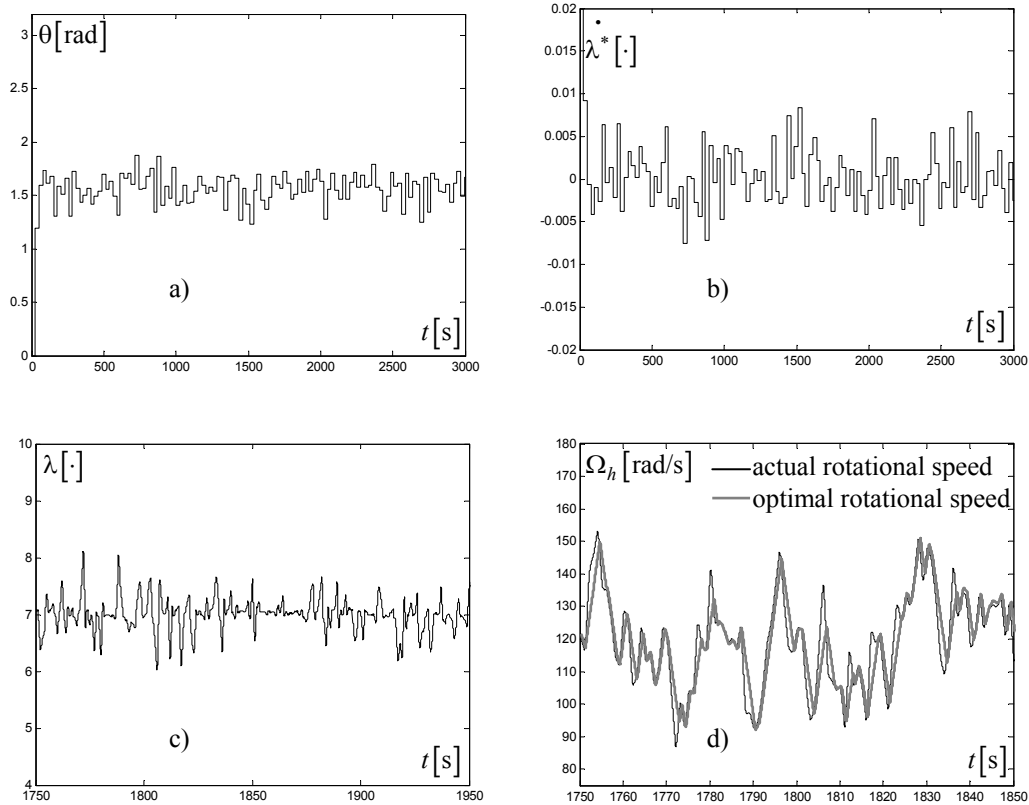


Fig. 4.12 Quality of the MPPT

Time evolutions of some variables illustrating the quality of tracking the maximum power point are to be seen in figure 4.12. In a) are presented the oscillations of the signal $\theta(t)$ around $\pi/2$, describing the movement of the operating point between the stall and the normal operating region; the computing time is also emphasized; in b) the gradient of the tip speed reference (the integrator's input) can be observed and in c) a zoomed evolution of the tip speed; figure 4.12d) presents some differences between the rotational speed of the turbine and the (necessary) optimal speed corresponding to the wind speed evolution.

Simulations with different values of the control parameter, k , have been also performed. Figure 4.13a) shows how the probability density of tip speed is changing. For small k (small searching speed), one obtains smaller standard deviations, but the average value differs from the optimal one, which denotes poor energetic efficiency. For large k (large searching speed), the standard deviation becomes large even if the mean of the tip speed remains close to the optimal value, meaning poor efficiency too. Figure 4.13 b) suggests that once the system is in steady-state regime, a small value of k can produce better performance. These remarks suggest the existence of a range of k

values for which closeness to optimality can be optimally designed: a good tracking of the optimal value along with a sufficiently small dispersion.

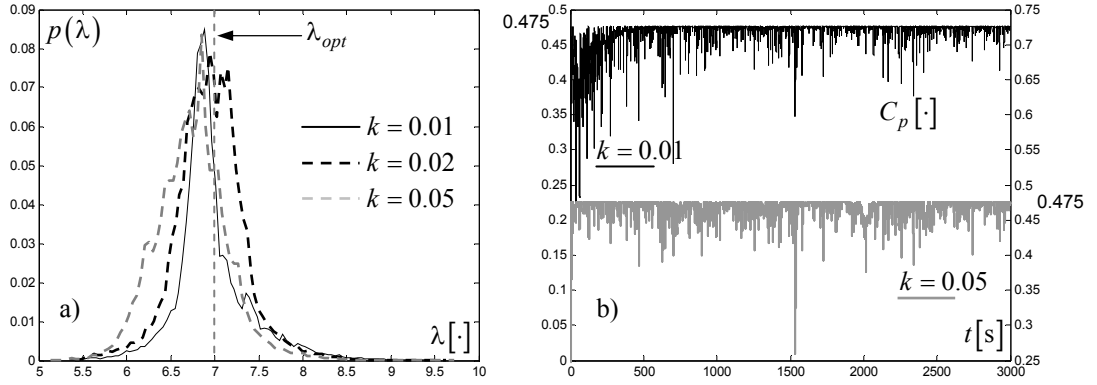


Fig. 4.13 Comparisons for different values of the integration parameter, k

4.5 Conclusion

This chapter has presented a version of the MPPT control method for variable speed WECS, which is based on the extremum seeking control. As MPPT methods prove their efficiency when the plant is not sufficiently and/or precisely known, an improvement concerning the measure information processing has been proposed. That is, based on measurements of the wind speed, the electrical (active) power and the rotational speed, one can compute the power coefficient, $C_p(t)$, and the tip speed, $\lambda(t)$, normalized signals over a sufficiently large time window. If the operating point on the $C_p - \lambda$ characteristic is on the stalling (ascending) part of the aerodynamic efficiency curve, the two signals will be in phase, otherwise (on the descending slope), the phase lag will be about π . To decide the position of the actual operating point in relation to the optimal one, a phase discrimination is performed, by computing the FFT of the two signals, extracting the phase information and computing the average phase lag, $\theta(t)$. The rotational speed reference is given by the output of an integrator whose gain represents the optimum searching speed; its sense is given by signal $\theta(t)$.

In order to validate the proposed method for small sized power HAWT, Matlab&Simulink simulations have been performed. Given the poor information available, the simulations have shown sufficiently good control performances which can be obtained with a reasonable control effort. The OP averagely moves around the optimal position for all the wind speed range in the partial load region. The control input is obtained as OP average position, $\theta(t)$, and consequently, its variations are of low frequency, meaning insignificant supplementary mechanical stress.

The approached control law cannot impose the OP excursion around the ORC and cannot ensure an average value of the tip speed equal with the optimal one, the dispersion of the tip speed depending on the wind turbulence intensity. The method is not applicable if the turbulence intensity is under a certain value or else the gathered information can become inconsistent. But this is a quite improbable situation; on the contrary, the turbulence level increases with the average wind speed, therefore the efficiency of this method is expected to increase also, leading to increased WECS energetic efficiency. The independency of the system parameters, as a result of using minimal knowledge about the system state, is the most valuable feature of the presented method.

Such concluding remarks allow considering the presented approach as a promising one for further developments.

Future work should be directed to achieving the OP position by convoluting the tip speed and the power coefficient signals, to designing an adaptive law of the searching speed with the turbulence intensity and to experimentally testing this MPPT approach on a more complex real time electromechanical wind turbine simulator. Also, a future point to investigate is obtaining the same feedback information by FFT-ing/convoluting measurements of the active power and HSS rotational speed, the wind speed measure being no longer necessary.

As in [ARIY 03], apart from k parameter, the amplitude and the period of the probing signal determines the speed convergence. But, as stated in [NICH 02], by increasing turbulence larger amplitude and frequency of wind variations are implied. This suggests that the influences of the two latter parameters on the searching speed convergence are compensating each other in a manner to be further studied.

Chapter 5

SLIDING MODE OPTIMAL CONTROL OF WIND ENERGY CONVERSION SYSTEMS

This chapter describes a manner in which the energy-reliability optimization of wind energy conversion systems' operation can be achieved by means of the sliding mode control. The proposed approach aims at designing a trade-off between maximizing the power harvested from the wind by a horizontal axis grid connected variable speed doubly-fed induction generator (DFIG) based WECS and minimizing its mechanical stress. The energy-reliability optimization of the wind turbine behaviour is here performed by torque controlling the generator. Thus, an appropriate sliding surface is to be found in the speed-power plane, which allows alleviating the torque variations by giving up tracking precision and vice versa. This is equivalent with operating the WECS more or less closer to the optimal regimes characteristic, depending on tuning the proposed control law's adjustable parameters. This law is validated by both off-line and real time simulation, the latter on a dedicated experimental rig, based upon the hardware-in-the-loop simulation concept, as detailed in the third chapter of this work. The results show that the control objective is fully accomplished.

5.1 PROBLEM STATEMENT AND LITERATURE REVIEW. DESCRIPTION OF THE PROPOSED SOLUTION

The linear methods for tracking the optimal tip speed ratio of a WECS are not always efficient because of the intrinsic, non negligible nonlinearities of the system and modelling uncertainties. Nonlinear robust methods become thus necessary. Some of these methods – the original MPPT and fuzzy control methods (§2.5.1) – have the main drawback of exclusively aiming at maximizing the energetic efficiency, by completely ignoring the large high frequency torque variations induced by tracking the shaft speed, $\Omega_{l\ opt}$, related to the system's reliability.

The variable structure control (VSC) as nonlinear method is particularly suitable to variable speed WECSs' control, provided the nonlinear nature of the system. Also, its robustness to disturbances and parametric uncertainties makes unnecessary a precise knowledge about the system. In addition, the VSC can be implemented by the power electronics already existing in the system. But, for the applications using the electromagnetic torque as control input the mechanical stress increases due to the chattering.

There is a certain difficulty about the VSC design, concerning the definition of a sliding surface with guaranteed properties of attractiveness and stability [LEVI 96], [YOUN 99]. VSC has been used on various configurations of WECSs, for regulating the generated power, as required by a general purpose user [LONG 99], [VALE 03], [BATT 00b], [BATT 04], or for multi-purpose optimization [BATT 98], [PENA 99], e.g., design of a trade-off between maximizing the harvested power and minimizing the control effort.

In [VALE 03], [VALE 04] a systematic variable structure control design method, based on combining the sliding mode techniques with passivity concepts, is proposed and applied to the power regulation of a solar/wind hybrid generation system. However, in the cited works the sliding surface is chosen instead of resulting from a

systematic procedure. It is also the case of the VSC strategies with integral compensation proposed in [PENA 99] for tracking a WECS's optimum, irrespectively from the wind speed. In [LONG 99] the harvested power regulation uses a H^∞ approach, based upon the quasi-linearization of the plant's nonlinear model, to design a stable sliding surface; it has the drawback of needing a quite precise modelling knowledge.

The design method developed in this chapter implicitly achieves a multipurpose (energy-reliability) optimization by proposing a sliding mode approach for tracking the energetic optimum for the class of variable speed WECS established in chapter 1. A sliding surface, depending on the wind speed, is systematically derived from the reduced order dynamics and allows the turbine operation more or less close to the ORC, as imposed by a trade-off between the torque (control input) variations and the optimum tracking.

The rest of the chapter is organized as follows. The second section is dedicated to present the modelling framework of the considered WECS. This model is used for the sliding surface and control law design, as detailed in the third section. The fourth section contains simulation results, both off-line and real time, the latter performed on a dedicated experimental rig, based upon the hardware-in-the-loop simulation concept, as developed in chapter 3. Conclusion and future work are grouped together in the last section, the fifth.

5.2 MODELLING ASSUMPTIONS

Figure 5.1 presents the block diagram of the studied variable speed grid connected WECS having rigid drive train and is an instance of the system in figure 2.1. The associated control system (CS in figure 2.1) is designed using sliding mode technique as shown in the sequel. The rectifier, together with the SCIG, forms the electromagnetic subsystem (EMS), while the pair inverter – local grid represents the grid interface system (GIS).

The variable speed operation is ensured by two local control blocks – namely the provided power regulation and conditioning (containing the GIS) and respectively the generator torque/speed control (containing the EMS) – and a global behaviour control block, which is of interest in this chapter. The GIS structure varies upon its scope (regulation of the active/reactive power, alleviation of the flicker, management of the total harmonic distortion, etc.) and is not of interest in this work. On a higher level one can find a supervisory control block.

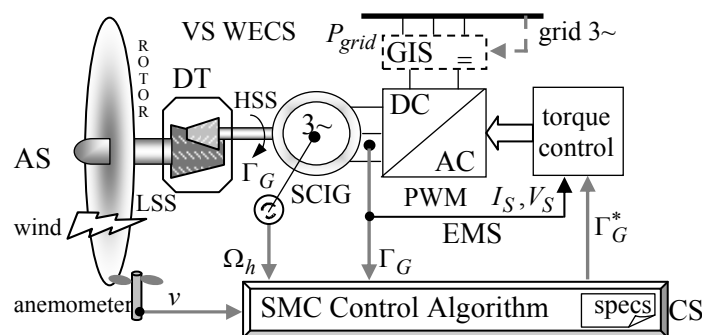


Fig. 5.1 Block diagram of the controlled variable speed WECS

The general modelling frame from chapter 2 stands also for this chapter. Supplementary assumptions are listed below:

- the wind speed is considered a scalar variable and is modelled as a stationary random process, having a mean (low frequency) component and a turbulence component with a limited frequency domain;
- the global power loss of the conversion chain induces an identifiable efficiency for the whole wind speed domain;
- the variable speed wind power system is torque controlled by means of a vector control scheme and the

EMS dynamics are of first order [PENA 00];

- the GIS is controlled for completely transferring the electrical power to the grid, conditioned at this latter's parameters;
- the full load region is characterized by limitation of the captured power by stall effect [BURT 01]; in this chapter the system operation in the partial load region is of interest, as this is the zone where the optimization by variable speed is generally applied;
- most of the AS, DT and EMS parameters are given by the system's manufacturer/integrator.

Let Ω_h denote the high speed (generator's) shaft of the WECS. Obviously, $\Omega_h = i \cdot \Omega_l$ (i denoting the speed multiplier ratio). For simplicity, the index h will be dropped in the sequel of the chapter; therefore $\Omega_h \equiv \Omega$.

Starting from the movement equation of the HSS (relation (2.16)), coupled with the first order dynamics of the EMS (§2.3.4) and considering unitary efficiency of the DT, the system's equations write:

$$(5.1) \quad \begin{cases} \dot{\Omega}(t) = \Gamma_{wt}(\Omega/i, v) / (i \cdot J_h) - \Gamma_G / J_h \\ \dot{\Gamma}_G(t) = -\Gamma_G / T_G + u / T_G \end{cases},$$

where the involved variables have been defined in chapter 2. The aerodynamic subsystem models the interaction between the rotor and the wind flow; its output represents the wind torque, Γ_{wt} . Using expression (1.2) of the harvested wind power and definition (1.4) of the tip speed ratio, it results:

$$(5.2) \quad \Gamma_{wt} = 0.5 \cdot \pi \cdot \rho \cdot R^3 \cdot v^2 \cdot C_p(\lambda) / \lambda = \Gamma_{wt}(\lambda)$$

Hence, the state vector is $\mathbf{x} = [\Omega \quad \Gamma_G]^T$ and the control input is $u = \Gamma_G^*$, the electromagnetic torque reference.

By sliding mode control the system's OP can be forced to evolve on a wisely chosen sliding surface, $\sigma(\mathbf{x}, u, t)$, corresponding to the "average" state trajectory [LEVI 96], [YOUN 99]. The reliability requirements imply a certain "freedom of moving" of the OP around the ORC, so the sliding surface must be positioned in the ORC neighbourhood, adjustable according to a so called trade-off variable.

5.3 SLIDING MODE DESIGN

5.3.1 Sliding surface design

Here, the goal is to find a sliding surface allowing to operating the turbine more or less close to the ORC, implicitly requiring an antagonistic sizing of the control effort. This requires the sought surface to depend on the wind speed; its image in the (Ω_l, P_{wt}) plane must have a nonempty intersection with the ORC for each value of the wind speed and also an adjustable slope for tuning the sliding mode dynamics.

Equations (5.1) may be written in the form:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, t) + \mathbf{B}(\mathbf{x}, t) \cdot u,$$

where $\mathbf{f}(\mathbf{x}, t) = [\Gamma_{wt}(\Omega/i, v) / (J_h \cdot i) - \Gamma_G / J_h \quad -\Gamma_G / T_G]^T$ is nonlinear because of the wind torque, $\Gamma_{wt}(\Omega/i, v)$, and $\mathbf{B}(\mathbf{x}, t) = [0 \quad 1/T_G]^T$. Note that the state equation is already in the regular form [LEVI 96]. Therefore, the reduced order dynamics are those circled in the relation below:

$$(5.3) \quad \begin{bmatrix} \dot{\Omega} \\ \dot{\Gamma}_G \end{bmatrix} = \begin{bmatrix} \Gamma_{wt}(\Omega/i, v)/(i \cdot J_h) - \Gamma_G/J_t \\ -\Gamma_G/T_G \end{bmatrix} + \begin{bmatrix} 0 \\ 1/T_G \end{bmatrix} \cdot u$$

The sliding mode dynamics (that is, on the sliding surface) may be imposed as equivalent to some linear ones:

$$(5.4) \quad \dot{\Omega} = (\Gamma_{wt}(\Omega/i, v)/i - \Gamma_G)/J_h \equiv [a_1 \quad a_2] \cdot [\Omega \quad \Gamma_G]^T,$$

where a_1 and a_2 correspond to the first order dynamics on the sliding surface, as detailed later. Let $\sigma(\mathbf{x}, u, t)$ denote the sliding surface. Equation (5.3) and condition $\frac{\partial \sigma}{\partial \mathbf{x}} \cdot \mathbf{B}(\mathbf{x}, t) \neq 0$ (existence of the equivalent control input [LEVI 96], [YOUN 99]), require that $\frac{\partial \sigma}{\partial \Gamma_G} \neq 0$; let $\frac{\partial \sigma}{\partial \Gamma_G} = a_3 \neq 0$ by notation. A first form of the switching surface may thus be written:

$$(5.5) \quad \sigma(\Omega, \Gamma_G) = \sigma_1(\Omega) + a_3 \cdot \Gamma_G$$

Equality $\sigma(\Omega, \Gamma_G) = 0$ implies that $\sigma_1(\Omega) + a_3 \cdot \Gamma_G = 0$ and, finally:

$$(5.6) \quad \sigma_1(\Omega) = -a_3 \cdot \Gamma_G$$

From relation (5.4) one can obtain:

$$(5.7) \quad \Gamma_G = \frac{1}{1 + a_2 \cdot J_h} \cdot (\Gamma_{wt}(\Omega/i, v)/i - a_1 \cdot J_h \cdot \Omega)$$

For simplicity, let $a_3 = 1 + a_2 \cdot J_h$. Relations (5.6) and (5.7), combined with equation (5.5), give the expression of the sliding surface (arguments being dropped):

$$(5.8) \quad \sigma = a_1 \cdot J_h \cdot \Omega + \Gamma_G \cdot (1 + a_2 \cdot J_h) - \Gamma_{wt}/i$$

Parameter a_1 represents the time constant of the sliding mode dynamics. The steady-state regime is imposed by choosing parameter a_2 ; in this way, the equilibrium on the sliding surface may be characterized. In our case, provided that the energetic optimization is of interest, the equilibrium point is set to *the optimal one* (that is, on the ORC). From the movement equation it holds that $\Gamma_{wt}/i - \Gamma_G = J_h \cdot \dot{\Omega}$; consequently, one can successively write:

$$(5.9) \quad \sigma = a_1 \cdot J_h \cdot \Omega + \Gamma_G \cdot a_2 \cdot J_h - \underbrace{(\Gamma_{wt}/i - \Gamma_G)}_{J_h \cdot \dot{\Omega}} = a_1 \cdot J_h \cdot \Omega + a_2 \cdot J_h \cdot \Gamma_G - J_h \cdot \dot{\Omega}$$

Therefore, the commutation surface depends on the derivative of a state variable (namely, the rotational speed), which is an inconvenient for the real time implementation. A first order high pass filter, having the transfer function $\frac{s}{T_f \cdot s + 1}$, with $T_f = 0.1$ s, may be used to estimate this derivative.

5.3.2 Control law design

This subsection is dedicated to computation of the two components of the sliding mode control law: the equivalent control input, u_{eq} , and the on-off component, u_N [LEVI 96].

To compute the *equivalent control input* the following relation is used:

$$(5.10) \quad u_{eq} = - \left[\frac{\partial \sigma}{\partial \mathbf{x}} \cdot \mathbf{B} \right]^{-1} \cdot \left[\frac{\partial \sigma}{\partial t} + \frac{\partial \sigma}{\partial \mathbf{x}} \cdot f(\mathbf{x}, t) \right]$$

Next, the expressions involved will be computed.

$$(5.11) \quad \frac{\partial \sigma}{\partial \mathbf{x}} \cdot \mathbf{B} = \begin{bmatrix} \frac{\partial \sigma}{\partial \Omega} & \frac{\partial \sigma}{\partial \Gamma_G} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1/T_G \end{bmatrix} = \frac{1}{T_G} \cdot \frac{\partial \sigma}{\partial \Gamma_G}$$

Because the sliding surface does not explicitly depend on time, then $\frac{\partial \sigma}{\partial t} = 0$. To compute the partial derivative of the sliding surface in relation to the first state variable,

$$\frac{\partial \sigma}{\partial \Omega} = a_1 \cdot J_h - \frac{1}{i} \cdot \frac{\partial \Gamma_{wt}}{\partial \Omega},$$

one may use the partial derivative of the wind torque:

$$\frac{\partial \Gamma_{wt}}{\partial \Omega} = 0.5 \cdot \pi \cdot \rho \cdot R^3 \cdot v^2 \cdot \frac{\partial C_\Gamma(\lambda)}{\partial \Omega} = K \cdot v^2 \cdot R \cdot \frac{\partial C_\Gamma(\lambda)}{\partial \lambda} \cdot \frac{\partial \lambda}{\partial \Omega} = K \cdot v \cdot R^2 \cdot \left(\frac{C'_p(\lambda) \cdot \lambda - C_p(\lambda)}{\lambda^2} \right),$$

where $K = 0.5 \cdot \pi \cdot \rho \cdot R^2$ is considered invariant, $C_\Gamma(\lambda) = C_p(\lambda)/\lambda$ and $C'_p(\lambda)$ is the derivative of the power coefficient in relation to λ . One obtains:

$$(5.12) \quad \frac{\partial \sigma}{\partial \Omega} = a_1 \cdot J_h - \left(K \cdot v \cdot R^2 \right) / i \cdot \left(C'_p(\lambda) \cdot \lambda - C_p(\lambda) \right) / \lambda^2 = a_1 \cdot J_h - A(\lambda, v),$$

where:

$$(5.13) \quad A(\lambda, v) = \frac{\left(K \cdot v \cdot R^2 \right) \cdot \left(C'_p(\lambda) \cdot \lambda - C_p(\lambda) \right)}{i \cdot \lambda^2}$$

Let:

$$(5.14) \quad \delta(\lambda) = \left(C'_p(\lambda) \cdot \lambda - C_p(\lambda) \right) / \lambda^2$$

Using that $\frac{\partial \sigma}{\partial \Gamma_G} = 1 + a_2 \cdot J_h$ in relation (5.11) and then in relation (5.10) of the equivalent control input, and

replacing relation (5.12) in relation (5.10), one obtains after some algebra:

$$u_{eq} = - \frac{T_G}{1 + a_2 \cdot J_h} \cdot \left(\frac{\Gamma_{wt}}{i} - \Gamma_G \right) \cdot (a_1 - A(\lambda, v)) - \Gamma_G$$

Provided that the dynamics on the sliding surface are:

$$J_h \cdot \dot{\Omega} = \Gamma_{wt}/i - \Gamma_G \equiv a_1 \cdot J_h \cdot \Omega + a_2 \cdot J_h \cdot \Gamma_G,$$

then the expression of the equivalent control input becomes:

$$(5.15) \quad u_{eq} = \Gamma_G - \frac{T_G}{1 + a_2 \cdot J_h} (a_1 \cdot J_h \cdot \Omega + a_2 \cdot J_h \cdot \Gamma_G) (a_1 - A(\lambda, v))$$

Expression (5.15) shows that the control law searched for has torque dimensions. Parameter a_1 is chosen to impose the dynamics in sliding mode regime: $a_1 = -1/T_{sm}$, where the time constant $T_{sm} > 0$. The value of a_2 results from imposing the “target” steady-state, namely the (optimal) operating point (OOP), corresponding to λ_{opt} :

$\dot{\Omega} = a_1 \cdot \Omega_{opt} + a_2 \cdot \Gamma_{opt} = 0$, with $(\Omega_{opt}, \Gamma_{opt})$ being the image of the OOP at the high speed shaft. From here it comes:

$$a_2 = -a_1 \cdot \frac{\Omega_{opt}}{\Gamma_{opt}}$$

Once entering the sliding mode, a_1 is the inverse of the time constant and a_2 is the (static) gain. One may attempt to *dynamically* modify a_2 , using the following expression:

$$(5.16) \quad a_2 = -a_1 \cdot \frac{\Omega_{opt}}{\Gamma_{opt} \left(1 + k \cdot \left(\Omega - \Omega_{opt} \right) / \Omega_{opt} \right)},$$

with $k \geq 0$. This results in reducing the operating point's variations around the OOP.

Expression (5.16) is not valuable but around the OOP, otherwise parameter a_2 can take values sufficiently large such that the system leaves the normal operating regime. In the next section it is shown that the larger the value of k is, the more quickly the optimal steady-state, $(\Omega_{opt}, \Gamma_{opt})$, is reached, therefore the ORC tracking has a better quality. The system is thus forced to follow more accurately the control goal, i.e. the energetic optimization, but the control input variations are more significant, affecting the reliability. This parameter adjusts the control effort and can be used to design a desired energy-reliability trade-off. Accordingly, as k increases, the slope of sliding surface's image in the (Ω, P) plane is increased to follow the ORC more closely. Because $(\Omega_{opt}, \Gamma_{opt})$ pair depends on the wind speed, it comes that the sliding surface changes with the wind speed.

The *on-off component* of the sliding control law, u_N , is obtained by choosing as Lyapunov (energy) function the square of the obtained sliding surface. One may thus deduce:

$$(5.17) \quad u_N = -\alpha \cdot \text{sgn}_h(\sigma),$$

where $\text{sgn}_h(\cdot)$ is a hysteretic sign function of width h .

The *total sliding mode control law* is the sum of the equivalent component (5.15) and the on-off component (5.17):

$$(5.18) \quad u = u_{eq} + u_N$$

5.3.3 Control algorithm and block diagram

Corroborating the above listed results, the total sliding mode control law, u , can be computed according to the following algorithm; the associated control diagram is given in figure 5.2.

Input data: $R, \rho, i, J_h, T_G, \lambda_{opt}, C_p(\lambda)$ curve.

Off-line computation:

1. Impose the sliding mode dynamics, T_{sm} , and compute $a_1 = -1/T_{sm}$.
2. Choose α, k and h .

On-line computation:

0. Measure v, Ω, Γ_G . Compute $\lambda = \Omega \cdot R / (v \cdot i)$, $(\Omega_{opt}, \Gamma_{opt})$.
1. Compute $\delta(\lambda) = \left(C_p'(\lambda) \cdot \lambda - C_p(\lambda) \right) / \lambda^2$ and $A(\lambda, v) = \left(0.5 \cdot \pi \cdot \rho \cdot v \cdot R^4 \right) / i \cdot \delta(\lambda)$.

2. Compute $a_2 = -a_1 \cdot \frac{\Omega_{opt}}{\Gamma_{opt} \left(1 + k \cdot \left(\Omega - \Omega_{opt} \right) / \Omega_{opt} \right)}$.
3. Obtain $\dot{\Omega}$ and compute the sliding surface, $\sigma = a_1 \cdot J_h \cdot \Omega + a_2 \cdot J_h \cdot \Gamma_G - J_h \cdot \dot{\Omega}$.
4. Compute the equivalent control input, $u_{eq} = \Gamma_G - \frac{T_G}{1 + a_2 \cdot J_h} \cdot (a_1 \cdot J_h \cdot \Omega + a_2 \cdot J_h \cdot \Gamma_G) \cdot (a_1 - A(\lambda, v))$.
5. Compute the on-off control input, $u_N = -\alpha \cdot \text{sgn}_h(\sigma)$.
6. Obtain the total control input, $u = u_{eq} + u_N$.

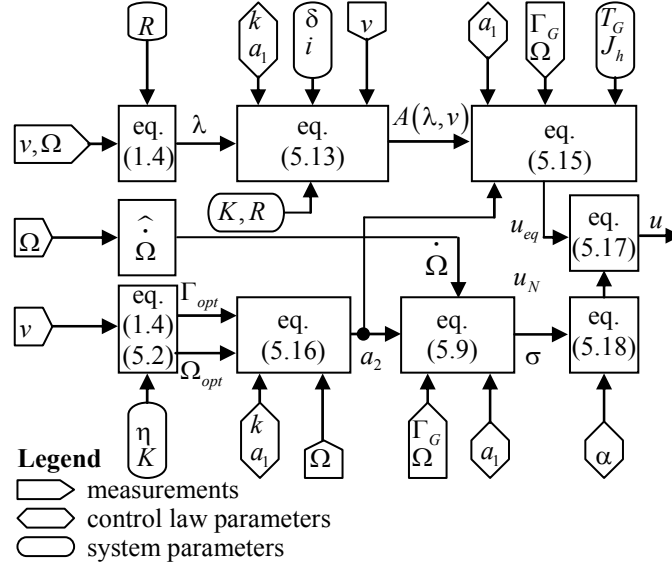


Fig. 5.2 Control block diagram

Note that $\delta(\lambda)$ is practically constant in a limited neighbourhood of the ORC, having an a priori computable value. a_1 and a_2 are the main control law parameters, the latter depending on the (energy-reliability) trade-off parameter, k . There are also some other adjustable parameters, determining the u_N component, which contribute to the control law's flexibility.

5.4 NUMERICAL AND REAL TIME SIMULATION RESULTS

Numerical (off-line) simulations have been performed under Matlab/SimulinkTM software. A Simulink diagram has been built for implementing the model described in §5.2 (rigidly driven **SCIG based WECS**), together with the algorithm detailed in the previous section. More information about these simulations is given in appendix E.

Real time validation experiments have been also performed on a 1:1 test rig implementing the same system as in the third chapter of this work (figure 3.10) – namely rigidly driven **DFIG based WECS** – built upon the HILS concept, according to the methodology detailed in the same chapter (associated parameters are given in appendix C). The block diagram from figure 5.2, implementing the sliding mode control law presented in §5.3.2, was translated for the target processor DS1005, using the Matlab/SimulinkTM Real Time Workshop (RTW) toolbox.

From the point of view of the above described control algorithm, the differences in operating the two WECS configurations (DFIG versus SCIG) can be neglected for the following reason. These differences consist in different EMS structures, which are both torque controlled by different vector control schemes. But the control result is the same, namely the two EMSs are dynamically equivalent within the frame of the global sliding mode control.

5.4.1 Numerical versus real-time simulation

This subsection discusses a comparison between the off-line (numerical) and the real time simulation results.

Figure 5.3 presents two kinds of off-line simulation results, namely evolutions in response to step changes in the wind speed (figures 5.3a..5.3c)) for trade-off parameter $k=0$, and to pseudo-random sequences of wind speed respectively (figures 5.3d..5.3i)). Figures 5.3a) and 5.3b) show that the operating point is attracted to the new sliding surface and then evolves in sliding mode to the OOP. Figure 5.3c) shows the relative position of the ORC versus the sliding surface's image in the ORC plane for different wind speeds. In the second and the third rows, simulations have been done for a minute sized time horizon, for a wind speed of medium turbulence intensity of $I=0.17$, obtained by using the von Karman spectrum in the IEC standard (figure 5.3d)) and $k=5$.

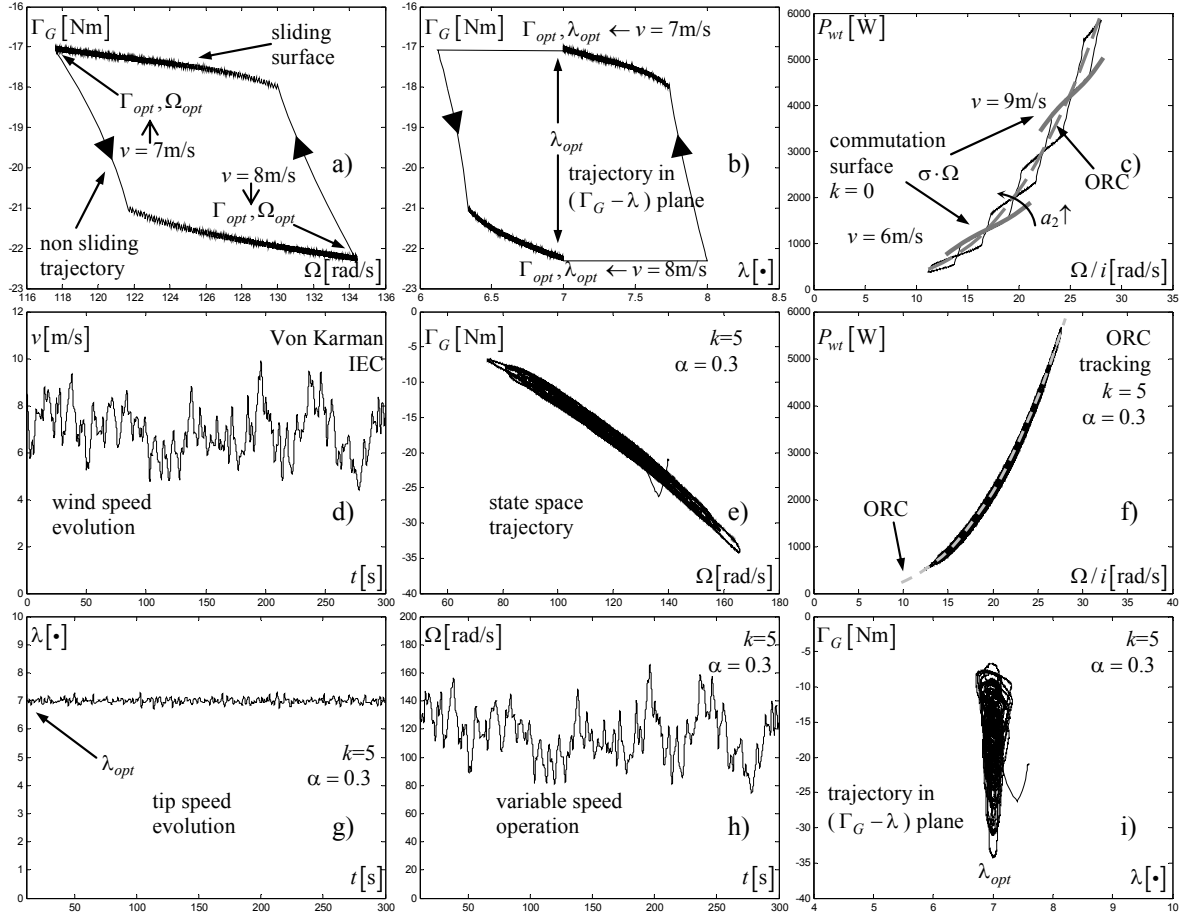


Fig. 5.3 Off-line simulation results ($\alpha=0.3$)

Figures 5.3e) and 5.3h) show the turbine's variable operation regime, while figures 5.3g) and 5.3f) show the control law efficiency in maintaining the optimal conversion regime. This efficiency has a direct dependency with the wind speed (figure 5.3i)), suggesting that an adaptive adjusting law of k parameter might be useful.

The control law computed by using the above algorithm has the following drawbacks:

- a) the optimal operating point's coordinates referred to the high speed shaft, $(\Omega_{opt}, \Gamma_{opt})$, must be computed using the turbine's parameters and the mechanical transmission and electrical generator efficiency;
- b) parameter $A(\lambda, v)$ values around the OOP must be estimated;
- c) the control input is based on a measure of the low speed shaft's rotational speed gradient;
- d) the effectiveness of the proposed optimal control law is not the same for all the operating range;
- e) using a relay function for the alternate control input induces unacceptable generator torque/current

variations.

Therefore, the original form of the sliding mode control law – relations (5.15) and (5.17) replaced in relation (5.18) – had to suffer some changes in order to be real time tested on a physical simulator; these changes are presented in the sequel.

Point a) can be surpassed by using a multiplying correction of value Γ_{opt} , denoted by η_{em} , representing an estimation of the electromechanical efficiency of the wind power system, to which one can add the integral of the tip speed ratio static error, $\lambda - \lambda_{opt}$. η_{em} has a sigmoid variation with the rotational speed, as established by measurements. This compensation concerns the equivalent control input, originally given by relation (5.15), where parameter a_2 is replaced by $a_2 = -a_1 \cdot \eta_{em} \cdot \Omega_{opt} / \Gamma_{opt}$ (see also appendix E and [MUNT 05c]).

Concerning point b), a consistent estimation of the instantaneous value of $A(\lambda, v)$ is possible if the operating point is sufficiently close to the ORC. Point c) can be dealt with if the measure of the rotational speed is sufficiently smooth. Points b) and c) can have a smaller dependence of the functional and constructive parameters if increasing the value of parameter α of the on-off control law component, u_N . This consequently will increase the sliding surface's attractiveness, so the robustness, but also the chattering.

Concerning point d), it is possible to find an adaptation law for parameter k , depending on the wind speed. It is this parameter that represents, in fact, the principal degree of freedom of the optimal sliding mode control law. Point e) is surpassed by using continuous hysteretic sigmoid (namely hyperbolic tangent) function, allowing to alleviating the supplementary fatigue due to electromagnetic torque and current oscillations without greatly affecting the control law robustness.

Real time simulations have been performed for the control law modified according to the previous comments.

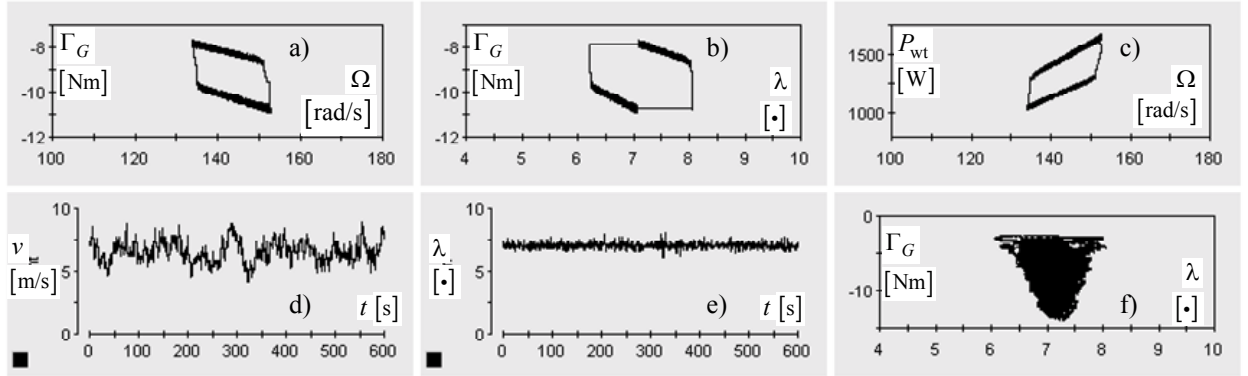


Fig. 5.4 Real-time simulation results to be compared with the similar off-line simulation results from figure 5.3

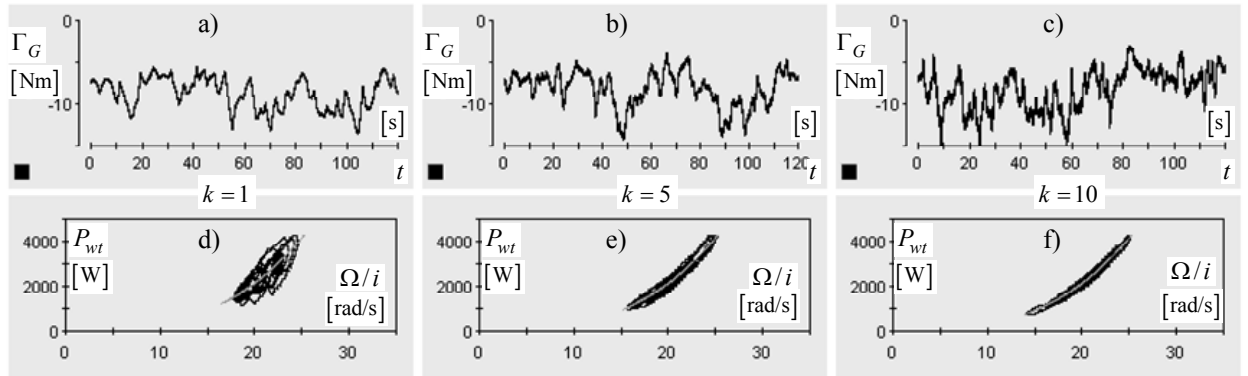


Fig. 5.5 Real-time simulation results, showing the energy-control effort trade-off as k parameter increases

In figure 5.4 one can see a set of ControlDesk captures which match the off-line simulation results from figure 5.3 (the differences are due to a scale coefficient equalling η_{em}). Wind speed sequences having the same statistic/spectral properties as in the off-line case have been here used. Figure 5.4f) shows that the control law efficiency is poorer than suggested by the off-line simulations (figure 5.3i)), the standard deviation of the tip speed values around its optimal value is larger.

Finally, figure 5.5 shows the influence of the trade-off parameter, k , on accomplishing the control goal. Indeed, the ORC tracking precision increases with the value of k (figures 5.5d..5.5f)). But the control input (electromagnetic torque) variations increase also (figures 5.4a..5.4c)), and so does the mechanical stress involved.

In figure 5.6 one can see the effects of using the hysteretic sigmoid in the alternate component of the control law, u_N , while performing real time experimentations. By comparing with figures 5.3a), b) and c), figure 5.6a) shows that there is practically no difference in the operating point behaviour. In figure 5.6b) the torque ripple due to u_N variations are significantly diminished in the case of using hysteretic sigmoid, thus reducing the electrical and mechanical stress.

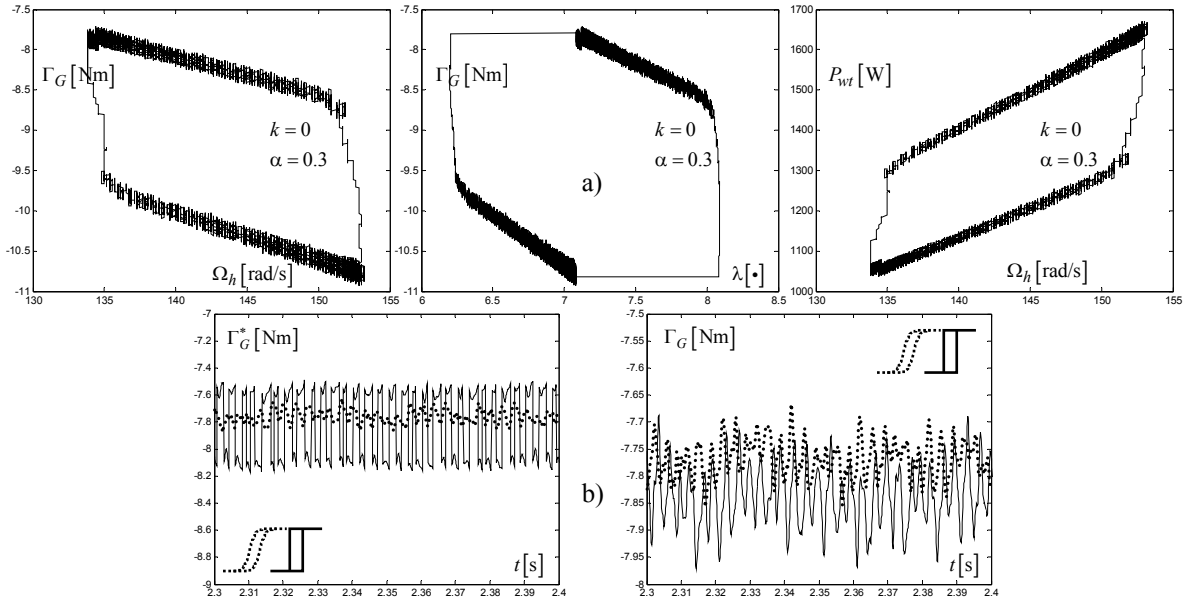


Fig. 5.6 a) OP behaviour if using the sigmoid based hysteresis; b) references and actual values of the electromagnetic torque for the signum versus sigmoid based hysteresis

5.4.2 Evaluation of the real-time simulation results

Let us now make a concluding discussion about the overall assessment of the real-time simulated controlled WECS. The set of ControlDesk captures from figure 5.7 illustrates the evolution of the main variables when an energy-reliability optimization by variable speed is implemented, as previously proposed. The trade-off coefficient has been chosen of a medium value, $k=5$, and the u_N amplitude is $\alpha=0.3$. The 2 minutes pseudorandom wind speed sequence in figure 5.7a) has medium turbulence and was obtained using the von Karman spectrum in the IEC standard. In response to the wind speed sequence, the closed loop WECS manages to change its rotational speed (figure 5.7e)), in order to maintain its operating point close to the optimal conversion regime, according to an imposed energy-reliability trade-off. This control objective is accomplished, as it can be seen on the temporal evolution of the tip speed ($\lambda_{opt} = 7$ tracking precision can be estimated from figure 5.7b) and on the power coefficient evolution (figure 5.7m)). The corresponding system's state trajectory is visible in figure 5.7c) and state

variables time evolutions are given in figures 5.7d) and 5.7e). Figure 5.7f) shows a non uniform effectiveness of the control law along the concerned operating range. The control effort can be seen in figure 5.7h). Differences between the HSS power, P_{em} – figure 5.7j) – and LSS power captured from the wind, P_{wt} – figure 5.7g) – are caused by the non unitary efficiency, η_{em} . One can remark – in figure 5.7k) – the relatively small variations of the $\delta(\lambda)$ parameter around the value corresponding to the OOP. This latter value has been chosen for computing the equivalent component of the control input. The ORC tracking precision is given in figure 5.7l) and the corresponding evolution of the aerodynamic efficiency in figures 5.7m) and 5.7l), this latter with respect to the tip speed ratio, λ . The evolution of the active power fed into the electrical grid is given in figure 5.7o), thus illustrating the final conversion result.

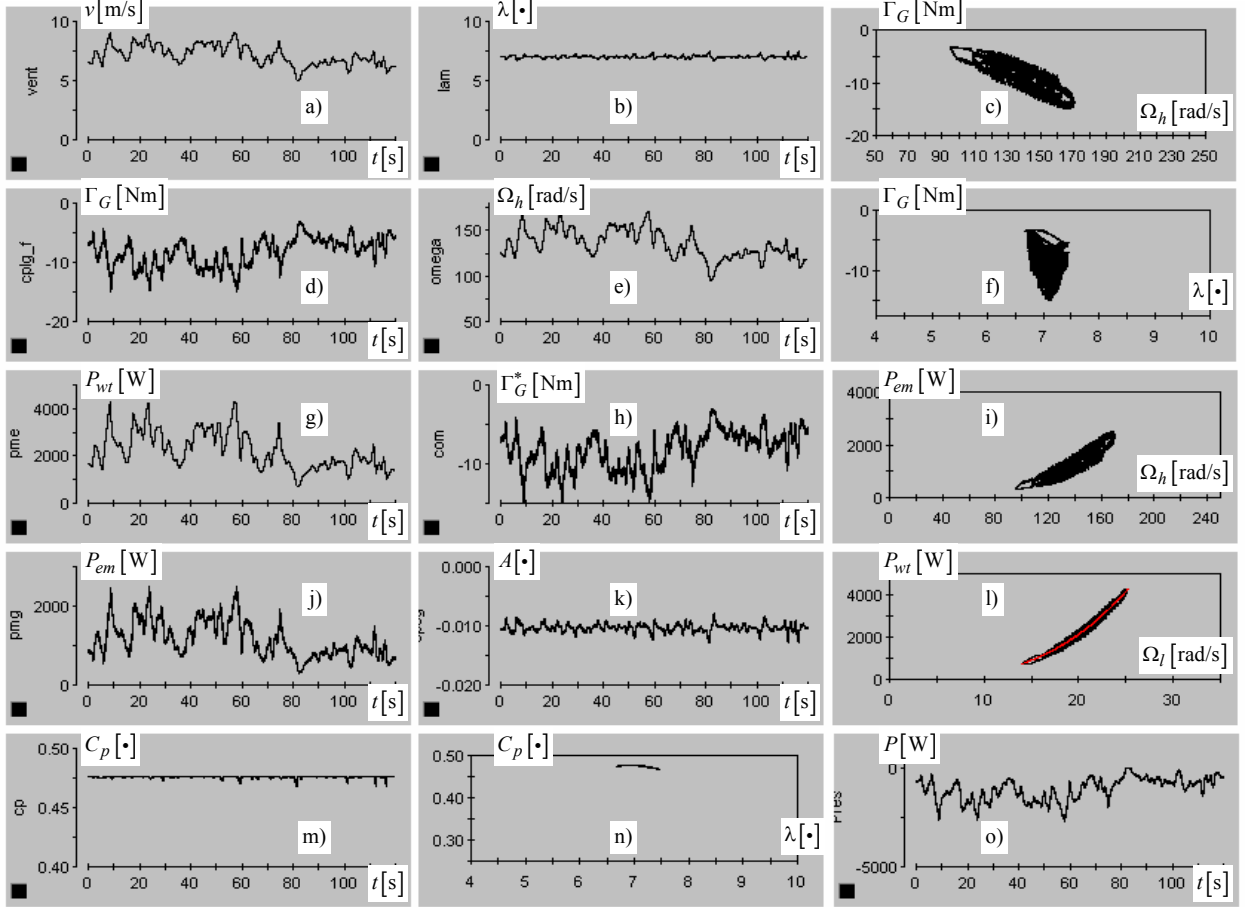


Fig. 5.7 ControlDeskTM captures to illustrate the overall behaviour of the HIL simulated controlled WECS ($k=12$, $\alpha=0.3$, sigmoid hysteresis)

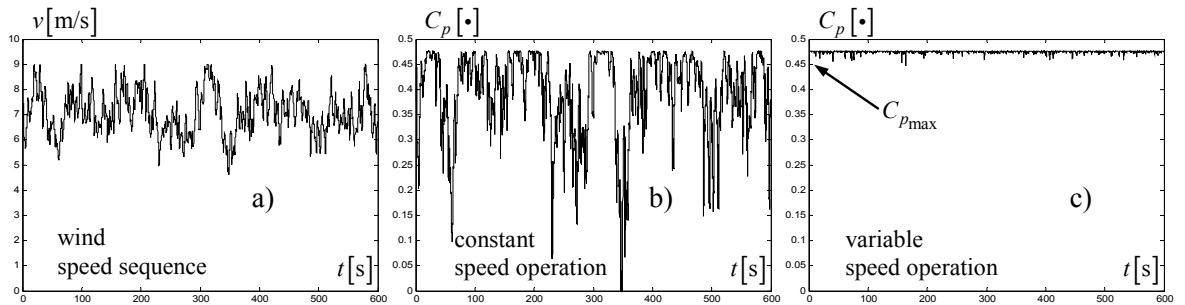


Fig. 5.8 Constant speed b) versus optimized by variable speed c) operation of the considered WECS, under a given wind profile a)

In figure 5.8 one can note a comparison between the constant speed regime and the optimized by variable

speed regime, under the same wind conditions, as reflected in the power coefficient evolution. By variable speed, the aerodynamic efficiency is prevented from decreasing (figure 5.8c)), as it happens in the constant speed operation case (figure 5.8b)).

5.5 CONCLUSION

In this chapter a sliding mode control law for maximizing the power harvested from the wind, while limiting the electromagnetic torque variations is proposed. Provided the strong torque variations due to tracking the optimal tip speed ratio, the choice of an appropriate sliding surface is not a trivial task. Such a surface, having a non empty intersection with the ORC, variant with the wind speed and depending on a desired energy-reliability trade-off, has been systematically found. Thus, a certain “freedom” of the operating point around the ORC is allowed, by imposing some desired reduced order dynamics. The possibility of driving the operating point in a conveniently sized neighbourhood of the ORC is ensured and implicitly allows the generator torque variations limitation in the high frequency range. In this way, the drive train mechanical fatigue induced by the generator control is alleviated and the number of operating hours of the WECS increases.

The possibility of adjusting of the trade-off coefficient, k , confers flexibility to the WECS, so that the wind energy conversion efficiency be significantly increased when the particular conditions of the site allow it (i.e., the mechanical stress induced by turbulences is not important).

The proposed sliding mode control law has been tested by both off-line numerical simulations and on a real-time electromechanical simulator, the latter based upon the HILS concept and allowing for validation under various wind regimes, irrespectively from the actual meteorological context. The theoretical form of the control law had to be modified such as to comply with some practical limitations and modelling uncertainties. Even if not controlled, the chattering frequency has proved to be sufficiently high versus the fastest dynamic of the system. The transfer to the real world applications takes place by software implementation of the control law in an industrial digital control system.

As future work three issues may be of interest. The first two concern a study of the closed loop system's robustness and respectively a design of a sliding mode control law (using the same framework) for harvested power regulation. Also, a quantitative expression of the achievable trade-off must be sought, that is how much is the stress reduced when giving up the tracking performance at a certain degree.

Chapter 6

A TWO LOOP OPTIMAL CONTROL STRUCTURE BASED UPON THE FREQUENCY SEPARATION PRINCIPLE (2LFSP)

This chapter presents a new optimal control structure for WECS, which ensures a trade-off between maximizing the energetic efficiency and minimizing the control input effort. This structure is based upon what has been called the *frequency separation principle* in analyzing the WECS's dynamics. According to this approach, WECSs have a two time scale dynamics, respectively corresponding to the two spectral ranges identified in the wind speed dynamics [BURT 01]: a *low frequency dynamic* due to the low frequency component of the wind speed and a *high frequency dynamic* resulted from the action of the turbulent wind speed. The control design uses previously detailed modelling results for the considered class of WECS.

6.1 PROBLEM FORMULATION AND LITERATURE REVIEW

As previously detailed, the control problem associated with the wind energy conversion systems essentially consists in optimizing the energy conversion, namely in maximizing the energy captured from the wind. This is equivalent with operating the system at its optimal tip speed ratio, λ_{opt} , as depicted in figure 2.22. If λ_{opt} is specified by the wind turbine producer, the optimal control may be implemented by tracking the desired value of the low speed shaft speed, $\Omega_l^{ref} = v \cdot \lambda_{opt} / R$ (called steady-state optimisation in chapter 2 – the controller from figure 2.1 may be instantiated with the structure from figure 2.24a)). But in most of cases the value of λ_{opt} is not known and the MPPT methods – detailed in the fourth chapter of this work – are preferred, which are based on an on-off controller using minimal information from the system. On the other hand, the operating point oscillates largely around the energetic maximum, which is harmful to the provided power quality and to the mechanical reliability.

The above methods have as exclusive goal the maximization of the energetic efficiency, while ignoring the possible drawbacks related to the system's reliability, due to some large control input efforts. The implications on the WECS's reliability, although important, have not been considered in the control of WECS but quite recently. In [NOVA 94], [EKEL 97] is stated that keeping λ_{opt} in turbulent winds is possible only with large generator torque variations (significantly high mechanical stress). Therefore, the supplementary mechanical fatigue of the drive train can be reduced by imposing the minimization of the generator torque variations, $\Delta\Gamma_G(t)$, used as control input, around the optimal operating point, as Ekelund [EKEL 97] has expressed by the combined optimization criterion (2.35):

$$(6.1) \quad I = \underbrace{E\left\{\alpha \cdot [\lambda(t) - \lambda_{opt}]^2\right\}}_{I_1} + \underbrace{E\left\{\Delta\Gamma_G^2(t)\right\}}_{I_2} \rightarrow \min ,$$

where $E\{\cdot\}$ is the statistical average symbol. The first term illustrates the energetic efficiency maximisation, whereas

the second term expresses the minimisation of the torque control variations. The trade-off between the two terms is adjusted by means of the weighting coefficient, α . The solution proposed to deal with the dependency of the linearized dynamical system's parameters on the average wind speed was a gain scheduling adaptive structure, together with a Kalman filter for state reconstruction, which uses the high speed shaft rotational speed, Ω_h , as output measure. The proposed adaptive structure, presented in figure 6.1, allows different control goals to be formulated, depending on a given operating point.

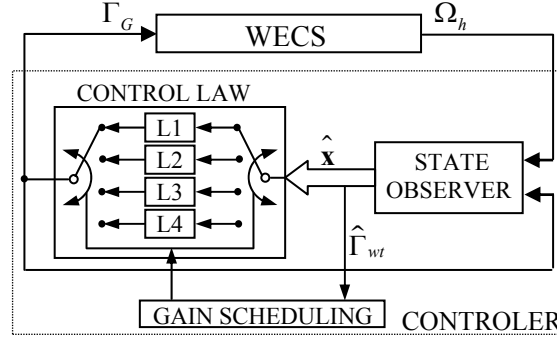


Fig. 6.1 Adaptive control structure proposed in [EKEL 97]

Apart its complexity, this adaptive structure has as drawback the necessity of quite precisely knowing the rotor characteristic. For example, computing the torque parameter, $\gamma(t)$, is necessary for each operating point, requiring the power coefficient curve, $C_p(\lambda)$, to be known, which is seldom an available information.

The class of WECS studied here is the same as the one approached in the above cited work and the optimal control goals are defined likely, that is, expressed as energy-reliability combined criteria. Here, the criterion to be minimized is stochastically defined for the normal operating (partial load) region, the aim being to eliminate, if possible, the adaptive structures and to reduce the required feedback information.

Thus, starting from the frequency separation idea in the wind speed (relation (2.1)), presented in [CUTU 02], [MUNT 03], [MUNT 05a], in this chapter is presented an original optimal control structure, which optimizes the combined criterion (2.35) *without using adaptive structures*. This approach – named *the frequency separation principle* – relies upon separating the turbulence (high frequency) and the low frequency wind speed components derived from the Van der Hoven wind model [NICH 02], by using a low-pass filter. The two components – the low frequency and the turbulent, as to relation (2.1) – excite the plant's dynamics in two distinct spectral ranges, as it is detailed in the next paragraph. Correspondingly, the proposed structure is formed by two loops, separately driven by the low frequency and the turbulence component respectively and, differently from the cited work, the optimization approach is here stochastic. This structure desensitizes the closed loop system subject to the static operating point.

6.2 FREQUENCY SEPARATION OF THE WECS DYNAMICS

The basic idea of the proposed approach is to distinctly dealing with the effects induced by the two components of the wind speed on the WECS's dynamics. They drive the system in two distinct spectral ranges: the low frequency component, v_s , determines the average position of the operating point on the wind turbine characteristic (these are slow, *low frequency* dynamics, considering that this component's spectrum is entirely placed inside the turbine's pass band), and the turbulence component, $\Delta v(t) = v - v_s \equiv v_t$, excites the high frequency dynamics by generating *high frequency* variations around this point.

Therefore, the WECS's global dynamical behaviour, expressed by the measurable variables' evolutions (i.e.,

generator's rotational speed, Ω_h), results from superposing a *slow dynamic*, induced by the low frequency component, and a *turbulent dynamic*, due to the turbulence component, as suggested in figure 6.2. Thus, it has appeared the idea of separately compensating the two dynamics [CUTU 02], by designing a two loop control structure, where each of loops uses estimated values of v_s and respectively v_t from the measured (total) wind speed, v . The system's output, Ω_h , serves for estimating the necessary feedback information.

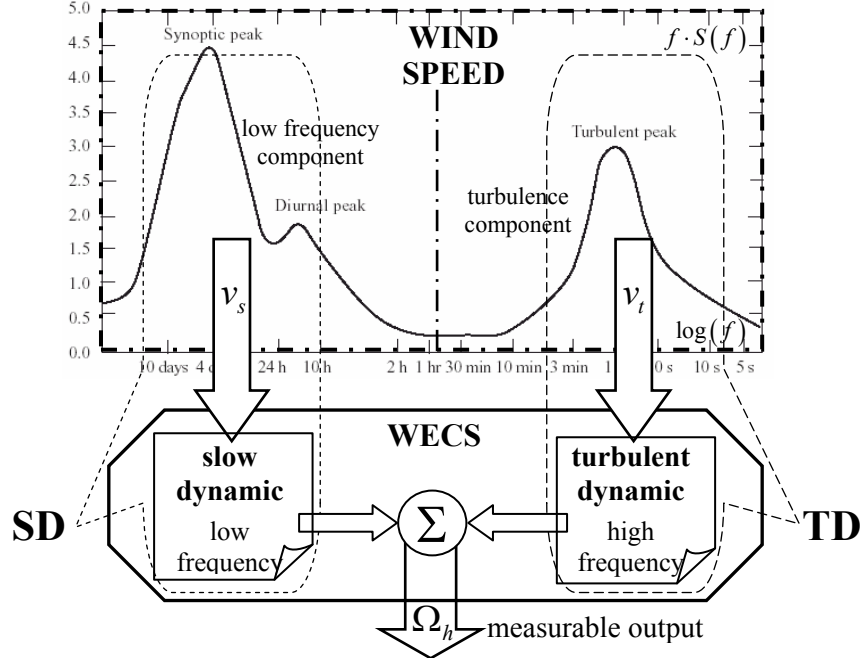


Fig. 6.2 Frequency separation principle applied in the WECS's dynamical behaviour analysis

6.3 DESCRIPTION OF THE PROPOSED SOLUTION

General block diagram

The WECS is torque controlled; it is considered that the electromagnetic subsystem is a first-order element providing electromagnetic torque at a time constant much smaller than that of the drive train [MUNT 04b].

The general optimisation problem, stated in §6.1, is split into two disjoint sub-problems, respectively associated with the two dynamics identified in the WECS (§6.2). Because the stress induced by the low frequency wind component is negligible, the optimisation problem related to the slow dynamic may be reduced to a steady-state control (i.e., λ_{opt} tracking). On the contrary, the mechanical fatigue induced by the turbulence wind component is significant, so, the optimisation problem associated to the turbulent dynamic may be formulated in terms of a LQG dynamic optimisation.

Briefly, the two components of the wind speed act separately within two loops of the proposed control structure: a **low frequency loop** (referred further to as LFL), using v_s within a steady-state optimal controller (tip speed controller – TSC) to drive and maintain the system *at* a steady-state operating point on the ORC and a **high frequency loop** (referred further to as HFL), using v_t within a LQG controller, for dynamic optimization, of the linearized system's behaviour *around* this point. **In this way, both energetic optimization in relation to the low frequency wind speed and mechanical stress alleviation due to the turbulence wind speed are possible.**

According to the frequency separation principle, any variable from the system is decomposed into two components: a steady-state one, of low frequency, and a high frequency one, representing variations around the

steady-state value. These two kinds of values describe respectively the two kinds of dynamics and will be dealt with within the corresponding control loops. Let notation adopted in §2.4 for a generic variable x be reconsidered:

$$\bar{x} = x|_{\text{static operating point}}; \Delta x = x - \bar{x}; \overline{\Delta x} = \Delta x / \bar{x}$$

Starting from WECS equations described in chapter 2, two kinds of linearized models will be developed: one suitable for the LFL and the other one for the HFL. The first one results from a linearization around a static operating point, as imposed by the low frequency wind speed. The second one uses variables' normalized variations around the static operating point fixed by the former model, such that to capture the high frequency WECS behaviour.

The steady-state value, $\bar{x}$, belongs to the low frequency loop and the normalized variation $\overline{\Delta x}$ is treated within the high frequency loop. Each of the two loops receives as feedback $\overline{\Omega}_h$ and $\overline{\Delta \Omega}_h$ respectively and separately provides a torque reference component, $\overline{\Gamma}_G$ and $\Delta \Gamma_G$ respectively, such that the total torque reference to be fed into the electromagnetic subsystem is the sum of them, $\Gamma_G^* = \overline{\Gamma}_G + \Delta \Gamma_G$. The slow dynamic embeds also the associated exogenous signal's dynamic, v_s ; the same holds in the case of the turbulent dynamic.

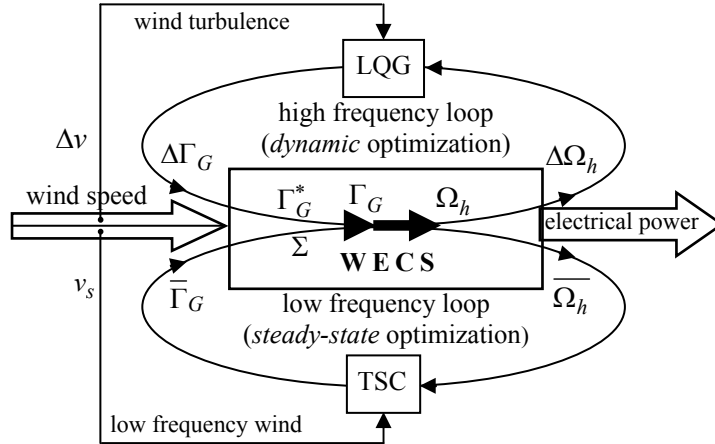


Fig. 6.3 Block diagram of the two loop optimal control structure based upon the frequency separation principle (2LFSP)

The turbulent dynamic is linearized around the static operating point reached within the low frequency loop (modelling results can be found in [EKEL 97], [MUNT 04b] and also in §2.4 of this work). Considering that the low frequency loop achieves the goal of maintaining the operating point on the ORC, then the turbulent dynamic is an invariant one [MUNT 02], because of maintaining the system's most variant variable, the torque parameter (2.22), γ , at $\gamma(\lambda_{opt})$, corresponding to the OOP. This allows solving the optimization problem within the high frequency loop (that is, associated to the turbulent dynamic) by a LQG **invariant** design procedure [MUNT 02], [MUNT 05a], as detailed further, and eliminates the necessity of using any adaptive structures.

The initial, global optimization problem was split into two sub-problems, each of which is intended to be solved to optimality, therefore the solution obtained by aggregating the two separate solutions is in general sub-optimal. One can remark that its closeness to the ideal, optimal solution ultimately depends upon how sharply the two wind dynamics can be separated.

The low frequency loop aims exclusively at maximizing the WECS energetic efficiency. This simply requires operating the system at variable speed, such that its (steady-state) operating point stays on the ORC. This is equivalent to maintaining the power coefficient, C_p , at its maximal value and is called **steady-state optimization**. It is realized by tracking the low rotational speed corresponding to λ_{opt} , $\Omega_{l\ opt} = v_s \cdot \lambda_{opt} / R$. A tip speed controller

(TSC in figure 6.3) is used for this purpose, whose reference is computed based upon the low frequency component of the wind speed, v_s , as this one determines the (slow) variation of the operating point. A classical PI and an on-off controller are two possible versions of such a controller, as it is detailed in the seventh chapter of this work.

Due to the high inertia of the turbine versus the wind speed variation, a control exclusively based on the steady-state optimization generates large torque variations at the generator's shaft, which could damage the mechanical subsystems (the gear-box for example). It is the high frequency loop performing the **dynamic optimization** of the turbulent dynamic of WECS which can alleviate the mechanical stress, by casting the control problem into a LQ Gaussian optimization problem. The associated performance index describes an energy-reliability trade-off in the form of (6.1).

As the performance index (6.1) shows and taking into account the previously introduced form (2.26) of the state model, with $\mathbf{x}(t) = [\overline{\Delta\Omega_l(t)} \quad \overline{\Delta v(t)}]^T$ as state vector and $u(t) = \overline{\Delta\Gamma_G(t)}$ as control input, the optimization problem reflects a trade-off between minimizing both the output variations and those of the control input variable [MUNT 02]. The first component results as a quadratic form of the state variable:

$$I_1 = E \left\{ \alpha \cdot \overline{\Delta\lambda^2(t)} \right\} \rightarrow \min \Leftrightarrow I_1 = E \left\{ \mathbf{x}^T(t) \cdot \mathbf{C}_\alpha^T \mathbf{C}_\alpha \cdot \mathbf{x}(t) \right\} \rightarrow \min ,$$

where $\mathbf{C}_\alpha = \sqrt{\alpha} \cdot \mathbf{C}$.

The reliability constraint is solved by the control input variations' minimization (Maximization of Energy with minimization of control input – **MEMci**). The second component is defined as:

$$I_2 = E \left\{ \overline{\Delta\Gamma_G^2(t)} \right\} = E \left\{ \mathbf{u}^T(t) \cdot \mathbf{N} \cdot \mathbf{u}(t) \right\} \rightarrow \min ,$$

where $\mathbf{N} = 1$ (the vector notation for $u(t)$ is used for formal conformity). Therefore, the global index is:

$$(6.2) \quad I = E \left\{ \mathbf{x}^T(t) \cdot \left(\mathbf{C}_\alpha^T \cdot \mathbf{C}_\alpha \right) \cdot \mathbf{x}(t) + \mathbf{u}^T(t) \cdot \mathbf{N} \cdot \mathbf{u}(t) \right\} \rightarrow \min$$

If using a state model having $\mathbf{x}(t) = [\overline{\Delta\Omega_l(t)} \quad \overline{\Delta\Gamma_{wt}(t)}]^T$ as state vector and $u(t) = \overline{\Delta\Gamma_G(t)}$ as control input, another form of the performance index can also be used, whose second component is given by:

$$I_2 = E \left\{ \left(\overline{\Delta\Gamma_{wt}(t)} + \overline{\Delta\Gamma_G(t)} \right)^2 \right\} \rightarrow \min$$

Here, the reliability demand is met by tracking the wind torque, minimizing a combined effort of the drive train (Maximization of Energy with wind torque tracking – **MEwt**). The global performance criterion results:

$$(6.3) \quad I = E \left\{ \mathbf{x}^T(t) \cdot \underbrace{\left[\left(\mathbf{M}^T \cdot \mathbf{M} \right) + \left(\mathbf{C}_\alpha^T \cdot \mathbf{C}_\alpha \right) \right]}_{\mathbf{R}_{xx}} \cdot \mathbf{x}(t) + 2 \cdot \mathbf{x}^T(t) \cdot \underbrace{\mathbf{M}^T}_{\mathbf{R}_{xu}} \cdot \mathbf{u}(t) + \mathbf{u}^T(t) \cdot \mathbf{R}_{uu} \cdot \mathbf{u}(t) \right\} \rightarrow \min ,$$

where $\mathbf{M} = [0 \ 1]$ and $\mathbf{R}_{uu} = 1$. This second form of the performance index is particularly suitable in the case of flexible drive train WECSs, as will be shown in chapter 8 of this work.

Proposed design procedure

As a conclusion, the proposed **design procedure** has the following major steps:

Step 1. Measure the wind speed, v , as being the output signal of the anemometer, and HSS rotational speed, Ω_h , from encoder.

Step 2. Obtain the low frequency wind speed, v_s , by low-pass filtering the signal v .

Step 3. Obtain the turbulence component of the wind speed, $\Delta v \equiv v_t = v - v_s$, and its normalized value, $\overline{\Delta v} \equiv \Delta v / v_s$.

Step 4. Obtain the low frequency component of the HSS rotational speed, $\overline{\Omega_h}$, by low-pass filtering the signal Ω_h .

Step 5. Obtain the normalized value of the HSS rotational speed high frequency component, $\overline{\Delta\Omega_h} = (\Omega_h - \overline{\Omega_h}) / \overline{\Omega_h}$.

Step 6. v_s and $\overline{\Omega_h}$ are fed into the low frequency loop, whose design may follow either a linear or a nonlinear procedure. The steady-state component of the control input, $\overline{\Gamma_G}$, results as output of the TSC.

Step 7. Δv and $\overline{\Delta\Omega_h}$ are fed into the high frequency loop, whose design is based upon the classical LQG synthesis. The dynamic component of the control input, $\Delta\Gamma_G$, results.

Step 8. The total control input (electromagnetic torque), Γ_G^* , is obtained by summing up the steady-state component and the dynamic component: $\Gamma_G^* = \overline{\Gamma_G} + \Delta\Gamma_G$.

Chapter 7

2LFSP APPLIED TO THE RIGID DRIVE TRAIN WIND ENERGY CONVERSION SYSTEMS

This chapter deals with applying the 2LFSP, the control strategy detailed in the previous chapter, to rigid drive train variable speed WECS (in the configuration from figure 2.1), based upon torque controlled asynchronous generators, in order to achieve a multi-purpose optimization, regarded as a “balance” between energetic efficiency and reliability.

First, the modelling approaches for both slow and turbulent dynamics are presented. Next, two versions for implementing the low frequency loop (LFL) control are detailed: the PI controller and respectively the on-off controller based LFL. The design procedures, as well as validations by simulation, are presented. The dynamic optimization within the high frequency loop (HFL) is formulated as a LQG optimization problem, whose performance index describes an energy-reliability trade-off. Simulation results are also provided.

The combined action of the two control loops within the proposed structure is largely illustrated by both numerical (Matlab/SimulinkTM – off-line) and real-time (on-line) simulation. The structure and operation of the experimental rig, consisting of an electromechanical WECS simulator, are described and the most relevant simulation results are discussed for assessing the global control performance.

7.1 MODELLING

7.1.1 Modelling of the slow dynamic of WECS

The slow dynamic of WECS is given by the coupling between the rotor and the rigid drive train, for which a linearized model can be deduced, assuming that the electromagnetic subsystem’s dynamic is negligible versus that of the mechanical subsystem; this modelling approach starts from the linearized model previously developed in [NICH 95], [MUNT 97] and uses some elements from §2.3 and §2.4 of this work.

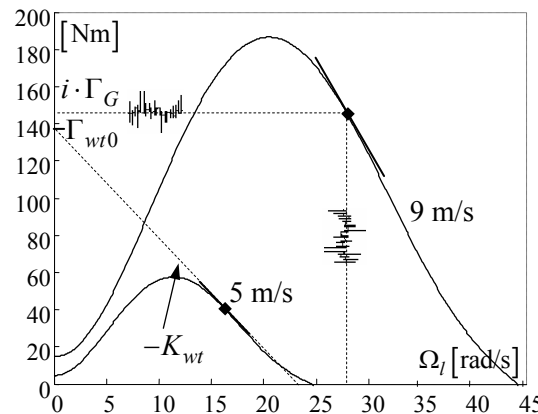


Fig. 7.1 Linearization of the aerodynamic characteristic around a stable operating point

Points of WECS’s stable operation are placed on the falling part of the wind torque (aerodynamic)

characteristic. The static wind torque characteristic can be linearized in such an operating point (see figure 7.1), by considering the first two terms of the Taylor's series. Using elements from figure 7.1, the wind torque becomes:

$$(7.1) \quad \Gamma_{wt} = -K_{wt} \cdot \Omega_l + \Gamma_{wt0}$$

The low speed shaft's rotational speed is chosen as state variable. According to relation (2.16), if neglecting the drive train's efficiency, the WECS's movement equation rendered at the high speed and at the low speed shaft respectively is:

$$\dot{\Omega}_h = \frac{\Gamma_{wt}}{J_h} - \frac{\Gamma_G \cdot i}{J_h} \quad \text{and} \quad \dot{\Omega}_l = \frac{\Gamma_{wt}}{J_l} - \frac{\Gamma_G \cdot i}{J_l},$$

where $J_l = i \cdot J_h$ is the inertia rendered at the low speed shaft, with J_h given by relation (2.18) and i being the drive train's ratio.

Replacing relation (7.1) in the last relation one obtains:

$$\dot{\Omega}_l = \frac{-K_{wt} \cdot \Omega_l}{i \cdot J_h} - \frac{\Gamma_G}{J_h} + \frac{\Gamma_{wt0}}{i \cdot J_h},$$

where the last term does not influence the dynamic, therefore it is neglected in obtaining the transfer function:

$$\left(s + \frac{K_{wt}}{i \cdot J_h} \right) \cdot \Omega_l(s) = \frac{-1}{J_h} \cdot \Gamma_G(s) \Rightarrow H_{lin}(s) = \frac{\Omega_l(s)}{\Gamma_G(s)} = -\frac{1}{J_h} \left/ \left(s + \frac{K_{wt}}{i \cdot J_h} \right) \right.$$

The linearized transfer function from the electromagnetic torque, Γ_G , to the low speed shaft rotational speed, Ω_l , results as follows:

$$(7.2) \quad H_{lin}(s) = -\frac{K_1}{s + K_2},$$

where $K_1 = \frac{1}{J_h}$ and $K_2 = \frac{K_{wt}}{i \cdot J_h}$.

In conclusion, supposing that Γ_G is instantaneously obtained (its dynamic is hundreds of times smaller than $1/K_2$), then **the rigid drive train WECS's slow dynamic can be approximated as being of first order**.

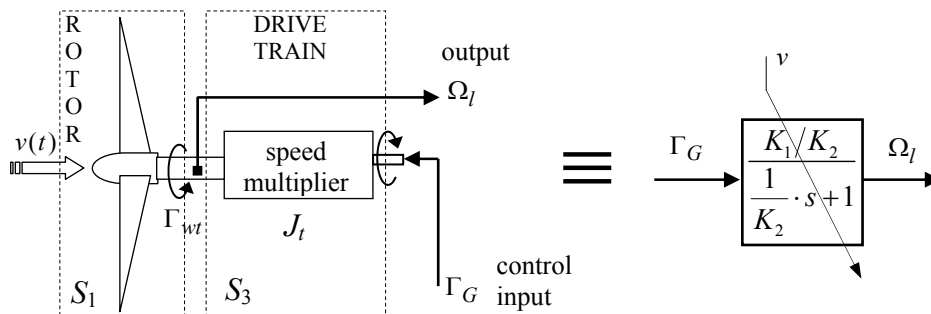


Fig. 7.2 WECS's slow dynamic (aerodynamic subsystem and drive train) approximated with a first order element

Remarks:

- Parameters of the linearized system described by $H_{lin}(s)$ depend of the mechanical constructive parameters.
- The gain and the time constant depend (through K_{wt}) on the wind speed (the system's time constant decreases once the wind speed increases) and on the turbine's load (torque $i \cdot \Gamma_G$).
- The time constant of a turbine linearized around a suitably chosen operating point (figure 2.22), equalling

$\frac{i \cdot J_h}{K_{wt}}$, depends on the rotor's inertia, but is significantly smaller due to the wind torque characteristic, which is as

abrupt as the wind speed is large.

- If the (static) operating point is kept around the ORC, then parameter K_2 's variations are small for wind speeds less than the maximal one.

One can finally conclude that the simplest linearized model of the slow dynamic of a torque controlled WECS is of first order; its parameters depend on the operating point's position on the rotor's aerodynamic characteristic. A tracking controller for this system can be designed by using either the nonlinear model (2.17) or the linearized model (7.2).

7.1.2 Modelling of the turbulent dynamic of WECS

In §2.4 the *linearized model with respect to low rotational speed and wind speed* of a rigid drive train WECS [EKEL 97] has been presented, which has as state variables the normalized variations of the low rotational speed and of the wind speed respectively (see relations (2.25) and (2.29)). Another form of the linearized in variations model can be obtained by considering as state variables the normalized variation of the low rotational speed around its steady-state value, $\overline{\Delta\Omega_l}$, and the normalized variation of the wind torque around its average value (that is, around its component given by the low frequency wind speed), $\overline{\Delta\Gamma_{wt}}$.

The state vector and the control input are re-defined as:

$$(7.3) \quad \mathbf{x}(t) = \begin{bmatrix} \overline{\Delta\Omega_l}(t) \\ \overline{\Delta\Gamma_{wt}}(t) \end{bmatrix}, \quad u(t) = \overline{\Delta\Gamma_G}(t)$$

Relation (2.21), giving the analytical expression of the linearized wind torque characteristic, is time derived:

$$(7.4) \quad \dot{\overline{\Delta\Gamma_{wt}}}(t) = \gamma \cdot \dot{\overline{\Delta\Omega_l}}(t) + (2 - \gamma) \cdot \dot{\overline{\Delta v}}(t)$$

In relation (7.4) the low speed shaft's movement equation is replaced as:

$$(7.5) \quad \dot{\overline{\Delta\Omega_l}}(t) = \frac{1}{J_T} \cdot (\overline{\Delta\Gamma_{wt}}(t) - \overline{\Delta\Gamma_G}(t)),$$

and so is the normalized wind speed variation, modelled as a pseudorandom process yielded by filtering a white noise, $e(t)$:

$$\dot{\overline{\Delta v}}(t) = \frac{1}{T_w} \cdot (e(t) - \overline{\Delta v}(t)),$$

where both time constants J_T , given by relation (2.24), and T_w , introduced in §2.2.2, depend on the operating point, that is, on v_s . Finally one obtains:

$$(7.6) \quad \dot{\overline{\Delta\Gamma_{wt}}}(t) = \frac{\gamma}{J_T} \cdot (\overline{\Delta\Gamma_{wt}}(t) - \overline{\Delta\Gamma_G}(t)) + \frac{(2 - \gamma)}{T_w} \cdot (e(t) - \overline{\Delta v}(t))$$

Supposing that $\gamma \neq 2$ (the wind speed influences the wind torque), from relation (2.21) results:

$$(7.7) \quad \overline{\Delta v}(t) = \frac{1}{(2 - \gamma)} \cdot \overline{\Delta\Gamma_{wt}}(t) - \frac{\gamma}{(2 - \gamma)} \cdot \overline{\Delta\Omega_l}(t),$$

which is used in (7.6). After calculi one obtains:

$$(7.8) \quad \overline{\Delta \Gamma_{wt}}(t) = \left(\frac{\gamma}{J_T} - \frac{1}{T_w} \right) \cdot \overline{\Delta \Gamma_{wt}}(t) + \frac{\gamma}{T_w} \cdot \overline{\Delta \Omega_l}(t) - \frac{\gamma}{J_T} \cdot \overline{\Delta \Gamma_G}(t) + \frac{(2-\gamma)}{T_w} \cdot e(t)$$

Relations (7.5) and (7.8) define the *linearized state model with respect to low rotational speed and wind torque*:

$$(7.9) \quad \begin{cases} \overline{\Delta \Omega_l}(t) = \frac{1}{J_T} \cdot \overline{\Delta \Gamma_{wt}}(t) - \frac{1}{J_T} \cdot \overline{\Delta \Gamma_G}(t) \\ \overline{\Delta \Gamma_{wt}}(t) = \left(\frac{\gamma}{J_T} - \frac{1}{T_w} \right) \cdot \overline{\Delta \Gamma_{wt}}(t) + \frac{\gamma}{T_w} \cdot \overline{\Delta \Omega_l}(t) - \frac{\gamma}{J_T} \cdot \overline{\Delta \Gamma_G}(t) + \frac{(2-\gamma)}{T_w} \cdot e(t) \end{cases}$$

Using notation (7.3) one can introduce the state matrix, **A**, the input matrix, **B** and the exogenous matrix, **L**:

$$(7.10) \quad \dot{\mathbf{x}}(t) = \underbrace{\begin{bmatrix} 0 & 1 \\ \frac{\gamma}{T_w} & \frac{\gamma}{J_T} - \frac{1}{T_w} \end{bmatrix}}_{\mathbf{A}} \cdot \mathbf{x}(t) + \underbrace{\begin{bmatrix} -\frac{1}{J_T} \\ -\frac{\gamma}{J_T} \end{bmatrix}}_{\mathbf{B}} \cdot u(t) + \underbrace{\begin{bmatrix} 0 \\ \frac{2-\gamma}{T_w} \end{bmatrix}}_{\mathbf{L}} \cdot e(t)$$

The output variable is the normalized variation of the tip speed ratio (relation (2.27)). This variable is expressed depending on the state vector:

$$\overline{\Delta \lambda}(t) = \overline{\Delta \Omega_l}(t) - \frac{1}{(2-\gamma)} \cdot \overline{\Delta \Gamma_{wt}}(t) + \frac{\gamma}{(2-\gamma)} \cdot \overline{\Delta \Omega_l}(t) = \frac{2}{(2-\gamma)} \cdot \overline{\Delta \Omega_l}(t) - \frac{1}{(2-\gamma)} \cdot \overline{\Delta \Gamma_{wt}}(t),$$

introducing the output matrix, **C**:

$$(7.11) \quad z(t) \equiv \overline{\Delta \lambda}(t) = \underbrace{\begin{bmatrix} \frac{2}{(2-\gamma)} & -\frac{1}{(2-\gamma)} \end{bmatrix}}_{\mathbf{C}} \cdot \underbrace{\begin{bmatrix} \overline{\Delta \Omega_l}(t) \\ \overline{\Delta \Gamma_{wt}}(t) \end{bmatrix}}_{\mathbf{x}(t)}$$

This model's block diagram is presented in figure 7.3; a more complete description of the modelling approach can be found in [MUNT 02]. The state model has the same form as the one from relation (2.29), except the form of the state vector and of matrices involved. It can be shown that the matrix pair (**A**,**B**) is controllable [MUNT 02].

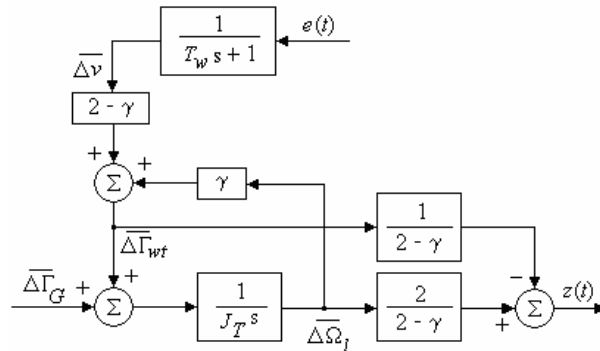


Fig. 7.3 Linearized model with respect to low rotational speed and wind torque – rigid drive train

7.1.3 Sensitivity of the linear model in relation to the low frequency wind speed

The parameters of the state model (7.10) – γ , T_w and J_T – depend on the operating point, that is, on the low frequency wind speed, v_s . The torque parameter, γ , depends significantly on the low frequency wind speed through the tip speed ratio (see relation (2.22)). J_T is defined as normalized inertia, as to relation (2.24), where $\overline{\Omega_l}$ and $\overline{\Gamma_{wt}}$

depend on v_s also. Time constant T_w depends inversely on the low frequency wind speed, v_s , and directly on the turbulence length (see §2.2.2). The γ parameter varies the most significantly with the operating point. For example, when λ varies in the range from 5 to 8, the γ parameter changes its sign in the range from 1.5 to -1.5 [EKEL 97].

Therefore, the system is variant in relation to the low frequency wind speed, which is an inconvenient for the control strategies design. The gain scheduling control solution proposed in [EKEL 97] was supposing the exact knowledge on how parameters γ , J_T and T_w depend on the operating point. Often, as the information about $C_p(\lambda)$ is poor or difficult to obtain, it is practically impossible to compute the value of γ .

The combined action of the two control loops inside the 2LFSP practically desensitizes the system in relation to the static operating point, by cancelling the variation of γ versus the tip speed, λ , as will be shown in the sequel.

7.2 STEADY-STATE OPTIMIZATION USING A LINEAR CONTROL

7.2.1 Linear tip speed controller design

In this case, the optimal tip speed, λ_{opt} , is maintained by tracking the low speed shaft's rotational speed that corresponds to the low frequency wind speed, v_s , $\overline{\Omega}_l^{ref} = \lambda_{opt}/R \cdot v_s$. Thus, the low frequency loop (LFL) can be based on a PI speed controller (figure 7.4) [CUTU 02], [MUNT 05a].

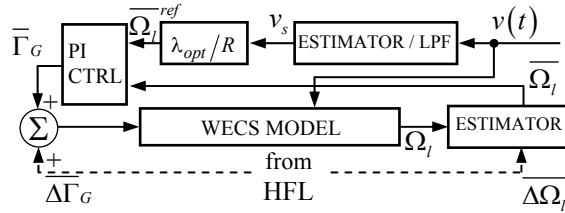


Fig. 7.4 Block diagram of PI controller based LFL

The low frequency component, v_s , is obtained by low-pass filtering the signal $v(t)$ provided by the anemometer. A fourth order Butterworth low-pass filter having the cut-off frequency at most equal with the WECS pass band may be used for this goal [MUNT 05a].

The low frequency (steady-state) component of the low rotational speed, $\overline{\Omega}_l$, is obtained also by filtering and its normalized variation results as $\overline{\Delta\Omega}_l = (\Omega_l - \overline{\Omega}_l)/\overline{\Omega}_l$ and is applied to the high frequency loop (HFL) (see the proposed design procedure in §6.3). The PI controller output is the low frequency component of the torque control feeding the electrical generator, the electromagnetic subsystem being considered as ideal [MUNT 04b].

The empirical Ziegler-Nichols procedure [ZIEG 42], [HAUT 97] may be employed to compute the PI controller's parameters. In any case, the choice of these parameters is not critical, because the low frequency wind speed varies much more slowly comparatively to the WECS's dynamics.

7.2.2 Validation by numerical simulation

Appendix F presents the LFL Simulink diagram, the low-pass filter's parameters and the PI controller's design. Total wind speed and low frequency wind speed evolutions are respectively presented in figures 7.5 and 7.6. A stationary modelling has been used for wind speed synthesis (see §2.2.2).

An image of how the LFL works is synthetically offered by figures 7.7 and 7.8.

Simulation was performed on a sufficiently large time window such to include significant variations of the low frequency wind speed (10 minutes); it shows that the control goal is reached. The tip speed is maintained at its optimal value with dynamical errors within 2% (figure 7.7).

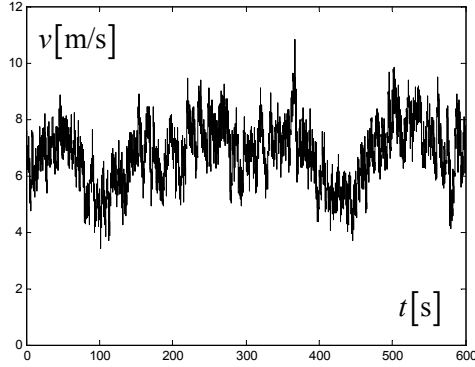


Fig. 7.5 Wind speed evolution

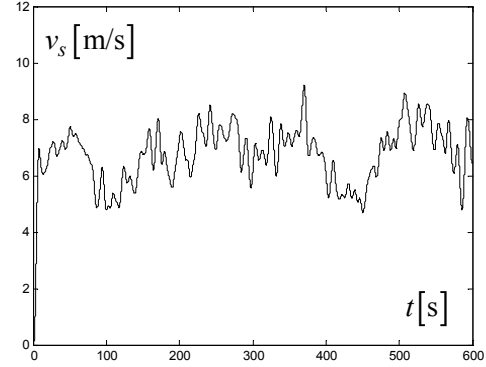


Fig. 7.6 Low frequency wind speed evolution

The torque parameter, γ , which depends on the tip speed, having the largest variation range within the linearized model of the turbulent dynamic, is maintained sufficiently close to the optimal regime, $\bar{\gamma} = \gamma(\lambda_{opt}) = -1$ (figure 7.8). The LFL's efficiency depends on the v_s level – the tip speed variations' amplitude is smaller as v_s is smaller [MUNT 03].

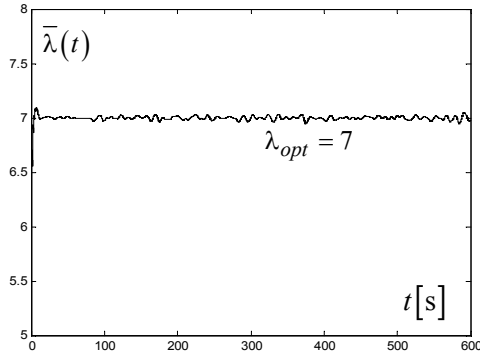


Fig. 7.7 Tip speed evolution

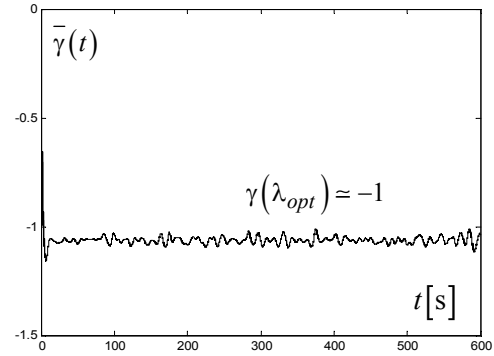


Fig. 7.8 Torque parameter evolution

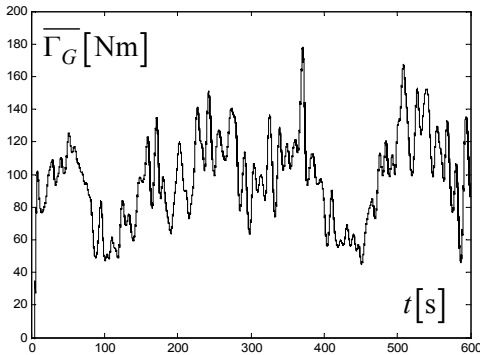


Fig. 7.9 Low frequency torque evolution, $\overline{\Gamma}_G$

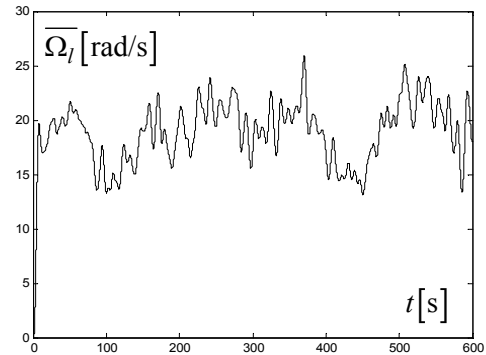


Fig. 7.10 Low frequency rotational speed evolution, $\overline{\Omega}_l$

Figures 7.9 and 7.10 describe the static operating point's evolution, influenced by the low frequency wind, v_s , and by the steady-state torque control input, $\overline{\Gamma}_G$.

7.3 STEADY-STATE OPTIMIZATION USING AN ON-OFF CONTROL

7.3.1 On-off tip speed controller design

This approach supposes that the WECS reacts sufficiently fast to variation of the low frequency wind speed. Thus, for ensuring the optimal energy conversion is sufficient to feed the electrical generator with the torque control value corresponding to the static operating point placed on the ORC. In this section an on-off controller based structure is proposed to zeroing the difference $\sigma(t) = \lambda_{opt} - \bar{\lambda}(t)$ [MUNT 04a], [MUNT 04c]. Choice of such a structure has been justified by its robustness to the parametric uncertainties inherent to any WECS.

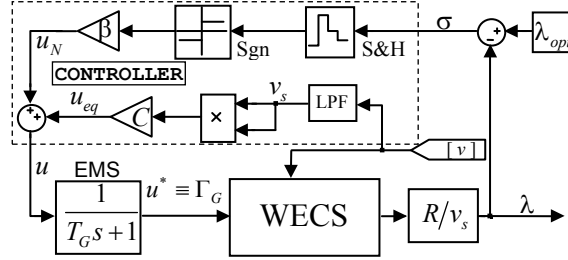


Fig. 7.11 Block diagram of on-off controller based LFL

The control law associated to the diagram from figure 7.11 provides the steady-state torque reference, u , which has two components:

$$(7.12) \quad u = u_{eq} + u_N,$$

where the *equivalent* control, u_{eq} , is a smooth component, corresponding to the optimal operating point (at λ_{opt}), and depends proportionally on the low frequency wind speed squared, $v_s(t)^2$:

$$(7.13) \quad u_{eq} = 0.5 \cdot \pi \cdot \rho \cdot R^3 \cdot v_s^2 \cdot \frac{C_p(\lambda_{opt})}{i \cdot \lambda_{opt}} = C \cdot v_s^2$$

As it is imposed that the control loop operate in self-oscillations, u_N is an alternate, high frequency component, which switches between two values, $+\beta$ and $-\beta$, $\beta > 0$:

$$(7.14) \quad u_N = \beta \cdot \text{sgn}(\sigma(t))$$

Component u_{eq} must drive the system to the optimal operating point, whereas u_N has the role of stabilising the system's behaviour around this point, once reached there. The control input has in this case a large spectrum, such that the EMS time constant, T_G , cannot be neglected anymore. The zero-order sample-and-hold (S&H in figure 7.11) has been introduced to limit the loop switching frequency. If this frequency is too large, the EMS's dynamic is too fast, such that the control loop become inefficient. Moreover, S&H grows the system's order, allowing the system be stabilised by self-oscillations [MUNT 04c].

Self-oscillations analysis

The LFL's self-oscillating regime is analysed by using the describing function method. This requires the torque characteristics be linearized for a given value of the low frequency wind speed, v_s , around a typical operating point, that is, placed on the falling region. The modelling approach is that detailed in §7.1.1, leading at the transfer function from relation (7.2).

For analysis purpose, the zero-order hold is approximated as a first-order low-pass filter with time constant

$T_1 \approx T_s/2$, where T_s is the S&H's sampling period, determined by fitting the step responses in a least squares sense. The analysis is performed on the loop region governed by u_N . In figure 7.12 the nonlinear part consists of an on-off relay („sgn” block), whereas the linear part contains the series connection of all the other blocks. Diagram from figure 7.12 is usually represented as in figure 7.13 [VOIC 86].

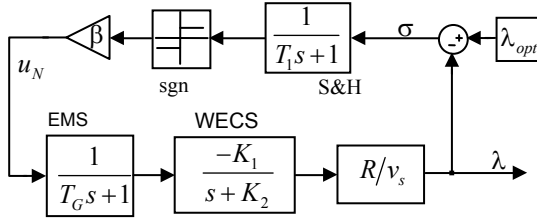


Fig. 7.12 Closed loop system used for self-oscillations analysis

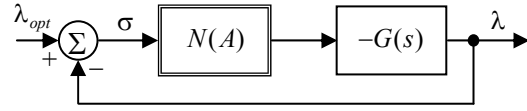


Fig. 7.13 Identifying the linear and nonlinear parts of the self-oscillating system from figure 7.12

$N(A)$ is the describing function of the on-off relay ([VOIC 86]):

$$(7.15) \quad N(A) = \frac{4\beta}{\pi A},$$

where A is the amplitude of the relay input. The transfer function of the linear part from figure 7.13 is:

$$(7.16) \quad G(s) = \frac{K_1 R}{v_s \cdot (T_G s + 1)(T_1 s + 1)(s + K_2)}$$

A closed loop containing a nonsymmetric nonlinearity is likely to self-oscillate (corresponding to some limit cycles in the state space) depending on whether the harmonic balance equation:

$$(7.17) \quad N(A) \cdot G(j\omega) + 1 = 0$$

has solutions or not [VOIC 86], [LEVI 96]. In this case, equation (7.17) has a unique solution, deduced by combining relations (7.15) and (7.16):

$$(7.18) \quad \begin{cases} A_0 = \frac{4\beta R \cdot K_1 T_G T_1}{\pi v_s \cdot [(T_G + T_1) + T_G T_1 (T_G + T_1) K_2^2 + (T_G + T_1)^2 K_2]} \\ \omega_0 = \sqrt{\frac{1 + (T_G + T_1) \cdot K_2}{T_G T_1}} \end{cases}$$

which represent the *self-oscillations' amplitude* and respectively *frequency* of the nonlinear part (i.e., relay) input signal. Therefore, the amplitude and frequency of the tip speed $\bar{\lambda}(t)$ are:

$$(7.19) \quad A_{0_\lambda} = A_0 \cdot \sqrt{\omega_0^2 T_1^2 + 1}, \quad \omega_{0_\lambda} = \omega_0$$

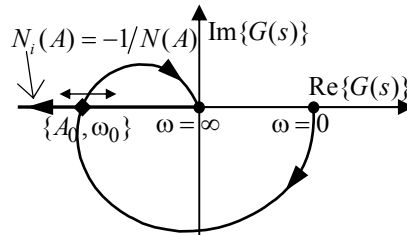


Fig. 7.14 Point of self-oscillation of the closed-loop system in the complex plane

Let $N_i(A) = -1/N(A)$ be the inverse negative describing function. Figure 7.14 identifies the point of self-oscillation in the complex plane as the cross-point of the linear part's Nyquist diagram and the nonlinear part's

inverse negative describing function. The following claim holds:

Proposition 1:

For any operating point (any ν_s fixed), the closed-loop system from figure 7.12 with parameters given by relation (7.18) has stable self-oscillations.

Justification:

According to Loeb's rule ([VOIC 86]), (A_0, ω_0) is point of stable self-oscillations if and only if:

$$(7.20) \quad S_0 = \left(\frac{dG_R}{d\omega} \right)_{\omega_0} \cdot \left(\frac{dN_{I_l}}{dA} \right)_{A_0} - \left(\frac{dG_I}{d\omega} \right)_{\omega_0} \cdot \left(\frac{dN_{I_R}}{dA} \right)_{A_0} > 0,$$

where $G(j\omega) = G_R(\omega) + jG_I(\omega)$ and $N_i(A) = N_{i_R}(A) + jN_{i_I}(A)$. Simple calculus gives that $dN_{i_I}/dA = 0$ for any A , $dN_{i_R}/dA = -\pi/(4\beta)$ and $(dG_I/d\omega)_{\omega_0} > 0$; consequently, relation (7.20) is true. $\square$

One should note that values given by relation (7.18) depend on changing the operating point, due to wind speed changing, v_s , but also on changing parameter K_2 , which depends on v_s . This means that the position of point $\{A_0, \omega_0\}$ in the complex plane changes. Each such point is characterized by stable oscillations, according to Proposition 1.

Robustness to parametric uncertainties

From relation (7.13) one can deduce that, for a given v_s , the equivalent control input is the optimal wind torque referred to the high speed shaft:

$$u_{eq} = \Gamma_{wt}(\Omega_{l\ opt}, v_s)/i = \Gamma_{wt_{opt}}/i,$$

where $\Omega_{l\ opt} = \lambda_{opt} \cdot v_s / R$. In most of cases, λ_{opt} is sufficiently accurately known, but in general computation of the optimal wind torque value, $\Gamma_{wt_{opt}}$, is affected by uncertainties. Let u_{eq_c} be the computed value of the equivalent control and $u_{eq_{nec}} \equiv u_{eq_{opt}}$ be its necessary value, given by the real value of $\Gamma_{wt_{opt}}$.

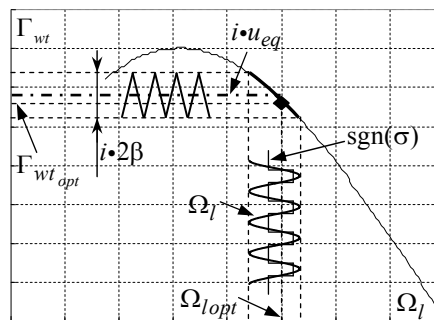


Fig. 7.15 Self-oscillations around a static operating point

A necessary condition for self-oscillations (like those in figure 7.15) is that difference $\sigma = \lambda_{opt} - \bar{\lambda}$ change its sign due to applying the switched control u_N . If $u_{eq_c} = u_{eq_{nec}}$, then σ and u_N change their signs for any β (relation (7.14)). When u_{eq_c} significantly differs from the necessary value $u_{eq_{nec}}$, there exist values of coefficient β for which σ never changes its sign.

Let $\Delta u_{eq} = u_{eq_{nec}} - u_{eq_c}$. Ideally, this difference is small enough (the control law parameters are sufficiently

precise), such that σ changes its sign for a small enough value of β . Taking into account the filtering effect of EMS (first-order dynamic), a sufficient condition for self-oscillations to take place may be:

$$(7.21) \quad \frac{\beta}{\omega_0 T} > \Delta u_{eq},$$

which provides a constraint for choosing β , given an estimated value of Δu_{eq} . If the control law parameters are imprecise (that is, Δu_{eq} is significantly large), then the control goal can be reached by growing β , but inducing a stronger mechanical stress.

In order to alleviate the torque variations induced by the alternate control input, in [MUNT 04a] a modified control law is proposed, also based upon relation (7.12). A controller ensuring robustness to parametric uncertainties is thus obtained, which also can limit the torque variations due to the switched control input component. The improved controller block diagram is presented in figure 7.16.

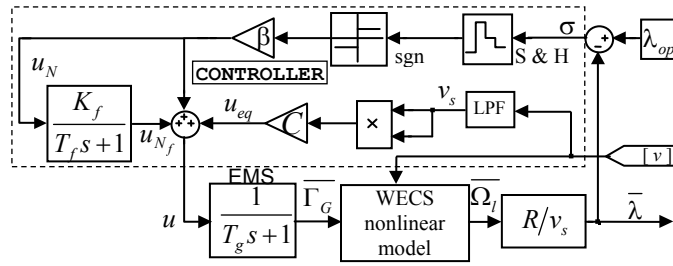


Fig. 7.16 Improved on-off control law to be used into the LFL

The modified control law, u_{mdf} , contains a low frequency supplementary component, denoted by u_{Nf} , obtained by filtering the alternate component, u_N (figure 7.16):

$$(7.22) \quad u_{mdf} = u_{eq} + u_N + u_{Nf},$$

which thus is proportional to the average value of u_N . It is this component that aims at zeroing the difference Δu_{eq} . The filtering time constant, T_f , results by imposing a maximum admissible ripple for u_{Nf} ; as regards the gain K_f , a sufficient value may be $K_f = \Delta u_{eq_{\max}} \cdot \omega_0 T / \beta$, where $\Delta u_{eq_{\max}}$ represents the maximum expected value of the difference Δu_{eq} .

7.3.2 Numerical simulation results

The proposed on-off control law has been tested by numerical simulation. for the low-power fixed pitch HAWT WECS whose parameters are given in appendix A; the (on-off controlled) LFL specifications are to be found in appendix F.

Figure 7.17 suggests the control goal being accomplished. The tip speed has small amplitude oscillations around its optimal value. The same figure presents the total and low frequency wind speed evolutions used in simulations (one can remark that $v_s(t)$ varies around a hourly average of 7 m/s).

Figure 7.18 shows the tip speed's oscillations, of amplitude $A_{0\lambda} = 0.005$ and period $T_{0\lambda} = 0.193$ s; these values meet expressions (7.18) and (7.19) for $v_s = 7$ m/s. Sufficiently small amplitude oscillations have been obtained for the entire speed range (partial load).

Figure 7.19 illustrates the self-oscillations starting process, corresponding to a limit cycle in (Ω_h, Γ_G) plane

for a constant low frequency wind speed $v_s = 7$ m/s (Γ_G and $\Omega_l = \Omega_h/i$ are state variables of the linearized system $G(s)$ – relation (7.16)).

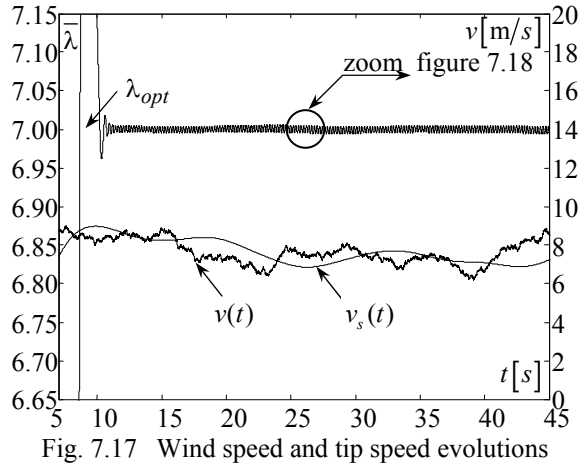


Fig. 7.17 Wind speed and tip speed evolutions

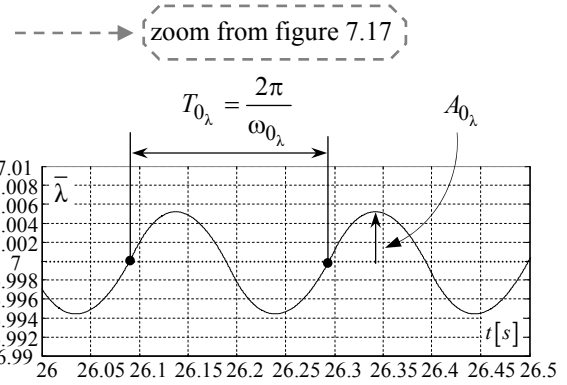


Fig. 7.18 Small amplitude tip speed oscillations (relative amplitude under 1‰)

From figure 7.20 one can conclude the robustified control law (7.22) efficiency versus the initial one, (7.12), under the same uncertainty conditions, Δu_{eq} . The improved control law allows the same results to be obtained, but employing a smaller value of β , which means smaller amplitude and frequency of the torque ripple, thus reduced mechanical fatigue. Robustness properties are maintained.

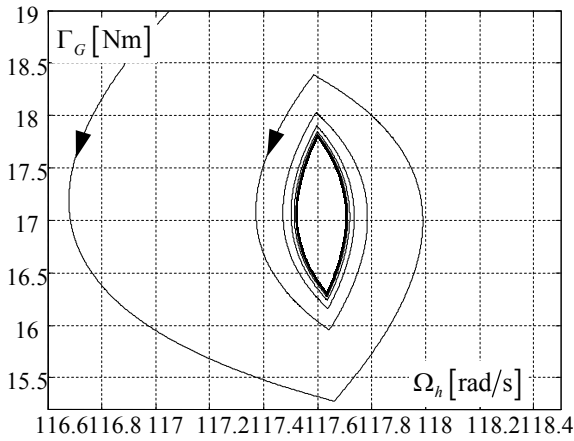


Fig. 7.19 Limit cycle in (Ω_h, Γ_G) plane

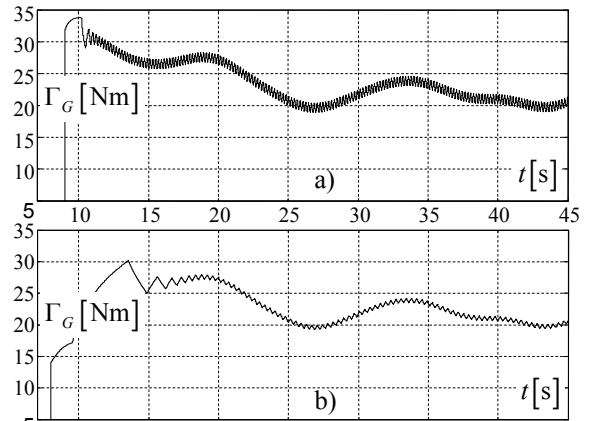


Fig. 7.20 Electromagnetic torque variations when using the initial control law a) versus using the modified control law b)

7.4 LQG DYNAMIC OPTIMIZATION

The high frequency loop (HFL) aims at performing the dynamic optimization, which means to extract the maximum power from the wind turbulence, meanwhile keeping the mechanical loads within reasonable limits. Mathematically, this contradictory requirement may be expressed by imposing a combined energy-reliability performance index to the turbulent dynamic of WECS, as previously shown in §6.3. Using the turbulent dynamic's linearized state model with respect to low rotational speed and wind torque – relations (7.10) and (7.11) – the goal of designing a trade-off between the above two contrary demands can be expressed by adopting a MEMci performance index – form (6.2) – where $\mathbf{C}_\alpha = \sqrt{\alpha} \cdot \mathbf{C} = \begin{bmatrix} 2 \cdot \sqrt{\alpha} / (2 - \gamma) & -\sqrt{\alpha} / (2 - \gamma) \end{bmatrix}$, $\mathbf{R}=1$, α being the trade-off coefficient. In this way, a stochastic (Gaussian) linear quadratic (LQG) problem is formulated.

7.4.1 LQG controller design

Provided that the LFL is properly working, the parameters of the turbulent dynamic are time invariant, therefore, the stated LQG problem is also time invariant.

Existence and uniqueness of solution are guaranteed if the open loop system meets a well-known set of structural properties [LEVI 96], [MUNT 02].

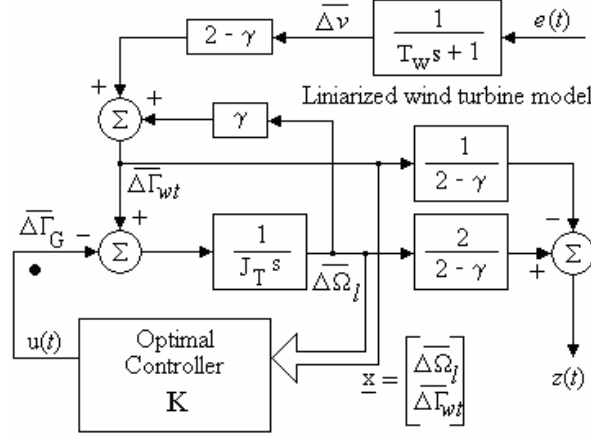


Fig. 7.21 HFL structure

The solution of this problem is the torque control input normalized variation obtained as full state feedback:

$$(7.23) \quad u(t) \equiv \overline{\Delta \Gamma_G} = -\mathbf{K} \cdot \mathbf{x}(t),$$

(see figure 7.21), with $\mathbf{K}$ being the feedback matrix gain:

$$\mathbf{K} = \mathbf{R}^{-1} \cdot \mathbf{B}^T \cdot \mathbf{S},$$

where $\mathbf{S}$ is the unique, symmetric and positive semi-definite matrix satisfying the Riccati algebraic matrix equation:

$$\mathbf{S} \cdot \mathbf{A} + \mathbf{A}^T \cdot \mathbf{S} + \mathbf{C}_\alpha^T \cdot \mathbf{C}_\alpha - \mathbf{S} \cdot \mathbf{B} \cdot \mathbf{R}^{-1} \cdot \mathbf{B}^T \cdot \mathbf{S} = 0$$

The asymptotic stability of the closed-loop system from figure 7.21, described by equation

$$\dot{\mathbf{x}}(t) = (\mathbf{A} - \mathbf{B} \cdot \mathbf{K}) \cdot \mathbf{x}(t) \text{ (whose elements are previously defined), is guaranteed [LEVI 96].}$$

7.4.2 Matlab/SimulinkTM simulation results

Matlab/SimulinkTM simulations have been performed for the WECS described in appendix A, under the wind sequence $v_t(t)$ obtained as in §2.2.2 (figure 2.11). The controller has been off-line computed for different values of the weighting coefficient α , for a low frequency wind speed of 7 m/s (in the middle of partial load domain), as shown in appendix G.

Simulations have proved that the performance index values are sensitive to values of α in a large domain of variation, namely between 0.1 and 100.

Figures 7.22 a) and b) suggest a qualitative interpretation of the simulation results and show how the electromagnetic torque variations and tip speed variations depend on α . The standard deviations associated to the presented evolutions, denoted by σ_Δ , are also given. The energy-reliability trade-off is adjusted by means of α . A large value of α shows that the accent falls on the energetic optimization. Therefore, the tip speed normalized variations, $\overline{\Delta \lambda}(t)$, decrease when α increases (figure 7.22a)). On the contrary, a small value of α denotes the accent given to the reliability aspect. The torque normalized variations, $\overline{\Delta \Gamma_G}(t)$, increase when α increases (figure 7.22b)).

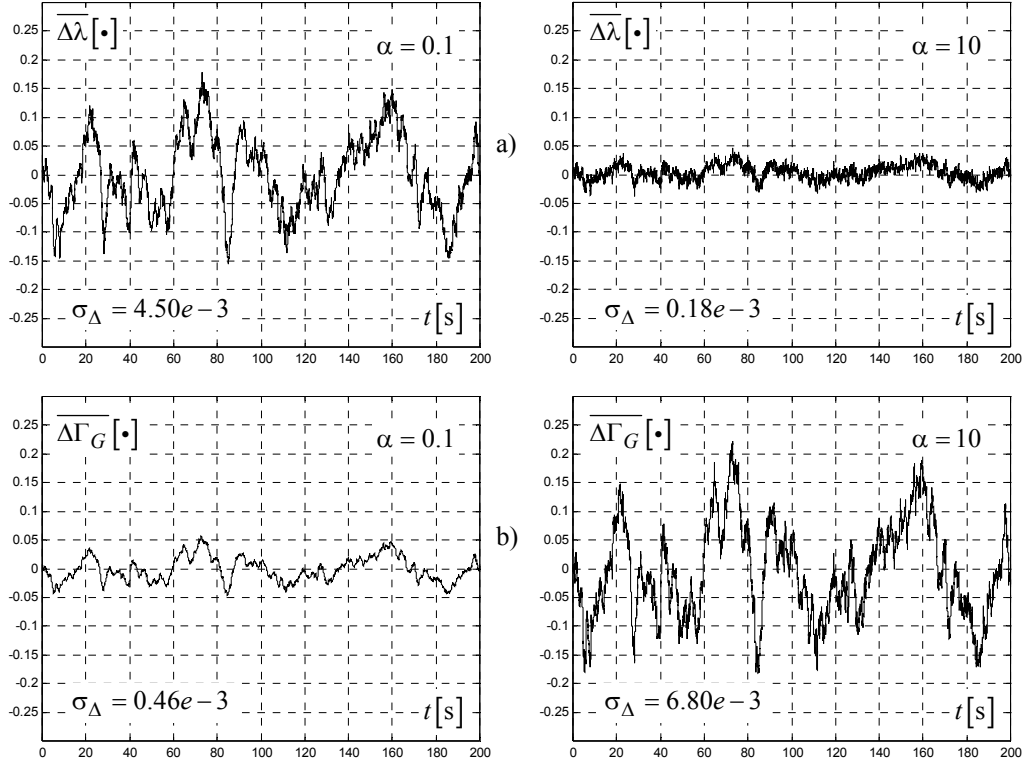


Fig. 7.22 Normalized variation for two values of the weighting coefficient, α : a) tip speed ratio and b) control input

Simulations have also shown that the HFL's properties do not change even if excited with wind turbulence sequences synthesized by significantly different means from those assumed in the linearized model (for example, by using a first-order shaping filter).

7.5 GLOBAL NUMERICAL AND REAL-TIME SIMULATION RESULTS FOR 2LFSP

The inter-conditioned operation of the LFL and HFL into the same optimal control structure (see figure 6.3), 2LFSP, has been validated by both numerical (off-line) and real-time (on-line) simulation, the latter on a physical electromechanical WECS simulator. In this paragraph some of the most relevant simulation results are discussed.

7.5.1 Off-line simulation results

The Matlab/SimulinkTM block diagram implementing the 2LFSP is presented in appendix G. The above presented control structures for low and respectively high frequency WECS dynamics structures have been combined to obtain an instance – shown by figure 7.23 – of the general figure 6.3; in this section, the LFL is based upon a PI controller.

Remarks:

- The wind is synthesized according to the stationary turbulence model given in §2.2.2, where the total wind speed is obtained by summing up the outputs of two shaping filters fed with the same white noise.
- The low frequency wind speed results as the output of a fourth order Butterworth low-pass filter, with 0.1 Hz as cut-off frequency.
- The variable speed 2-bladed fixed pitch active stall rigid drive train torque controlled asynchronous

generator based WECS whose parameters are given in appendix A was used for simulations.

- The steady-state electromagnetic torque, $\overline{\Gamma}_G$, is generated by a PI controller, as detailed in §7.2.1.
- The dynamic electromagnetic torque, $\Delta\Gamma_G$, is provided based on the LQG controller's output, as detailed in §7.4.2.
- Filtering blocks have been used for splitting the involved wind and rotational speed components.

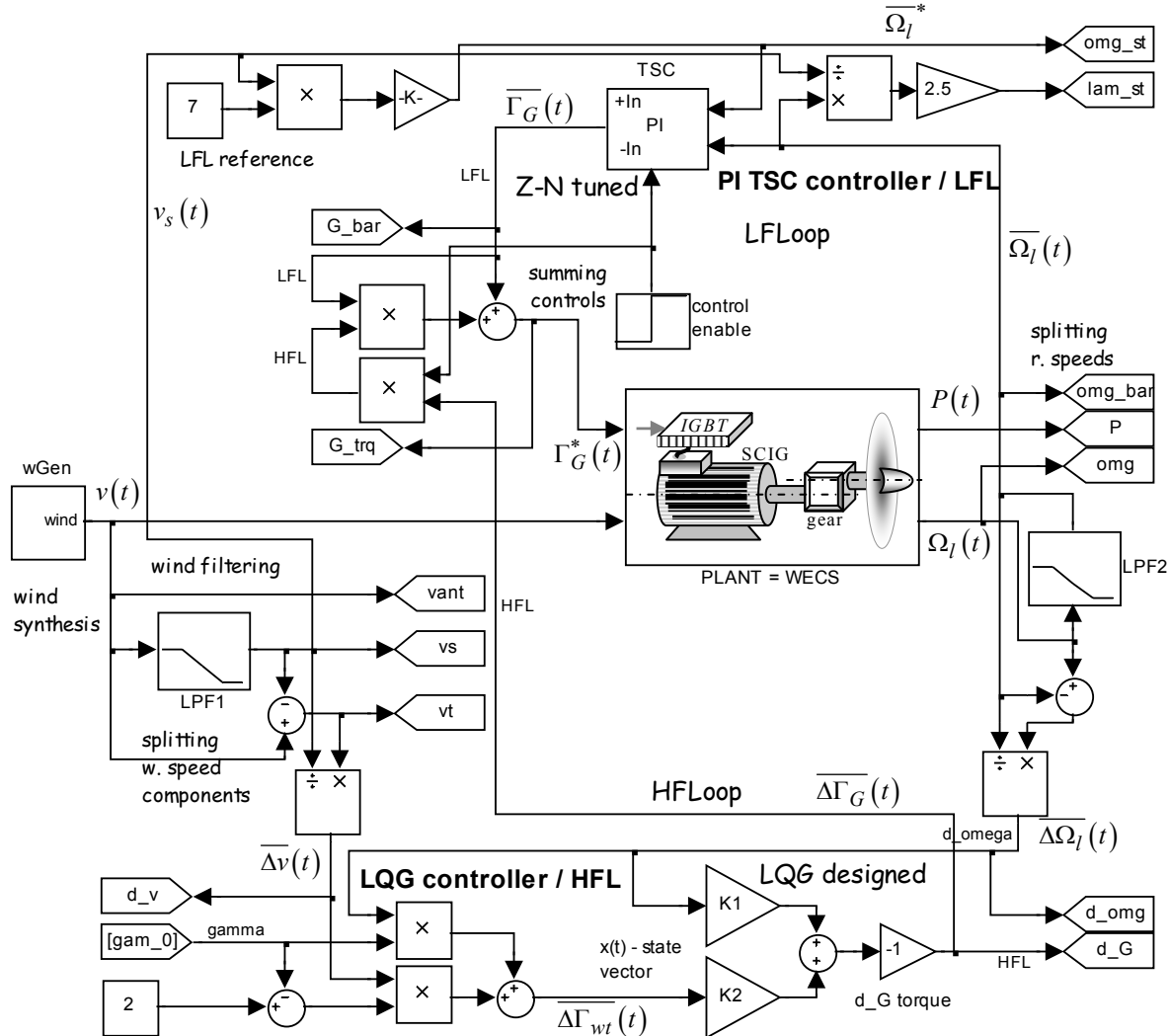


Fig. 7.23 Simulink block diagram of the 2LFSP for WECS

The closed-loop system's behaviour has been simulated for a 10 minutes time horizon, performing numerical integration by `ode45` Matlab function, with a maximum step size of 5 ms (small enough for capturing the HFL dynamics). For results consistency, in all simulation cases, the WECS was excited by the same wind sequence.

Time evolutions of some relevant variables are presented, which show the closeness of the operating point to the optimal one and also the mechanical load intensity induced by the torque variations for constant PI parameters and various values of α .

Figure 7.24 emphasizes how the trade-off between minimizing the tip speed normalized variations, $\overline{\Delta\lambda}(t)$, and minimizing the electromagnetic torque normalized variations, $\overline{\Delta\Gamma_G}(t)$, is managed, by using different values of the trade-off parameter, α .

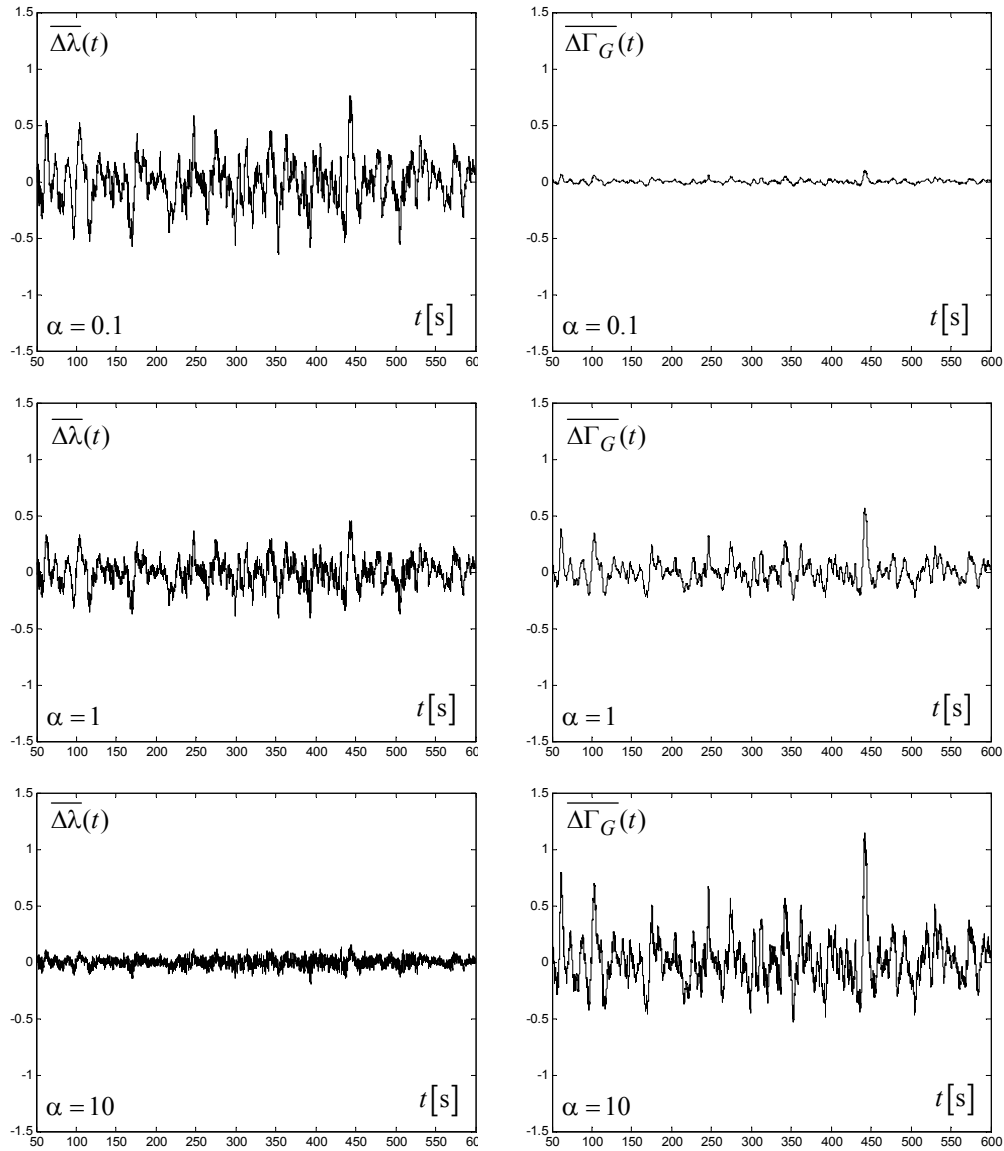


Fig. 7.24 Tip speed and respectively electromagnetic torque (control input) normalized variations for different values of the weighting coefficient, α

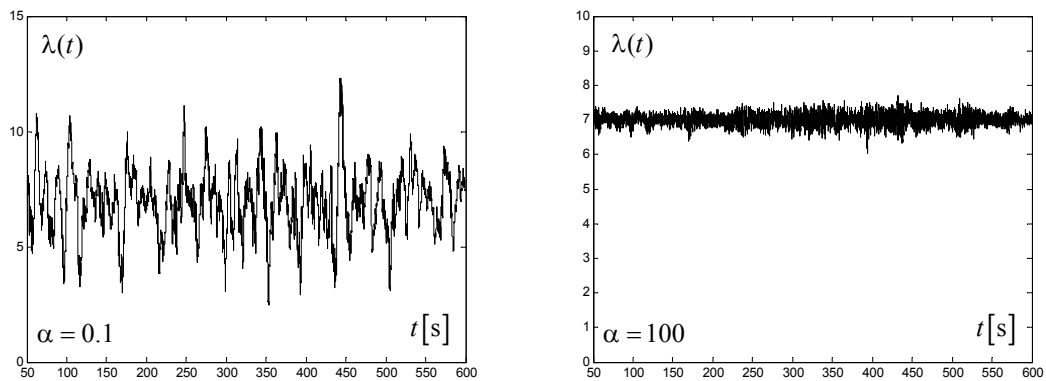


Fig. 7.25 Tip speed evolution for the 2LFSP global operation

Figure 7.25 presents the tip speed evolutions for a small (left) and respectively a large (right) value of α ; the conversion regime is as far from optimality as the weighting coefficient is small. The other way round, using a small α ensures reduced torque variations, as the corresponding electromagnetic torque evolutions for the same two values

of α show (figure 7.26).

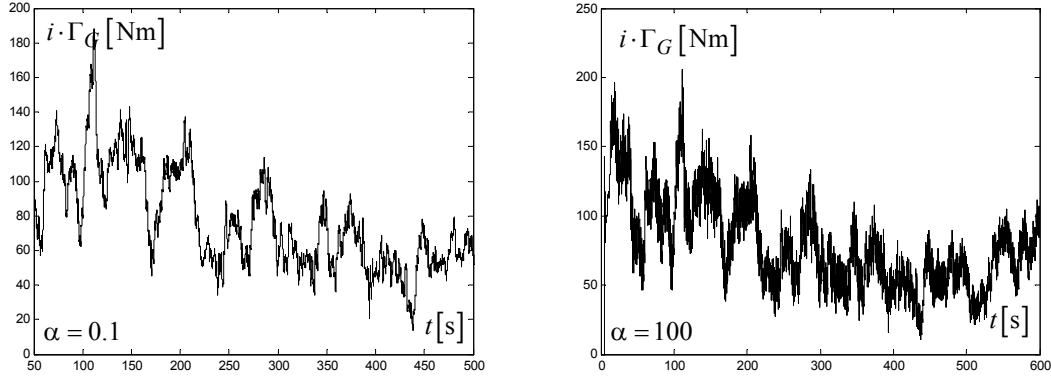


Fig. 7.26 Electromagnetic torque evolution for the 2LFSP global operation

The standard deviations, denoted by $\sigma_{\Delta}(\cdot)$, of the normalized variations $\overline{\Delta\lambda}(t)$ and $\overline{\Delta\Gamma_G}(t)$ for various values of the weighting coefficient, α , are given in table 7.1.

σ_{Δ}/α	$\alpha = 0.1$	$\alpha = 1$	$\alpha = 2$	$\alpha = 5$	$\alpha = 10$	$\alpha = 20$	$\alpha = 100$	$\alpha = 200$
$\sigma_{\Delta}(\overline{\Delta\lambda})$	0.2	0.12	0.087	0.052	0.037	0.029	0.02	0.019
$\sigma_{\Delta}(\overline{\Delta\Gamma_G})$	0.019	0.10	0.14	0.19	0.21	0.22	0.24	0.25

Table 7.1 Standard deviations of the normalized variations $\overline{\Delta\lambda}(t)$ and $\overline{\Delta\Gamma_G}(t)$ versus α

The graphical representations of these deviations versus α may be viewed in figure 7.27, suggesting that a saturation limit is finally reached in increasing α for obtaining a better conversion efficiency.

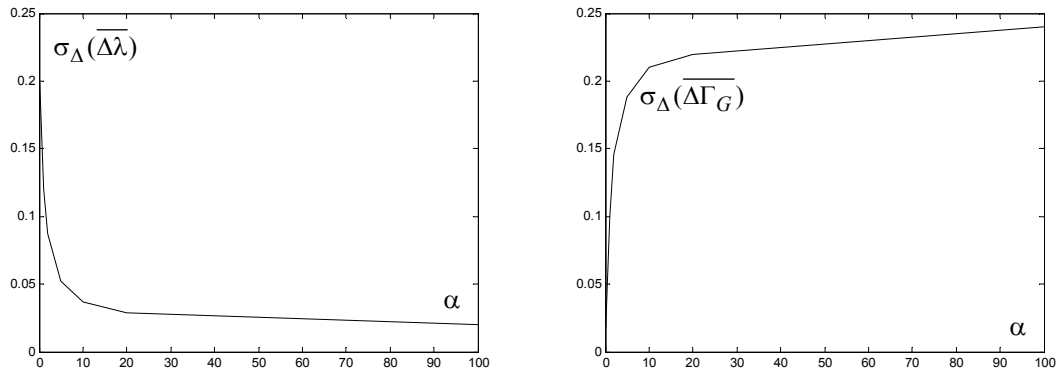


Fig. 7.27 Evolution of $\overline{\Delta\lambda}(t)$ and $\overline{\Delta\Gamma_G}(t)$ standard deviations versus α

Figure 7.28 presents how the operating point moves around the ORC for different values of the weighting coefficient, α . Its deviation around the ORC becomes non significant for hundred sized values of α , implying very good aerodynamic efficiency.

Remark:

The weighting coefficient variation range must be limited for the reasons hereafter. For small α the WECS's operating point largely varies around the ORC, the conversion regime is far from optimality. Moreover, the system might operate incorrectly, that is, the weak control input variations might induce motoring regimes of the generator. On the other hand, excessively large values of α do not significantly increase the harvested power amount, but can induce significant supplementary mechanical stress.

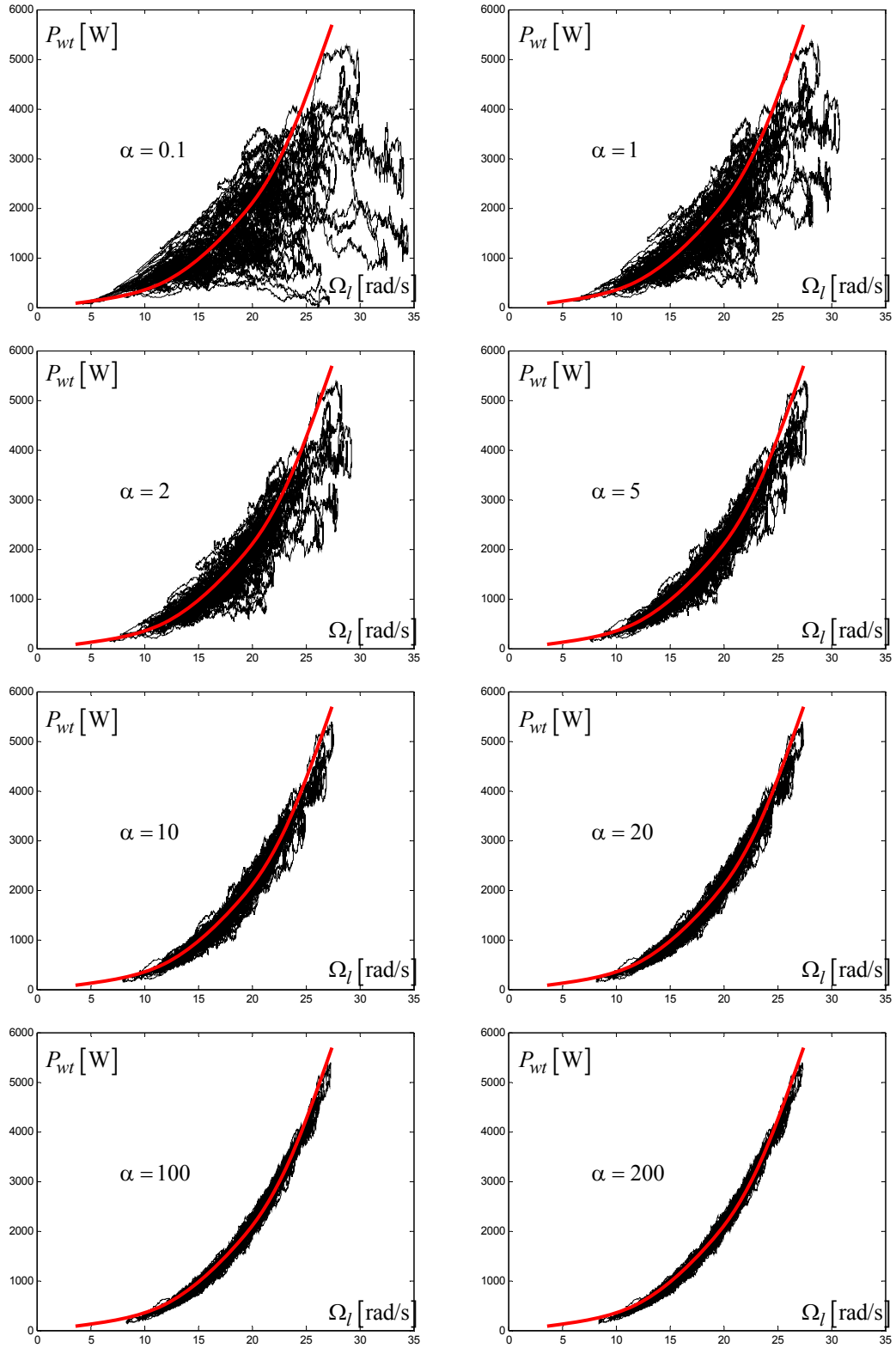


Fig. 7.28 Operating point's evolution under the 2LFSP global operation: tracking the ORC

7.5.2 On-line simulation results

Description of the experimental rig

The control strategy exposed in this chapter is also validated by real time simulation using a small scale electromechanical simulator of a WECS (figure 7.29). This simulator is conceived as in §3.4.2, having the HSS

rotational speed as driving variable [DIOP 99b], [CUTU 05].

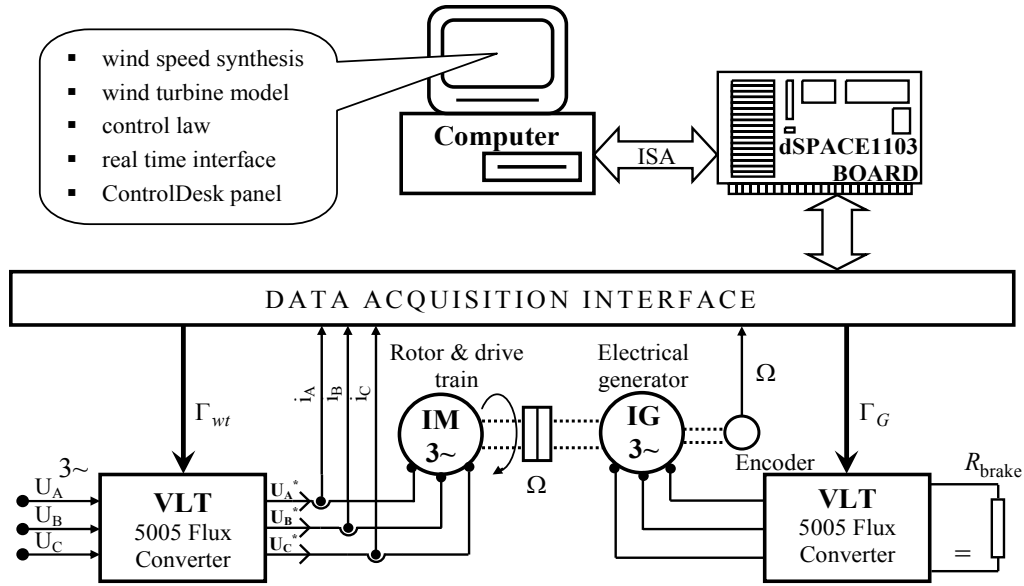


Fig. 7.29 Hardware structure of the 2LFSP test rig

The simulator consists in two identical rigidly coupled cage induction machines. One of them, denoted by IM (induction motor) emulates the aerodynamic subsystem and the drive train of the WECS; the second one, denoted by IG (induction generator) is a torque controlled generator. The wind speed is computer synthesized and imposes the rotational speed of the coupling.

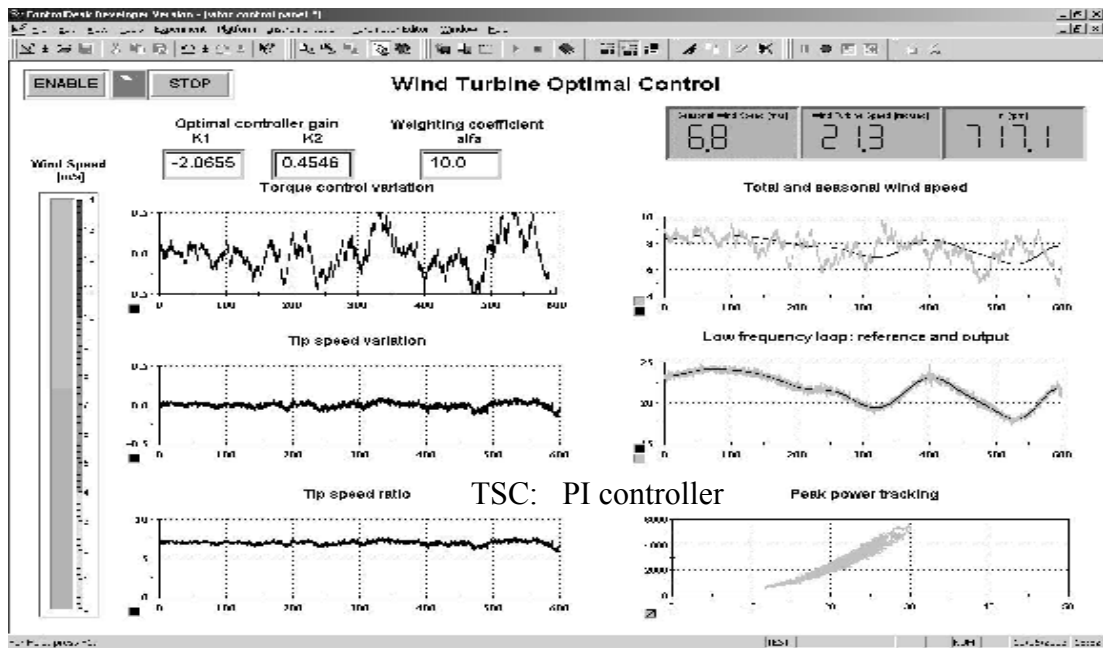


Fig. 7.30 ControlDesk™ panel of the 2LFSP test rig – PI controller based LFL

The two induction machines are controlled via power electronics converters, namely VLT 5005 Flux. The computer implements:

- the wind turbine model, utilized to provide the wind torque reference, Γ_{wt} (referred to the high-speed shaft), using the computed wind speed and the measured rotational speed, Ω_h ;
- the control law, which provides the generator torque reference, Γ_G^* .

The bidirectional information flux between the physical part and the computer is supported by a data

acquisition interface. A ControlDesk panel (figures 7.30 and 7.31) is used to visualize the functional parameters of the simulated WECS and for getting user-supplied data in real time. A more detailed description of this simulator can be found in [CUTU 04].

Both structures – namely 2LFSP with PI TSC and 2LFSP with on-off TSC – have been tested. The simulation schemes have been built under Matlab/Simulink, using Real Time Interface, and run on the DS1103 PPC controlled board (dSPACE), which is equipped with a Power PC processor for fast floating-point computation at 400 MHz.

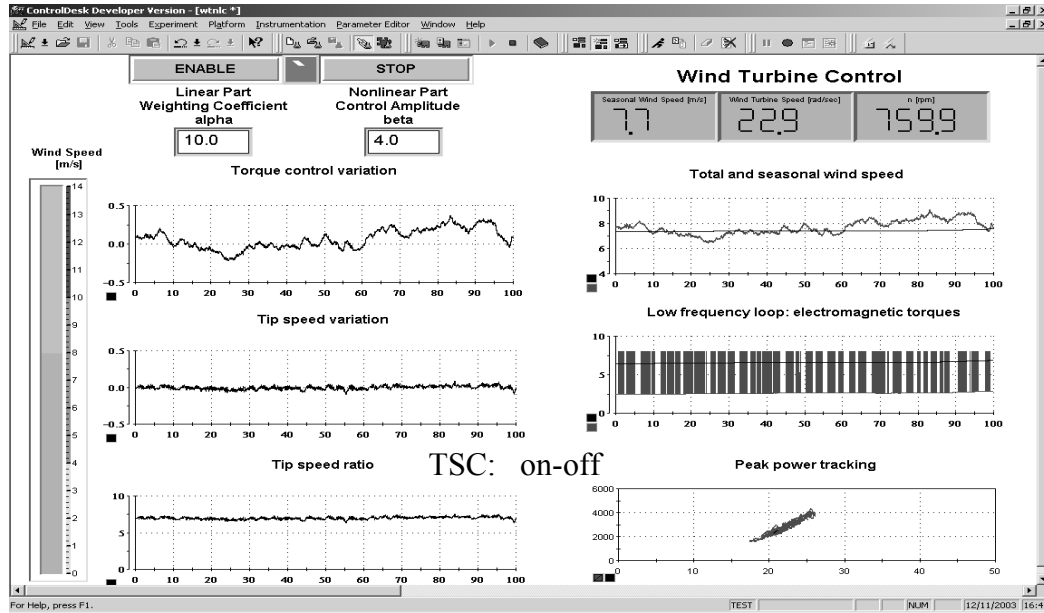


Fig. 7.31 ControlDesk™ panel of the 2LFSP test rig – on-off controller based LFL

Global on-line simulation results for PI controller based LFL

Real-time simulations have been performed using the same parameter values as in the off-line simulation; the control block diagram used here is essentially the same as the one in figure 7.23 (except for some supplementary elements required for interfacing the physical subsystem) and can be seen in appendix G.

The low frequency loop is excited by the low frequency component of the wind speed (figure 7.32a)), taking values in the usual range, from 4 to 10 m/s. Its role – of maintaining the operating point on the ORC, corresponding to the tip speed of λ_{opt} – is illustrated in figure 7.32b). The variable γ , which is strictly dependent of λ (see relation (2.22)), will have reasonably small variations around the value $\gamma(\lambda_{opt}) = -1$. The amplitude of these variations depends on the low frequency component of the wind, v_s , which is the output of the separating filter, visible in figure 7.32a).

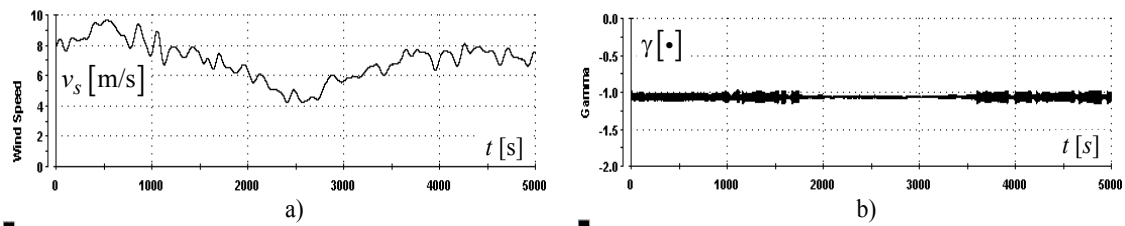


Fig. 7.32 Evolution of the PI controller based LFL: a) – low frequency wind speed, b) – γ parameter

Concerning the high frequency loop, the variables of interest are normalized variations around a static

operating point – characterizing the smooth, steady-state regime – i.e., that of the tip speed ratio, $z(t) = \overline{\Delta\lambda}(t)$, and that of the generator torque, which is the control input of the linearized wind power system, $u(t) = \overline{\Delta\Gamma_G}$. The maximum variations of the OP are defined by an interval of $\pm 20\%$ around the values characterizing the OOP.

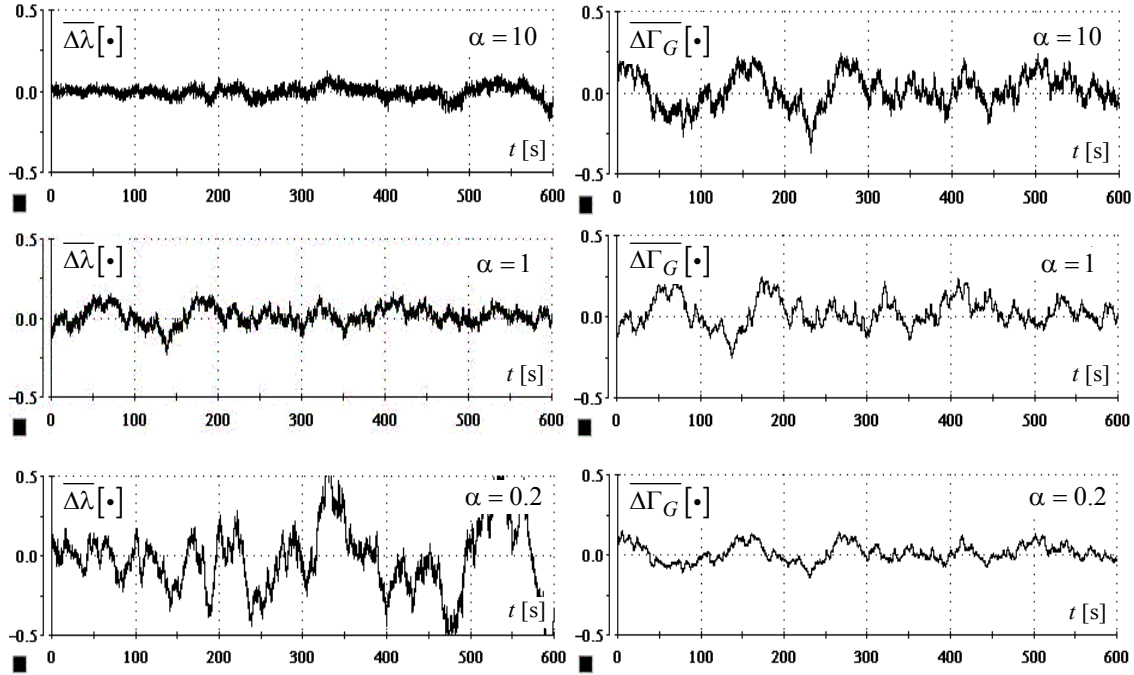


Fig. 7.33 Evolution of the tip speed ratio (left) and of the generator torque (right) normalized variations for three values of the weighting coefficient, α

Simulations have been performed on the above described test rig for several values of the weighting coefficient, α . For each value of α , the state feedback, $\mathbf{K}$, has been computed based upon the model's parameters obtained for v_s in the middle of its variation range. For example: $\mathbf{K} = [-0.11 \ -0.02]$ for $\alpha = 0.2$ and $\mathbf{K} = [-6.49 \ 2.34]$ for $\alpha = 100$.

Figure 7.33 suggests a qualitative interpretation of the simulation results and shows how the normalized variations of the tip speed ratio and of the electromagnetic torque depend on α . Indeed, as it was expected, the amplitude of the tip speed ratio normalized variation, $\overline{\Delta\lambda}$, decreases with the value of α , while that of the electromagnetic torque, $\overline{\Delta\Gamma_G}$, increases. The variations' amplitudes are both placed within the band of $\pm 20\%$ around zero, meaning that the unnormalized values are oscillating around the operating point with the same amplitude.

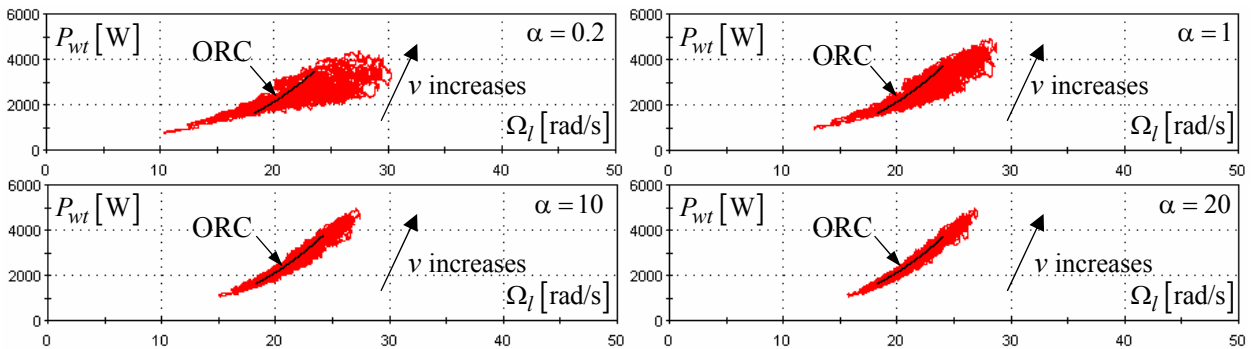


Fig. 7.34 Evolution of the operating point: tracking the ORC – case of PI controller based LFL

Figure 7.34 shows the combined functioning of the two loops, namely the variations of the operating point around the ORC for four values of α . As expected, for small α (left side), these variations are significantly larger than those for large α (right side). Also, it can be noted that these variations increase as the wind speed increases.

Global on-line simulation results for on-off controller based LFL

For real time validation of the 2LFSP method having on-off TSC, the simulation diagram from figure 7.23 has been used, where the LFL is replaced with the scheme from figure 7.11. The on-off controller parameters are the same as in §7.3.2. Generally speaking, the on-line simulation results in this case are similar with those obtained when using PI controller based LFL under the same conditions.

The switched control amplitude is fixed at $\beta = 4$; the modified (robustified) controller has been used in simulation tests (see §7.3.1). The low frequency wind speed evolution and that of the torque parameter, γ , can be seen in the first row of figure 7.35.

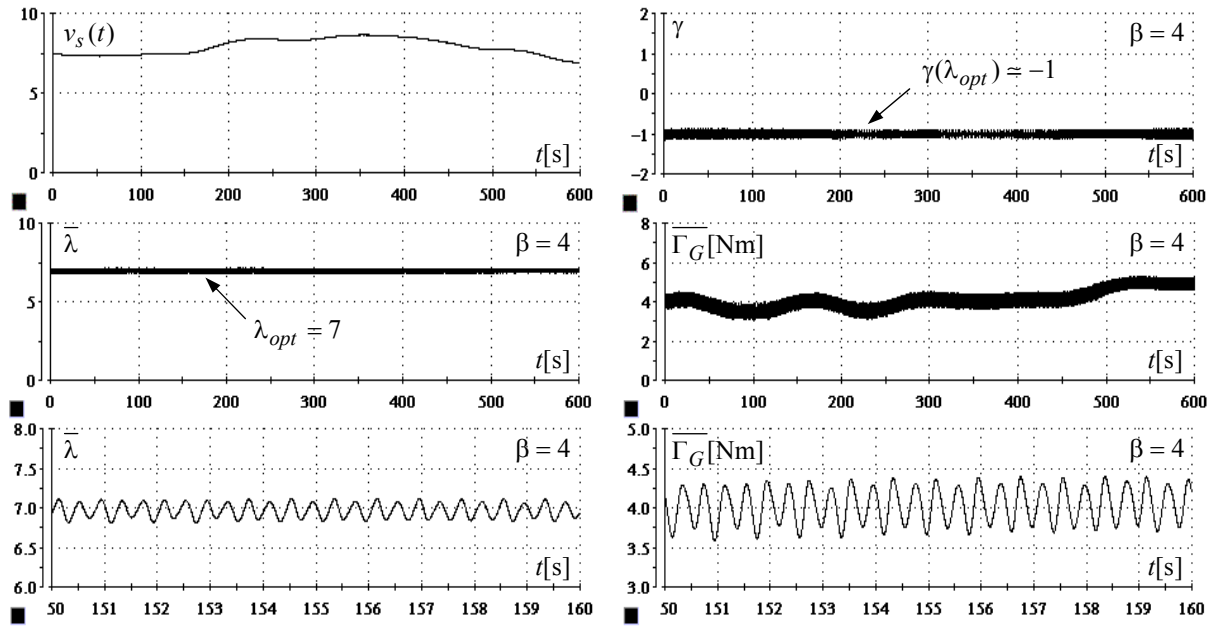


Fig. 7.35 Evolutions of relevant variables within the on-off TSC based LFL

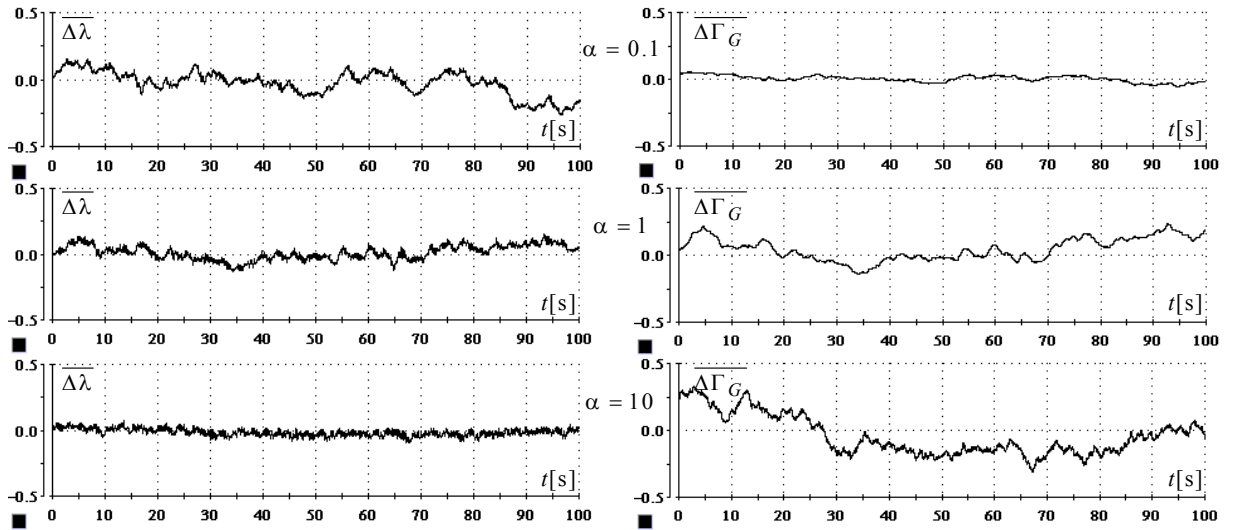


Fig. 7.36 On-line simulation results for the HFL operation

One can remark electromagnetic torque oscillations of sufficiently reduced amplitude, as well as tip speed

oscillations under 2% (these are sensibly larger than those noted in off-line simulation conditions).

Figure 7.36 describes the HFL's operation, that is, balancing the energy-reliability trade-off by means of the weighting coefficient, α . These results illustrate the high frequency behaviour of the controlled WECS as it has been predicted by preliminary results from figure 7.22. The same qualitative interpretation as in the case of the PI controller based LFL holds.

Figure 7.37 depicts operating point's excursions around the ORC (parts d), e) and f)) for different wind sequences (parts a), b) and c)) and for three different values of the weighting coefficient ($\alpha \in \{0.1; 1; 10\}$).

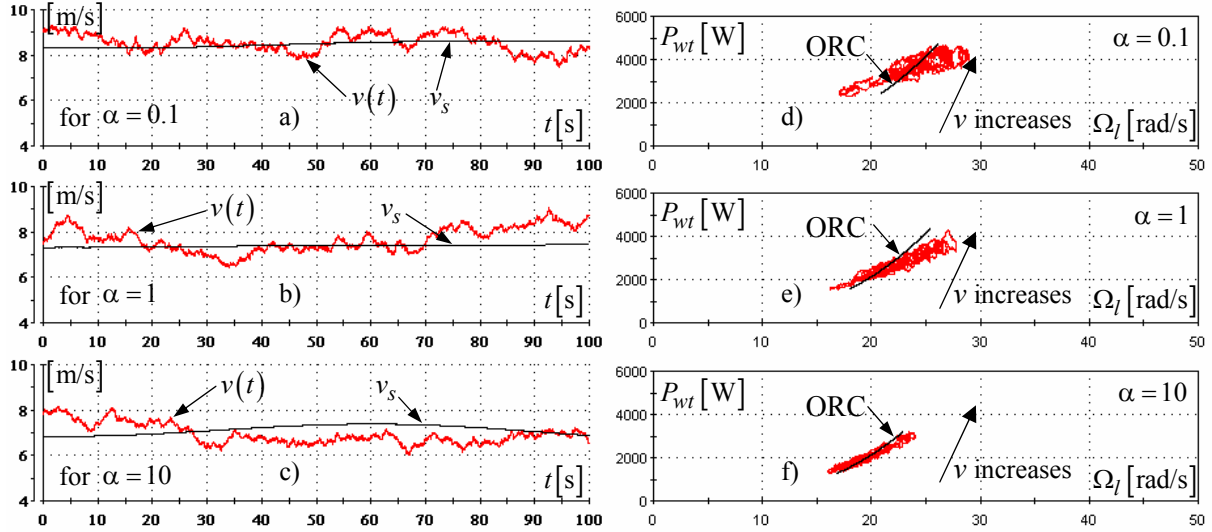


Fig. 7.37 Evolution of the operating point: tracking the ORC – case of on-off controller based LFL

7.6 CONCLUSION

In this chapter a two loop control structure for optimizing the dynamical behaviour of variable speed fixed pitch rigid drive train WECS has been proposed. The optimization goal has been defined as a *trade-off between maximizing the power available in the wind and keeping the mechanical loads induced by the control input (electromagnetic torque) effort under some reasonable limits*. This structure is operational only for the partial load region, that is, for wind speeds smaller than the rated one and for stationary wind speed regimes (the case of wind gusts has not been considered).

The proposed control structure, denoted by its acronym 2LFSP, is based upon the *frequency separation principle*, according to which the WECS's global dynamic is exhibited in two distinct spectral ranges, respectively excited by the two components of the wind speed, the low frequency one and the turbulence one. Thus, a two loop torque control is implemented: a *low frequency loop* (LFL), governed by the low frequency wind speed, aiming at harvesting the maximum power available in this, and a *high frequency loop* (HFL), excited by the turbulence wind speed, envisaging a trade-off between capturing the maximum energy from turbulence and minimizing the mechanical stress due to torque variations.

The **LFL** is a tip speed tracking system; two types of controller have been proposed to achieve this goal: a *classical PI tip speed controller*, whose reference is computed based upon the definition relation of the tip speed, and respectively an *on-off controller*, which zeroes the difference between the real tip speed and the desired (optimal) one. The **HFL** is based upon a *LQG controller* designed by solving an optimization problem for the WECS linearized around the optimal operating point (effectively established by the LFL's control action).

The 2LFSP allows to combining the robustness of the LFL design with the dynamic optimization's flexibility, adopted in the HFL design. Indeed, it is the weighting coefficient, α , that confers flexibility to the closed loop system, such that the captured power be grown (by choosing a large value for α) when the particular wind site conditions allow it, that is, when the stress due to turbulence is not important. On the contrary, if the wind turbulence is quite high, then the drive train's protection can be improved by means of the same coefficient (namely, choosing a small value for α), but this means to admit a reduction of the harvested power. The variation domain of α should be however limited. Thus, a saturation limit may be noted in the HFL control action when increasing the value of α , whereas for small values of this coefficient the electrical generator may exhibit abnormal motoring regimes.

2LFSP has been *validated by both numerical and real-time simulation*, the latter on an electromechanical simulator for variable speed WECSs. The simulation results have shown that the mechanical stress due to control input variations can be strongly reduced, with good influence on the WECS's reliability and availability.

As regards the LFL, the on-off controller implementation induces more stress than the PI controller version, due to the alternate control input component. On the other hand, the first variant offers a better robustness to parametric uncertainties, given the nonlinearity of the slow dynamic, dependent on the operating point.

There are some points to improve in the proposed approach, as follows. Estimation of the low frequency component is rather rough, yielding an unrealistically delayed version of this component. This inconvenient can be corrected if using a prediction method, combined with a better funded choice of the separation filter's cut-off frequency. Estimation of the steady-state component of the rotational speed may be also improved.

Starting from general reliability requirements imposed to a given WECS, one should be able to indicate the maximum admissible level of mechanical stress to be experienced by the drive train system during its forecasted operation lifetime. This should further lead to properly choose the corresponding range of the LQG control law's weighting coefficient. Solving this problem is an interesting future issue to investigate.

2LFSP may also be used for a flexible drive train WECS, as it will be detailed in the next chapter. In this case, variables within the HFL are not available for measure anymore; therefore an estimation method (for example, by using a classical pole placement procedure) is imperatively required.

Chapter 8

2LFSP APPLIED TO THE FLEXIBLE DRIVE TRAIN WIND ENERGY CONVERSION SYSTEMS

In this chapter it is shown how the 2LFSP, the control strategy described in the sixth chapter of this work, can be applied to *flexible* drive train variable speed torque controlled asynchronous generator based WECSs, for trading off the energetic requirements and those of reliability. The mechanical stress and electrical power harmonics induced by the wind turbulences are usually alleviated if the turbine rotor interacts with the electromagnetic subsystem (EMS) through an elastic coupling based drive train. The associated modelling assumptions remain the same as in chapter 7. The main differences of this approach from the application to rigid drive train WECS, exposed in the previous chapter, consist in adopting a different performance index for the LQG dynamic optimization in the HFL, in using an observer based state feedback and finally in using a prediction method for estimating the low frequency wind speed (in LFL), instead of simply low pass filtering it from the total wind (visible in figure 8.1).

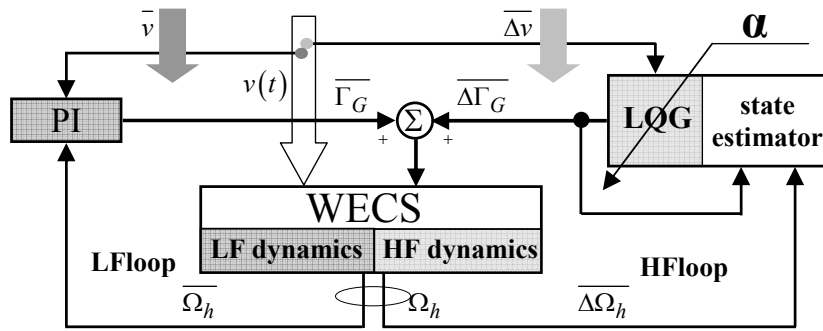


Fig. 8.1 General envisaged control diagram

The LFL is here built upon a PI controller (TSC), tuned by using the low frequency dynamics in the same manner as in chapter 7. In the sequel, the design procedures associated to LFL and HFL are presented and the combined action of the two control loops within the proposed control structure is illustrated by using numerical Matlab/SimulinkTM simulation results. The 2LFSP control performance for flexible drive train WECSs is assessed by discussing the most representative simulation results.

8.1 MODELLING

Model of the slow WECS dynamic

The drive train exhibits high frequency dynamics in the sense adopted by the frequency separation principle in the WECS behaviour. Therefore, the drive train (DT) dynamics are to be considered within the HFL and, consequently, the low frequency dynamics of WECS will be modelled using the same approach as in §7.1.1.

Remark:

The associated steady-state optimisation control will be treated in the same manner as in §7.2.1, using a PI tip speed controller.

Model of the high frequency WECS dynamic

The modelling of the high frequency (turbulent) dynamic of a flexible drive train WECS uses here a linearized model in normalized variations around the static operating point established by the LFL [MUNT 05b].

Elements of a flexible drive train are depicted in figure 8.2.

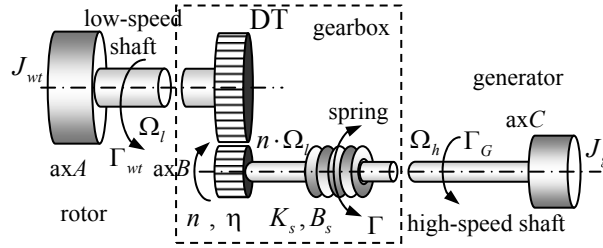


Fig. 8.2 Schematics of a flexible drive train

Differently from the rigid coupling, the two parts of the high-speed shaft, axB and axC in figure 8.2, are now turning at different speeds, $i \cdot \Omega_l$ and Ω_h respectively, where i is the transmission ratio of the gearbox. The elastic energy variations yield a new state variable, the internal torque, Γ . Denoting by J_g axC's inertia and by J_B axB's inertia, it holds that:

$$J_B = \eta / n^2 \cdot J_{wt},$$

where η is the transmission efficiency and J_{wt} is the low-speed shaft inertia. The flexible drive train's model is composed of axB and axC movement equations and the dynamic of the internal torque [BATT 98], [AKHM 03]:

$$(8.1) \quad \begin{cases} \dot{\Omega}_l = 1/J_{wt} \cdot \Gamma_{wt} - i/(J_{wt} \cdot \eta) \cdot \Gamma \\ \dot{\Omega}_h = 1/J_g \cdot \Gamma - 1/J_g \cdot \Gamma_G \\ \dot{\Gamma} = K_s \cdot (i \cdot \Omega_l - \Omega_h) + B_s \cdot (i \cdot \dot{\Omega}_l - \dot{\Omega}_h) \end{cases},$$

where K_s and B_s are respectively the stiffness and the damping coefficients of the spring.

Remember notation adopted in §2.4 for a generic variable x of the model:

$$\bar{x} = x|_{\text{static operating point}}; \Delta x = x - \bar{x}; \overline{\Delta x} = \frac{\Delta x}{x}$$

Being defined in a *static* operating point, $\bar{x}$ is called steady-state value. The nonlinear characteristic of the turbine (2.11) is linearized around such an operating point, yielding relation (2.21), where the linearized model of turbulence is:

$$\dot{\bar{\Delta v}}(t) = -1/T_w \cdot \bar{\Delta v}(t) + 1/T_w \cdot e(t),$$

with T_w being the time constant of the shaping filter. Relations (8.1) must also be linearized. Choosing

$$\mathbf{x}(t) = \begin{bmatrix} \dot{\Delta \Omega}_l & \dot{\Delta \Omega}_h & \dot{\Delta \Gamma} & \dot{\Delta \Gamma}_{wt} \end{bmatrix}^T \text{ as state vector, } u(t) = \overline{\Delta \Gamma}_G \text{ as control input and the normalized variation of the}$$

tip speed ratio, $z(t) = \overline{\Delta \lambda}(t)$, as output (measure) variable, relation (2.21) and relations (8.1) linearized lead to the state space matrix equation:

$$(8.2) \quad \begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A} \cdot \mathbf{x}(t) + \mathbf{B} \cdot u(t) + \mathbf{L} \cdot e(t), \\ z(t) = \mathbf{C} \cdot \mathbf{x}(t) \end{cases}$$

with:

$$(8.3) \quad \begin{cases} \mathbf{A} = \begin{bmatrix} 0 & 0 & -1/J_T & 1/J_T \\ 0 & 0 & 1/J_G & 0 \\ K_A & -K_A & -B_S(1/J_B + 1/J_g) & B_S/J_B \\ \gamma/T_w & 0 & -\gamma/J_T & \gamma/J_T - 1/T_w \end{bmatrix}, \\ \mathbf{B} = \begin{bmatrix} 0 & -1/J_G & B_S/J_g & 0 \end{bmatrix}^T, \\ \mathbf{L} = \begin{bmatrix} 0 & 0 & 0 & (2-\gamma)/T_w \end{bmatrix}^T, \\ \mathbf{C} = \begin{bmatrix} 2/(2-\gamma) & 0 & 0 & -1/(2-\gamma) \end{bmatrix}, \end{cases}$$

where γ is the torque parameter (relation (2.22)), $J_T = \overline{\Omega}_l \cdot J_{wt} / \overline{\Gamma}_{wt}$ and $J_G = \overline{\Omega}_l \cdot i^2 \cdot J_g / \overline{\Gamma}_{wt}$ are time constants, whereas $K_A = \overline{\Omega}_l \cdot K_S \cdot i^2 / \overline{\Gamma}_{wt}$ is the inverse of a time constant. J_T , J_G and K_A depend on the static operating point, $(\overline{\Omega}_l, \overline{\Gamma}_{wt})$. Relations (8.2) and (8.3) represent the linearized model of the flexible drive train WECS, describing the high frequency dynamics around the static operating point, impressed by the turbulence component of the wind speed, $\Delta v(t)$. The parameters of the model depend on the steady-state operating point (established in LFL), so ultimately on the wind speed. A detailed procedure for obtaining this model is presented in appendix H.

8.2 STEADY-STATE OPTIMIZATION USING A LINEAR CONTROL

8.2.1 Linear controller design

The control problem associated with the LFL concerns the steady-state optimization, which consists in operating a wind turbine at variable speed such that its static operating point remains on the ORC. As in §7.2.1, this goal is achieved by tracking the rotor's speed corresponding to λ_{opt} ,

$$(8.4) \quad \overline{\Omega}_l^{ref} = \lambda_{opt} / R \cdot v_s,$$

by means of a PI controller (figure 8.3), as to the Ziegler-Nichols empirical method [ZIEG 42], [HAUT 97], to compensate the (weak) nonlinearities in the neighborhood of an usual operating point. The control practice shows that the PI choice is not critical, even more in the LFL, where the low frequency wind speed varies sufficiently slowly in relation to the wind turbine dynamics. As it was previously shown also, a general property of the LFL is that the mostly variable parameter of the linearized system, γ , is maintained constant with respect to the low frequency wind speed at $\gamma = -1$, and so the system (8.2) is invariant in relation to this parameter [MUNT 05a]. The LFL generates the static component of the electromagnetic torque, $\overline{\Gamma}_G$ (applied to the high speed shaft), necessary to drive the operating point of the low speed shaft on the ORC.

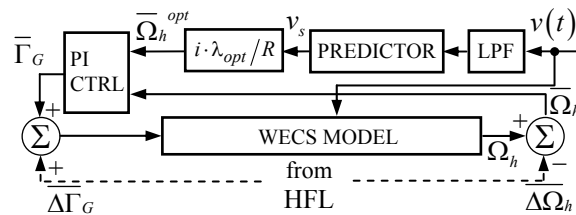


Fig. 8.3 LFL within 2LFSP for flexible drive train WECS

The low frequency component of the wind speed, v_s , can in principle be extracted from the (total) wind speed, $v(t)$, by a high order low-pass filter, whose cut-off frequency must be at most the turbine's bandwidth. But,

given the system's complexity more important than in the rigid DT case, this solution cannot be used in this case without experiencing stability problems due to large phase lags, no matter the chosen control method is. It could happen that the reference torque level be significantly higher than the wind torque, thus compromising the operation of the wind turbine. Different ways have been adopted in order to avoid this problem: to increase the cut-off frequency of the low-pass filter, then to make use of the filtering properties of a classical PI controller [MUNT 05a], or to implement an on-off controller to zeroing the difference $\bar{\lambda} - \lambda_{opt}$ [MUNT 04a]. Here, a more accurate estimation of v_s is obtained by combining a reduced order low-pass filtering (LPF) of the total wind with an ARMA model based prediction, as detailed in the sequel.

8.2.2 Prediction based wind speed estimation

Let v_s^f be the output of the LPF and v_s^p the estimation of v_s by filtering and prediction. The speed references computed using either v_s^f or v_s^p in relation (8.4) will make the system turn at two tip speed ratios, $\bar{\lambda}^f$ and $\bar{\lambda}^p$, as the turbine experiences the real low frequency wind speed, v_s (see figure 8.4).

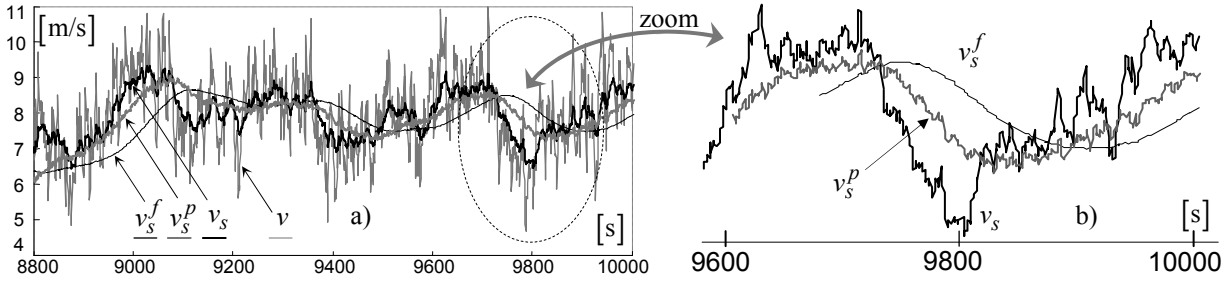


Fig. 8.4 Predicted versus filtered low frequency wind speed

Figure 8.4a) shows the superiority of the presented method versus simple low-pass filtering. For example, at time 9800, v_s is much less than v_s^f ; a reference computed using v_s^f would be difficult to track, because the real power available is much below (see figure 8.4b). Meanwhile, the predicted value, v_s^p , is much closer to the real low frequency component, v_s , ensuring a better tracking of the ORC within the LFL. One can compare the following standard deviations: $\sigma(\bar{\lambda}^f - \lambda_{opt}) = 0.72$, $\sigma(\bar{\lambda}^p - \lambda_{opt}) = 0.44$.

The ARMA model is recursively implemented for the prediction of the k -th sample of v_s^p from v_s^f :

$$(8.5) \quad v_{s_k}^p = \sum_{i=1}^n a_i \cdot v_{s_{k-i}}^f + \sum_{j=1}^m b_j \cdot (v_{s_{k-j}}^p - v_{s_{k-j}}^f)$$

In the present work the prediction horizon is of 2 minutes, the filter's order is $m=3$, the regressing vector dimension is $n=6$ and a_i , b_j result from a recursive least mean squares procedure with a unitary forget factor [LEVI 96].

8.3 LQG DYNAMIC OPTIMIZATION

8.3.1 Problem statement

The most stressed mechanical part of a WECS is the drive train, supporting both the wind torque variations,

$\Delta\Gamma_{wt}$, at the input shaft, and those of the electromagnetic torque, $\Delta\Gamma_G$, at the output shaft. Here the energy-reliability trade-off will be expressed differently from the rigid drive train case, namely between the minimization of the tip speed variations around λ_{opt} and the minimization of the total load excitations, that is, $\overline{\Delta\Gamma_{wt}}(t) + \overline{\Delta\Gamma_G}(t)$. This means to track the wind torque variations (Maximization of Energy with wind torque tracking – MEwt – see §6.3) and the associated performance index becomes:

$$I = E \left\{ \underbrace{\alpha \left(\overline{\Delta\lambda} \right)^2}_{I_1} \right\} + E \left\{ \underbrace{\left(\overline{\Delta\Gamma_{wt}}(t) + \overline{\Delta\Gamma_G}(t) \right)^2}_{I_2} \right\} \rightarrow \min ,$$

where the weighting coefficient, α , plays the well-known role, of adjusting the energy-reliability trade-off. The first component results as a quadratic form of the state variable:

$$I_1 = E \left\{ \alpha \cdot \overline{\Delta\lambda}^2(t) \right\} \rightarrow \min \Leftrightarrow I_1 = E \left\{ \mathbf{x}^T(t) \cdot \mathbf{C}_\alpha^T \mathbf{C}_\alpha \cdot \mathbf{x}(t) \right\} \rightarrow \min ,$$

where $\mathbf{C}_\alpha = \sqrt{\alpha} \cdot \mathbf{C}$, with matrix $\mathbf{C}$ given in relation (8.3). The global performance criterion may be then put into the form (6.3):

$$(8.6) \quad I = E \left\{ \mathbf{x}^T(t) \cdot \underbrace{\left[\left(\mathbf{M}^T \cdot \mathbf{M} \right) + \left(\mathbf{C}_\alpha^T \cdot \mathbf{C}_\alpha \right) \right]}_{\mathbf{R}_{xx}} \cdot \mathbf{x}(t) + 2 \cdot \mathbf{x}^T(t) \cdot \underbrace{\mathbf{M}^T}_{\mathbf{R}_{xu}} \cdot u(t) + u^T(t) \cdot \mathbf{R}_{uu} \cdot u(t) \right\} \rightarrow \min ,$$

where $\mathbf{M} = [0 \ 0 \ 0 \ 1]$ and $\mathbf{R}_{uu} = 1$.

8.3.2 LQG controller design

Supposing that the LFL is working, form (8.6) corresponds, here also, to a *linear quadratic invariant stochastic* (Gaussian) optimization problem. The existence and the uniqueness of the problem's solution are guaranteed, as a well-known set of conditions concerning the structural properties of the controlled system [LEVI 96] is verified. The unique optimal control input minimizing index (8.6) for the dynamic system given by relations (8.2) and (8.3) is the full-state feedback law, $u(t) = -\mathbf{K} \cdot \mathbf{x}(t)$, with $\mathbf{K} = \mathbf{R}_{uu}^{-1} \cdot \left(\mathbf{R}_{xu}^T + \mathbf{B}^T \cdot \mathbf{S} \right)$, where $\mathbf{S}$ is the unique, symmetric and positive semi-definite matrix satisfying the Riccati matrix equation:

$$\mathbf{S} \cdot \mathbf{A}_r + \mathbf{A}_r^T \cdot \mathbf{S} + \left(\mathbf{R}_{xx} - \mathbf{R}_{xu} \cdot \mathbf{R}_{uu}^{-1} \cdot \mathbf{R}_{xu}^T \right) - \mathbf{S} \cdot \mathbf{B} \cdot \mathbf{R}_{uu}^{-1} \cdot \mathbf{B}^T \cdot \mathbf{S} = 0 ,$$

where $\mathbf{A}_r = \mathbf{A} - \mathbf{B} \cdot \mathbf{R}_{uu}^{-1} \cdot \mathbf{R}_{xu}^T$. The asymptotic stability of the closed loop, described by $\dot{\mathbf{x}}(t) = (\mathbf{A} - \mathbf{B} \cdot \mathbf{K}) \cdot \mathbf{x}(t)$, is guaranteed.

This approach assumes that all the states are available for measure, which is not the case here. In fact only $\overline{\Delta\Omega_h}$ from the state vector is measurable with reasonable costs. Therefore, an observer is used to compute state variables that are not accessible from the plant. Similar to the above design of the LQ controller, the observer design consists in computing a constant vector, $\mathbf{L}_o$, so that its transient response be faster than the response of the controlled loop (HFL), in order to yield a rapidly updated estimation of the state vector.

The $\mathbf{L}_o$ vector has been obtained using a pole placement procedure and the observer canonical form, by following the design methodology given in [NISE 00]. The observer embeds the model (8.3) of the high frequency WECS behaviour and has the below expression:

$$\begin{cases} \dot{\hat{\mathbf{x}}}(t) = \mathbf{A} \cdot \hat{\mathbf{x}}(t) + \mathbf{B} \cdot u(t) + \mathbf{L}_o \cdot (y(t) - \hat{y}(t)) \\ \hat{y}(t) = \mathbf{C}_o \cdot \hat{\mathbf{x}}(t) \end{cases}$$

In this case the transient response of the observer is required to be much faster than that of the uncontrolled plant: hundred times for the normalized variation of the wind torque, $\overline{\Delta\Gamma_{wt}}$, and fifteen times for the other state variables. More details regarding the observer design can be found in appendix H.

Simulations showing the observer efficiency are presented in figure 8.5. A very good performance of the internal torque estimation, $\widehat{\Delta\Gamma}$, can be noted in figure 8.5a); the same result applies also for $\overline{\Delta\Omega_l}$ and $\overline{\Delta\Omega_h}$ variables from the state vector. For the wind torque variation, $\overline{\Delta\Gamma_{wt}}$, the estimation performance is satisfactory, as suggested by figure 8.5b).

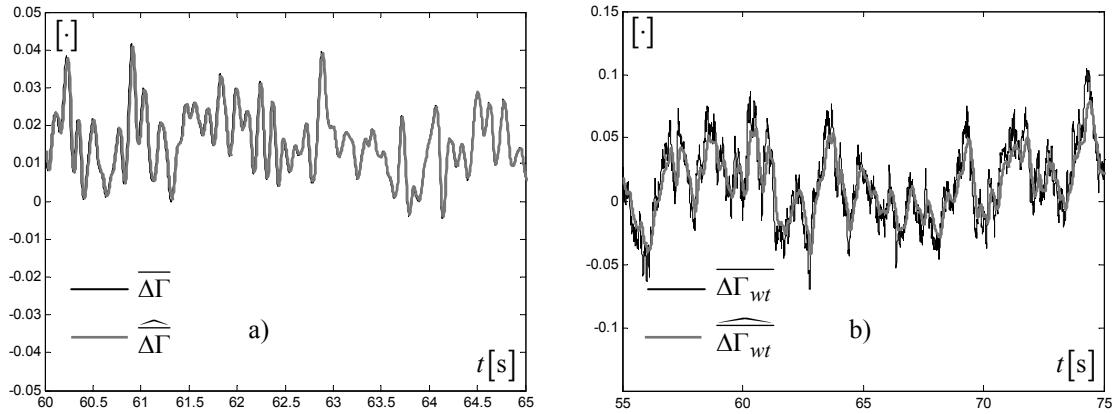


Fig. 8.5 Simulation results showing the state observer performance (flexible DT case)

8.4 GLOBAL NUMERICAL SIMULATION RESULTS

A suggestive image of the 2LFSP configuration used in the case of flexible drive train WECSs is presented in figure 8.6. Both LFL and HFL are built around the corresponding controllers and designed according to the associated specifications, namely λ_{opt} and the weighting coefficient, α , respectively (see appendix H).

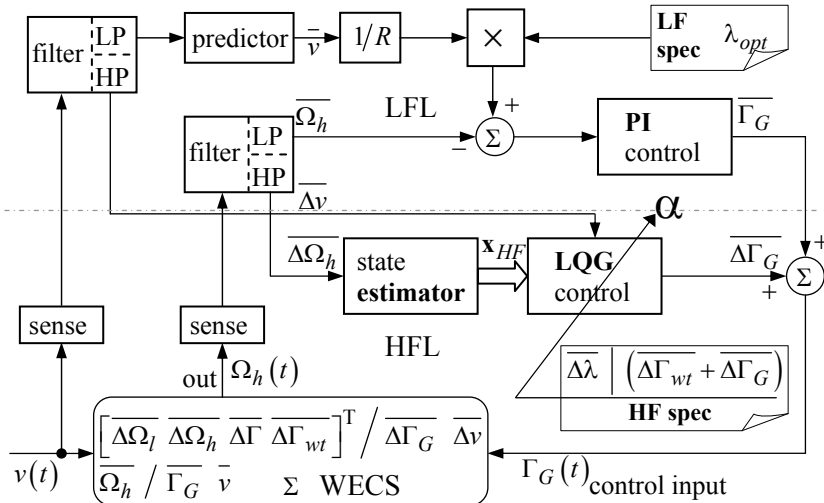


Fig. 8.6 Block diagram of the 2LFSP for flexible drive train WECS

Structure from figure 8.6, ensuring the combined operation of the LFL and HFL, has been implemented in Matlab/SimulinkTM and parameters of the elements used within can be found in appendix H. In the sequel the most representative simulation results picked up from the two loops are presented.

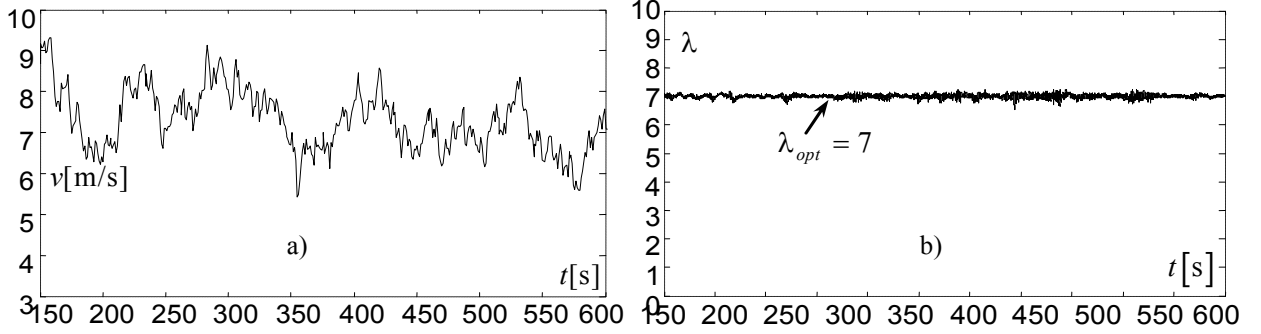


Fig. 8.7 2LFSP for flexible drive train WECS: steady-state tip speed ratio kept optimal (LFL)

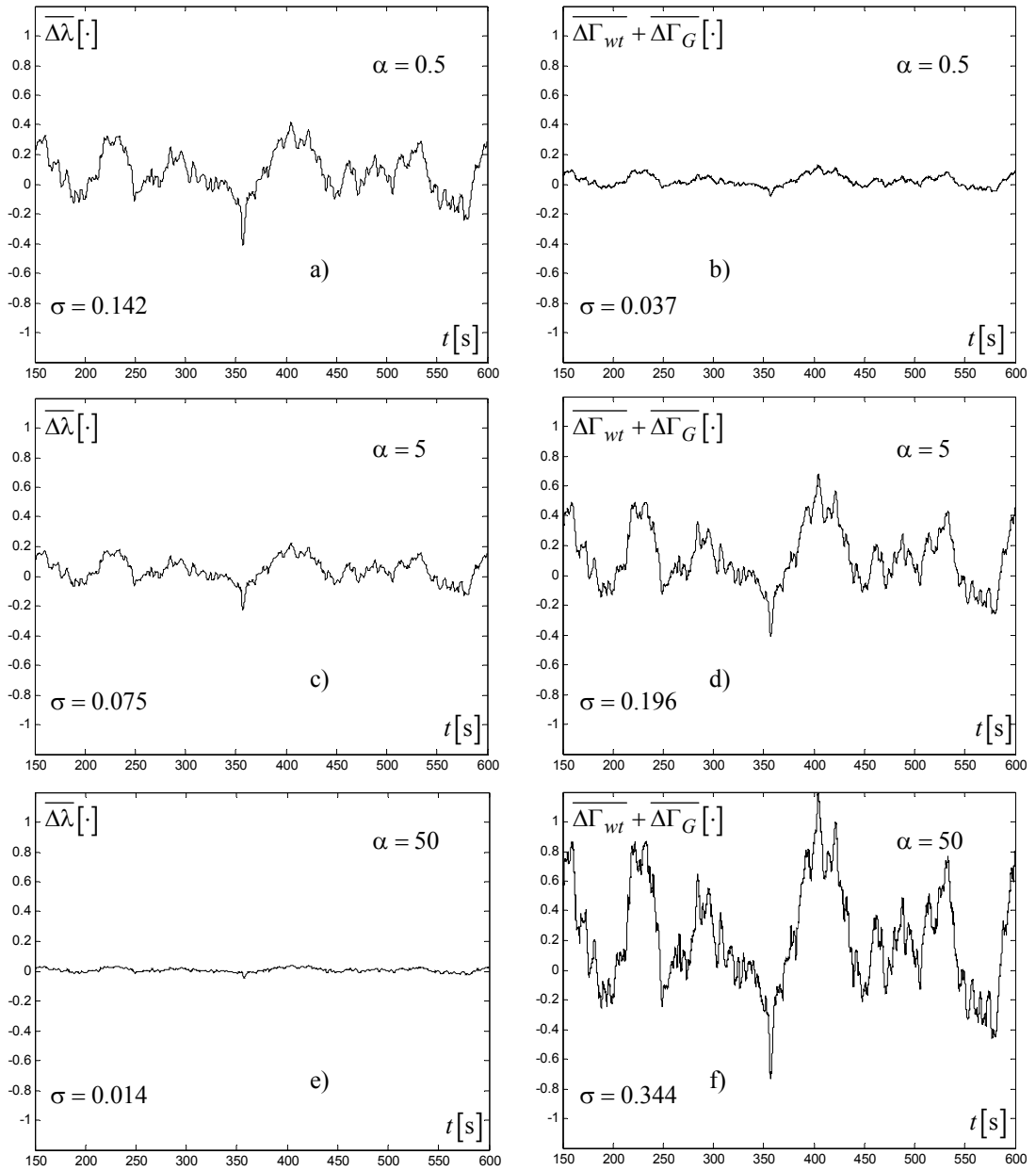


Fig. 8.8 HFL operation for flexible drive train WECS; left column: evolution of the speed ratio variations; right column: evolution of the torque variations sum

The wind speed exciting the turbine's rotor has been obtained by using the simplified model from §2.2.2 (see figure 2.9); its evolution can be seen in figure 8.7a). The LFL performance can be assessed from figure 8.7b): the steady-state value of the tip speed is maintained around its optimal value ($\lambda_{opt}=7$) with satisfactory small deviations (under 5%).

Figure 8.8 shows how the normalized variations of the tip speed ratio, $\overline{\Delta\lambda}$ (left side), and of the torque variations sum, $\overline{\Delta\Gamma_{wt}}(t) + \overline{\Delta\Gamma_G}(t)$ (right side), depend on α for the same wind sequence (figure 8.7a)).

As it was expected, the standard deviation of the tip speed normalized variation (expressing the energetic efficiency) decreases with α , while that of the sum of torques standard deviation increases (and so does the mechanical stress). One can note that, when α increases from 0.1 to 10, the standard deviation of $\overline{\Delta\lambda}$ decreases from $\sigma_\lambda = 0.23$ to 0.01, while the standard deviation of $\overline{\Delta\Gamma_{wt}}(t) + \overline{\Delta\Gamma_G}(t)$ increases from $\sigma_\Gamma = 0.03$ to 0.53.

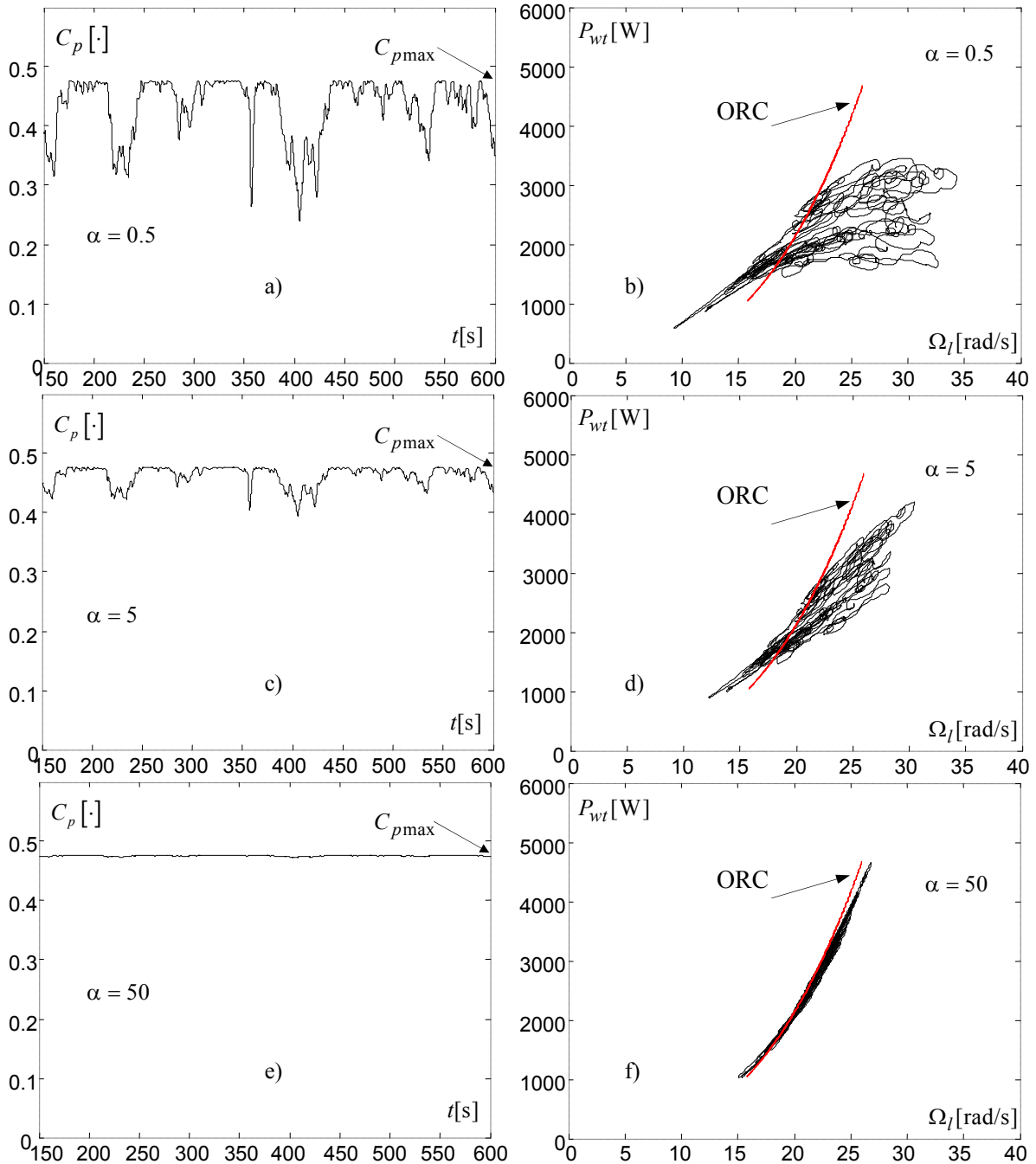


Fig. 8.9 2LFSP operation: tracking the optimal operating regime (flexible DT case)

Figure 8.9 shows the aerodynamic efficiency evolutions (left side) and the excursion of the operating point in relation to the ORC (right side) for the wind speed sequence in figure 8.7a) and for the same three values of α as in figure 8.8. Small α (upper side) leads to large deviations from optimal operating regime, so poor energetic efficiency; on the contrary, good efficiency is obtained for large values of α (lower side), when the deviations from $C_{p\max}$ and OOP become insignificant. Also, one can note that the control law performance depends on the wind speed, since the operating point trajectory in the (Ω_l, P_{wt}) plane is not “centred” on the ORC; the controller becomes unreliable for large wind speed values. The specifications of the control structure from figure 8.6 can be viewed in appendix H.

8.5 CONCLUSION AND FUTURE WORK

This chapter has concerned the application of the two loop control structure, 2LFSP, for optimizing the dynamical behaviour of variable speed fixed pitch flexible drive train WECSs in the partial load region. The particular configuration of the control structure – yielded by the *frequency separation principle* adopted in the wind/WECS modelling (see §6.2 and §6.3) and used also in chapter 7 – consists of two different loops: a steady-state maximum energetic efficiency loop, governed by the low frequency wind speed component (the low frequency loop – LFL), and an optimal control loop, ensuring an adjustable energy-reliability trade-off, governed by the turbulence component (the high frequency loop – HFL).

The LFL harvests the maximum energy available in the low frequency wind speed, being built around a PI controller, whose reference is computed using a predicted value of the low frequency wind speed. As the low frequency behaviour does not introduce mechanical stress, reliability aspects are not considered in the LFL; therefore, a steady-state optimisation is achieved here. The HFL is based upon a LQG controller, such that the available turbulence energy is captured more or less, depending on the admissible mechanical stress level. The possibility of tuning the weighting coefficient, α , confers flexibility to the control system, so that the wind harvested energy be significantly increased when not prevented by a large level of wind turbulence or by user preferences.

Three future issues may be of interest. First, the proposed approach should be tested on a WECS with more complex aerodynamics. Second, one should investigate the nature of the quite important deviations of the operating point from the ORC for high winds, which can be due to some non negligible prediction errors, to PI controller loss of robustness or may be a combined dysfunction of the two loops. Finally, real time validation on dedicated test rigs should be envisaged.

Chapter 9

GENERAL CONCLUSION. FUTURE DEVELOPMENT

9.1 Conclusion

The variable speed concept applied to wind turbines is considered to be a significant advance in WECS technology. Applying this concept in this field has had a considerable growth in the last years, taking into account its positive impact on the wind turbines' efficiency. This efficiency is an economical requirement resulted from the competition with other types of energy sources and is expressed by two main aspects: the provided energy quantity (under certain quality requirements) and the involved costs. Studies indicate that increasing of the energy capture without affecting the service lifetime is not a trivial task, given the erratic nature of wind. From a more technical point of view, a wind turbine is a time variant nonlinear system excited by stochastic inputs which significantly affect its reliability. Therefore, the control of the variable speed wind turbines is still in the phase of developing technical solutions, as none of the WECS control techniques has become classical such to be widely used by wind turbine integrators.

In this context, the use of the modern control techniques for the WECS efficiency maximisation is required. Given the multiple aspects of the wind turbine global efficiency (such as its reliability, its availability, remote operation and maintenance costs, electrical generation regimes, captured power, etc), controlling wind turbines may imply the necessity of formulating multi-purpose optimisation problems.

The present work is consistent with this approach. Its main scope is the optimal control in the WECS's partial load regime (below the rated wind speed), using the variable speed capability. The approached class of WECS is widely spread, given its reliability and large area of applications. Their generator vector control ensures smooth generator torque response, which is the most suitable for turbine's variable speed operation.

The approaches presented in this work employ simple and reliable wind turbine models under a reasonable set of modelling assumptions for the purpose of developing WECS controllers. To overcome the drawbacks possibly induced by a "poor modelling", some advanced control techniques have been employed, conferring robustness to the resulted controlled WECS. The global optimisation embedded in these techniques supposes two directions: ***harvesting maximum power from the wind, while limiting the mechanical fatigue induced by the control input (electrical generator's torque) or wind variations***. The study presented in this work follows two main directions: when knowledge of the WECS parameters is consistent and, respectively, when many parameters are unknown (or insufficiently precisely known).

In the concerned literature, the preliminary experimental validation of WECS control laws is always performed on simulators containing HILS systems, because a real wind turbine does not allow deterministic tests in its natural environment; here, a likely approach is employed. A systematic design methodology for building generic HILS systems has been proposed and its application in designing a variable speed low power WECS real time simulator has been detailed.

Following these remarks, three main approaches in WECS optimal control have been developed in this work.

First, a version of the reliable control method called **Maximum Power Point Tracking (MPPT)**, requiring

minimal knowledge about the system, has been proposed. *Based on the extremum seeking principle, this method intends to drive the average operating point of the turbine towards the optimal one, thus ensuring optimal conversion regime, by using the turbulence component of the wind speed as search (probing) signal.*

The operating point position is estimated using the average phase shift between the power coefficient and the tip speed ratio time variations. Discrete Fourier transform has been applied to these signals in order to extract the phase of each harmonic component. Then, one compute the phase lag of each components corresponding to the two signals; their average values contain information concerning the operating point position, which is further integrated for obtaining a control input (rotational speed reference) for slowly driving the turbine's operating point towards the optimal one. Since the concerned control is dealing with average operating values, the inflicted supplementary mechanical stress is negligible. Also, this method has an improved efficiency as the average wind speed increases, because the turbulence (searching signal) level increases too, yielding better WECS energetic efficiency.

Secondly, a **sliding mode control** law aiming at maintaining the turbine's operating point in a certain neighbourhood of the optimal regime characteristics has been developed. The system's state trajectory is restricted in this case to the sliding surface. *For reasons concerning the control effort, this surface cannot be the ORC itself, but it can be designed such that to have a nonempty intersection with the ORC. In this manner, the operating point has a certain freedom around the ORC, implicitly allowing the possibility of limiting the control effort.* The equivalent component of the control input ensures an adjustable slope of the sliding surface, allowing it to approach the ORC more or less, thus forcing the WECS to follow as accurately as desired the optimal conversion regime, according to a trade-off coefficient.

The on-off alternating component, adding robustness to the controlled system, has been computed based on a sigmoid hysteresis for limiting even more the undesired high frequency torque variations (chattering). Some drawbacks of the control law have been signalled, which can however be easily overcome in practice under some realistic assumptions.

A third approach is based on **the frequency separation principle implying the separate processing of the two components identified in the wind spectrum and employs a two loop control configuration (2LFSP)**. This structure is intended to be a more successful alternative to the previously developed adaptive optimal WECS control using LQG controllers.

Using the low frequency wind speed component – obtained by low pass filtering – one makes a steady-state optimisation by maintaining the static operating point on the ORC; the induced mechanical stress is insignificant as there are no high frequency torque variations involved. This is done by employing either a PI controller or an on-off controller for maintaining the average tip speed ratio to its optimal value; this results in fact in a rotational speed tracking structure. This low frequency loop has a double role: beside the above stated one, it maintains constant the most variable parameter of the linearized (in variations) model describing the high frequency WECS dynamics, namely the torque parameter. The turbulent high frequency wind component is treated within a high frequency loop built around a LQG controller. This controller ensures optimal dynamic behaviour of the WECS around the static operating point established by the low frequency loop. Its parameters are computed by solving a LQG optimisation problem associated to the linearized model describing the high frequency WECS behaviour, whose performance index expresses a trade-off between maximisation of the captured wind energy and minimisation of the drive train mechanical fatigues (given by the control or/and wind variations).

Defining the quadratic performance index depends upon the drive train type, which can be either rigid or flexible. In the first case, the goal is to limit the generator's torque variations, while optimizing the energetic regime. The associated LQG problem has been developed on a suitable linearized model of the rigid drive train based

WECS. In the second case the optimisation index expresses the scope of limiting the cumulated variations of the electrical generator's and turbine rotor's torques – which constitutes the total mechanical fatigue experienced by the drive train – while optimizing the energetic regime. The associated LQG problem has been developed on the linearized model of the WECS with flexible drive train.

All the three above listed approaches have potential for their use in real world applications, as the preliminary validation showed. For the sliding mode control and for the 2LFSP control method applied on the rigid drive train WECS, real time experimentations (which perfectly matches the off-line simulations) on electromechanical wind turbine simulators have also been performed.

The sliding mode and 2LFSP approaches confers flexibility in WECS operation, as the parameters ensuring the energy-reliability trade-off can be changed by the system's operator when encountering variable wind conditions (higher turbulent winds will require a controller based on a smaller trade-off coefficient). For example, in the 2LFSP case, this is done by switching the LQG controller – its parameters being off-line a priori computed – such that torque variations remain within some admissible limits provided by the turbine's manufacturer.

The 2LFSP control structure is more sensitive to parametric or modelling uncertainties than the proposed sliding mode control structure but provides an easier to handle control solution. Also, the separation of the two wind components represents an inconvenient because of the delays induced by filtering. The sliding mode control structure is robust to uncertainties and the inflicted chattering can be conveniently reduced to insignificant variations, but it is more complex from the computing point of view.

As for the proposed MPPT control structure, its lack of flexibility is overcome by its robustness and simplicity. It represents a reasonable choice in WECS optimal control when disposing of poor knowledge about the system.

As general conclusion, the chosen WECS control structure to implement in a real world application is not necessarily a (purely technical) optimal solution, but must represent the best trade-off between the closeness to the targeted optimum and simplicity and robustness, on the other hand.

9.2 Contributions

The original contributions of the author (most of which have been published in journals and international conference proceedings volumes) are listed as follows:

- Development of a robust optimal control law belonging to the MPPT methods for a class of WECS. This approach, based on the extremum seeking control, employs an original method of obtaining the operating point position on the aerodynamic efficiency curve, namely by using a discrete Fourier Transform (DFT) computation of the average phase lag between the tip speed ratio and the power coefficient.
- Development of a sliding mode control law for optimizing the dynamic behaviour of a class of WECS; the operating point excursion around the one representing optimal conversion can be controlled. The feature key is here the wise choice of a sliding surface having a nonempty intersection with the optimal regimes characteristic for each wind speed in the partial load region. This surface can be tuned to be more or less close to the optimal regimes characteristic by means of a balancing parameter ensuring an energy-reliability trade-off.
- Proposing a two loop optimal control structure based on the frequency separation principle applied to modelling both the wind speed and the WECS dynamics (2LFSP). The low frequency loop handles the steady-state optimisation and desensitizes the high frequency WECS model with respect to the wind speed variation. The high

frequency loop optimizes the WECS behaviour around the optimal operating point established by the action of the low frequency loop. This optimisations concerns a trade-off between energetic efficiency and mechanical stress.

- Application of the 2LFSP approach to a rigid drive train based WECS. Applying the frequency separation principle, one optimizes the high frequency WECS behaviour around the optimal operating point, while maintaining the steady-state optimal conversion regime. Limiting the mechanical loads generating fatigue on the drive train components concern the control input, that is, the electrical generator's torque applied to the system's high speed shaft. A suitable controllable high frequency rigid drive train based WECS model has been developed to serve for stating the associated LQG problem.

- Application of the 2LFSP approach to a WECS having flexible drive train. The frequency separation principle based control structure optimizes the high frequency WECS behaviour around the optimal operating point, while maintaining the steady-state optimal conversion regime. In this case the mechanical loads concern the cumulated mechanical efforts induced by the electrical generator's torque (control input) applied to the system's high speed shaft and by the turbine rotor's (wind) torque applied to the low speed shaft (turbulent wind variations). The associated LQG problem has been stated on a suitable high frequency flexible drive train based WECS model and the non-measurable variables have been estimated by means of an observer.

- Proposing a systematic design methodology for building generic hardware-in-the-loop simulation (HILS) systems. This procedure uses terminology and elements introduced in previous works, cast in a new methodological vision for developing HILS systems. This methodology, applicable for any industrial system, has been illustrated for building a real time variable speed wind turbine electromechanical simulator.

9.3 Future development

As the proposed WECS control approaches present some drawbacks or have been incompletely developed, some future works are to be further considered.

Concerning the **MPPT approach** some work should be directed to designing an adaptive law of the searching speed, which must take into account the turbulence intensity, and to experimentally testing this approach on a real time electromechanical wind turbine simulator (implementing a more complex aerodynamic model). Also, getting the operating position by convoluting the tip speed and the power coefficient signals is a procedure worthy to be tested. A study concerning the controlled WECS speed convergence to the optimal conversion regime in different wind conditions must also be done.

In the **WECS sliding mode control**, a study of the closed loop system's robustness in different operating conditions deserves a particular attention. A quantitative expression of the achievable trade-off must be sought, i.e. how much is the stress effectively reduced when giving up the tracking performance at a certain degree. The design of a sliding mode control law for harvested power regulation within the same framework is of interest, as it can be useful for WECS control in the full load operation regime.

Concerning the **2LFSP approach**, there are some points to improve as follows. Splitting the wind components is rather rough by filtering, providing an unrealistically delayed version of the low frequency component and consequently a slightly deformed turbulent component. This inconvenient can be corrected if using a prediction method rather than a low-pass filter in the low frequency loop, along with a better funded choice of the separation filter's cut-off frequency. Estimation of the steady-state component of the rotational speed may be also improved. Also, a study must be done in designing the energy-reliability trade-off coefficient. For guaranteeing a

certain service lifetime without failure, its value must be related to admissible values of the high frequency torque variations provided by the drive train manufacturer (or wind turbine integrator) for a specific WECS. Considering the electrical generator efficiency captured into the mathematical expression of the energetic sub-criterion is also a point of interest for future works. These remarks hold for both rigid and flexible drive train based WECSs.

In the case of the ***2LFSP application to the flexible drive train WECSs***, one should investigate the nature of the quite important deviations of the operating point from the operating regimes characteristic for high winds, which can be due to some non negligible prediction errors, to PI controller loss of robustness or may be a combined dysfunction of the two loops. If parametric variations of the high frequency WECS model are the main cause of the above mentioned effect, a gain scheduling approach may be envisaged for correction. Also, the proposed approach should be tested on a WECS with more complex aerodynamics and real time validation on dedicated test rigs should be aimed at.

Implementing these control approaches on real world wind turbine installations is a last but not least objective to be envisaged as future development of this work.

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APPENDICES

Appendix A

STRUCTURE AND PARAMETERS OF THE APPROACHED VARIABLE SPEED WECS

A synthetic variable speed WECS image, containing its main parts modelled in chapter 2, can be seen in figure A.1.

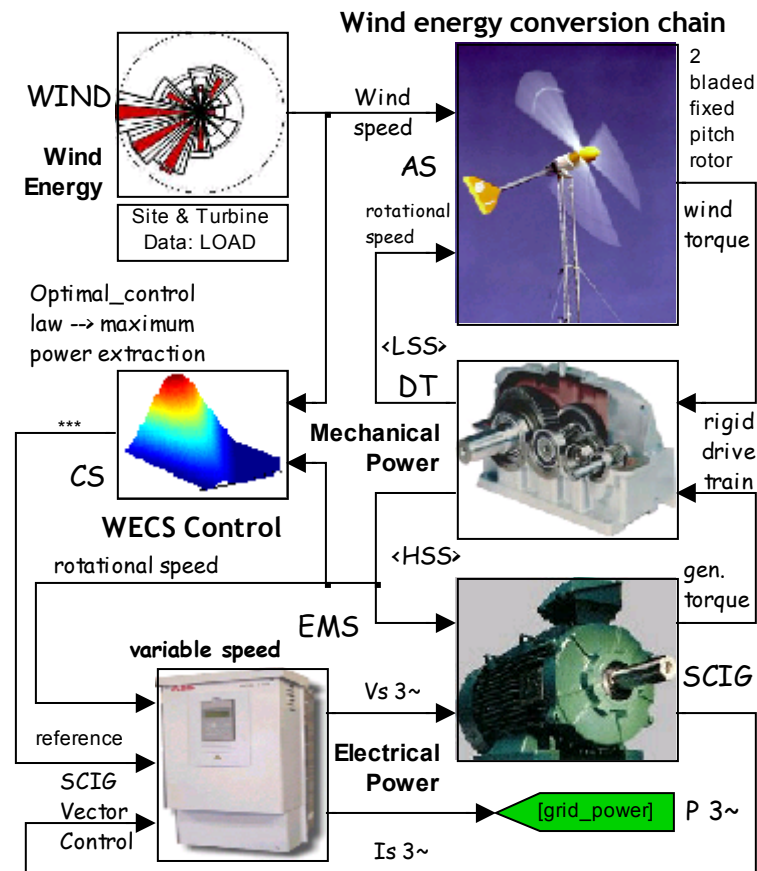


Fig. A.1 Simulink generic scheme of the variable speed WECS

Features	Parameters
Aerodynamics (S_1)	
- type of the rotor: horizontal axis; - 2 bladed high speed - fixed pitch in partial load - power limiting: active stall - teetered rotor for tower shadow effect alleviation - vane for rotor orientation	- air density: $\rho=1.25 \text{ Kg/m}^3$ - blade length: $R=2.5 \text{ m}$ - rated power: 6 kW - rated wind speed: 10 m/s, - cut-in & maximum wind speed: 5.5 m/s, 20 m/s - maximum aerodynamic efficiency: $C_{p_{\max}} = 0.47$ - optimal tip speed: $\lambda_{opt} = 7$

	- torque coefficient at maximum efficiency: $C_T = 0.067$ - rotor inertia: $J_t = 3.5 \text{ kgm}^2$ - static friction torque: 2 Nm $a_6 \div a_0$: -4.54×10^{-7}; 1.3027×10^{-5}; -6.5416×10^{-5}; -9.7477×10^{-4}; 0.0081; -0.0013; 0.0061
Drive train (S_3)	
- single stage fixed ratio - rigid coupling - flexible coupling*	- multiplication ratio: $i = 6$ - average efficiency: $\eta = 0.95$ - stiffness*: $K_S = 75 \text{ Nm/rad}$ - damping*: $B_S = 0.5 \text{ kgm}^2/\text{s}$
Generation system (S_2)	
- squirrel cage induction machine - back-to-back IGBT based converter	SCIG: - 4 poles, 3 phased, 50 Hz, 380 V - ratings: 7 kW, 1500 rpm, $\Gamma_{G_{max}} = 40 \text{ Nm}$ - modelling parameters: $J_g = 0.05 \text{ kg}\cdot\text{m}^2$, $R_s = 2.1\Omega$, $R_r = 1.7\Omega$, $L_s = 0.4186\text{H}$, $L_r = 0.4186\text{H}$, $L_m = 0.4058\text{H}$; 7.5 kW inverters, 600 V DC-link EMS time constant: $T_G = 3 \text{ ms}$

Remarks:

Only the basic parameters/features from a functional viewpoint have been considered.

* used only in chapter 8.

The SCIG model has been implemented in Matlab code using the following s-function [MATL 00]:

```
% ASMCN - s-function modelling SCIG
function [sys,x0,str,ts] = asmcn(t,x,u,flag,Rs,Rr,Ls,Lr,Lm,p)

% inputs: u=[Vsd Vsq omg_electric omgs]
% omgs = stator frequency
% omg_electric=omg_mecanic*p
% states: x=[isd isq ird irq]
C=1-Lm^2/(Ls*Lr); % sigma
D=C*Lr*Ls;

% state matrix;
A=[-Rs/(C*Ls) Lm^2/D Lm*Rr/D Lm/(C*Ls); Lm^2/D -Rs/(C*Ls) Lm/(C*Ls)...
Lm*Rr/D; Lm*Rs/D Lm/(C*Lr) -Rr/(C*Lr) 1/C; Lm/(C*Lr) Lm*Rs/D 1/C -...
Rr/(C*Lr)];
% input matrix, multiplying [Vsd Vsq Vrd Vrq]' Vrd=Vrq=0
B=[1/(C*Ls) 0 -Lm/D 0; 0 1/(C*Ls) 0 -Lm/D; -Lm/D 0 1/(C*Lr) 0; 0 -Lm/D 0...
1/(C*Lr)];

switch flag,
case 0,
[sys,x0,str,ts]=mdlInitializeSizes;
case 1,
sys=mdlDerivatives(t,x,u,A,B);
case { 2, 4, 9 },
sys = [];
case 3,
sys=mdlOutputs(t,x,u,p,Lm);
otherwise
error(['Unhandled flag = ',num2str(flag)]);
end
% end asmcn

% mdlInitializeSizes
function [sys,x0,str,ts]=mdlInitializeSizes()
sizes = simsizes;
```

```

sizes.NumContStates = 4;
sizes.NumDiscStates = 0;
sizes.NumOutputs     = 5;
sizes.NumInputs      = 4;
sizes.DirFeedthrough = 0;
sizes.NumSampleTimes = 1; % at least one sample time is needed
sys = simsizes(sizes);
x0 = zeros(4,1);
str = [];
ts = [0 0];
% end mdlInitializeSizes
% mdlDerivatives
function sys=mdlDerivatives(t,x,u,A,B)

A(1,2)=u(4)+A(1,2)*u(3);
A(1,4)=A(1,4)*u(3);
A(2,1)=-u(3)*A(2,1)-u(4);
A(2,3)=-u(3)*A(2,3);
A(3,2)=-u(3)*A(3,2);
A(3,4)=u(4)-u(3)*A(3,4);
A(4,1)=u(3)*A(4,1);
A(4,3)=u(3)*A(4,3)-u(4);
% states derivatives
sys(1:4)=A*x(1:4)+B*[u(1:2)' 0 0]';
% end mdlDerivatives
% mdlUpdate
function sys=mdlUpdate(t,x,u)
sys = [];
% end mdlUpdate
% mdlOutputs
function sys=mdlOutputs(t,x,u,p,Lm)
% outputs are(isd isq ird irq)...
sys(1)=x(1);
sys(2)=x(2);
sys(3)=x(3);
sys(4)=x(4);
% ... and generator's torque
sys(5)=(3/2)*p*Lm*(x(3)*x(2)-x(4)*x(1));
% end mdlOutputs

```

Appendix B

PARAMETERS CONCERNING WIND SPEED SYNTHESIS

Nonstationary modelling

The concerned simulations have been performed on the diagram from figure 2.7 (according to the *second approach* of nonstationary modelling), instantiated with the following values:

- daily average of the wind speed: $v_0=7$ m/s,
- low frequency component model parameters, $H_s(s) : K=2000, T=3000$ s, $T_0 = F(v_s) = 10 \cdot v_s(t) - 40$,
- parameters of the Butterworth filter: unitary gain, low-pass cut-off frequency 0.01 Hz, order 4,
- turbulence model:

$$H_t(s) = \frac{33.33s + 1}{187.5s^2 + 20s + 1}$$

Stationary modelling

The associated simulations have been performed mainly on the diagram from figure 2.9, where:

- daily average of the wind speed: $v_0=7$ m/s,
- parameters of the shaping filters, $H_t(s) = \frac{k_t}{T_t s + 1}$ and $H_s(s) = \frac{k_s}{T_s s + 1}$, are: $k_t=50, T_t=2$ s, $k_s=750$ and $T_s=100$ s,
- the gain $k=0.2$ is a measure of the turbulence intensity/power.

For the simple turbulence synthesis – see figure 2.11 – a constant low frequency component $v_s = 7$ m/s has been used, and two values of the turbulence length, $L_{t1} = 150$ and $L_{t2} = 100$ respectively.

Appendix C

PARAMETERS OF WECS SIMULATED ON THE HIL DEVELOPMENT PLATFORM FROM CHAPTER 3

The development platform built upon the hardware-in-the-loop simulation (HILS) principle, as described in the third chapter of this work, has been tested for a WECS having the main features given in appendix A.

Based on a DC machine, the real time physical simulator (RTPS) emulates the coupling aerodynamic subsystem – drive train.

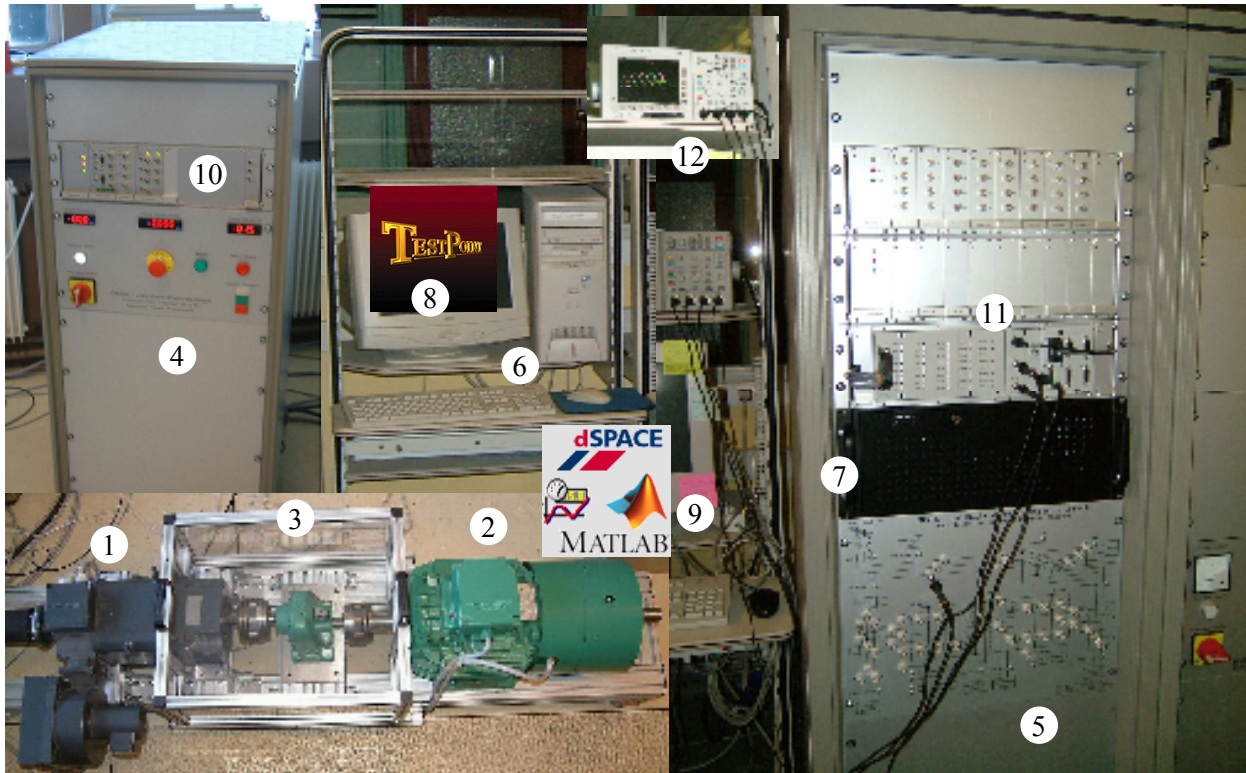


Fig. A.2 Components of the experimental test rig used for variable speed WECS simulation in chapter 3 (courtesy to Laboratoire d'Électrotechnique de Grenoble – France)

Figure A.2 shows the components of the HIL WECS simulator:

1. DC motor from RTPS (DCM);
2. Doubly-fed induction generator (DFIG);
3. Gear box used for DCM-DFIG coupling;
4. Power electronics for driving DCM;
5. Power electronics for driving DFIG;
6. Personal computer PC2 (in §3.6.1);
7. Personal computer PC1 (in §3.6.1);
8. TestPoint interface on PC2;
9. Simulink & ControlDesk interface on PC1;
10. DSP TMS320F240 implementing DCM torque control;
11. DSP DS1005 (dSPACE) implementing WECS and DFIG control;
12. Oscilloscope.

Main features of the EFT physical components:

- DC machine Siemens 1G 5 106-0EH-3UV1, having rated power 6.5 kW, rated rotational speed 3850 rpm, maximal torque 20.2 Nm, torque constant 0.87 Nm/A, mechanical time constant 3.6 s, electromechanical time constant 4.6 ms, inertia 0.02 Kg·m²; stator resistance 78 Ω, rotor resistance 0.78 Ω, rotor inductance 3.6 H, speed constant 0.9 V/rad/s;
- DC motor speed reduction gear of ratio 1.41;
- 10 kW rectifier-chopper (IGBT based);
- current loop parameters: real-time processor DSP TMS320F240, time frame $T_e = 200 \mu\text{s}$, PI control parameters $K_p = 3.44$, $K_i T_e = 0.156$.

The generation subsystem parameters:

Features	Parameters
Generation system (S_2)	
- doubly-fed induction machine - back-to-back IGBT based converter	DFIG: - Leroy Somer FSLB 160M, - 4 poles, 3 phased, 50 Hz, 380 V - ratings: 7,5 kW, 1440 rpm, $\Gamma_{G_{max}} = 40 \text{ Nm}$ - modelling parameters: $J_g = 0.03 \text{ kg}\cdot\text{m}^2$, $R_s = 0.0751 \Omega$, $R_r = 0.13 \Omega$, $L_s = 0.0143 \text{ H}$, $L_r = 0.0143 \text{ H}$, $L'_m = 0.0132 \text{ H}$; 10 kW IGBT based inverters, 800 V DC-link EMS time constant: $T_G = 5 \text{ ms}$

Table A.1 EMS parameters used for the WECS simulator in chapter 3

Appendix D

SPECIFICATIONS OF THE MPPT CONTROLLER

Rotational speed control:

- PI controller: $K_p = 1$, $K_I = 4$, reference limit: 280 rad/sec, reference rate limit: $\pm 1000 \text{ rad/s}^2$;
- torque reference limits: $\Gamma_G \in [0; 40] \text{ Nm}$;
- control enabled by an operating point (OP) on the stable zone of the torque characteristic;
- Simulink scheme in figure A.3.

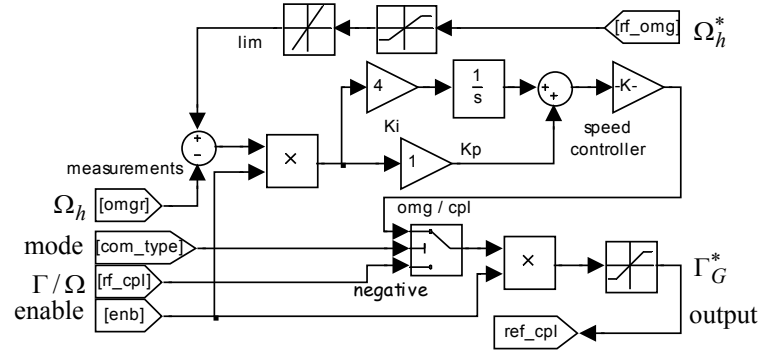


Fig. A.3 Simulink implementation of WECS speed control

MPPT algorithm specifications:

- sample time: $T_S = 0.1 \text{ s}$, time for computing the average lag, $\theta : T_C = 256 \cdot T_S$;
- the Matlab s-function used for computing the average phase shift, θ , is given in the code bellow:

```
function [sys, x0]=test_def_clk(t,x,u,flag,npts,ts)
global tact;
if flag == 0
    % Initialization
    nstates = 2*npts + 6;
    sys = [0;nstates;2;2;0;0];
    x0 = zeros(nstates/2,2);
    x0(1,1) = 1;
    x0(nstates/2,2) = 0;
    x0 = x0(:);
elseif abs(flag) == 2 % Flag equals 2 on a real-time hit
    nstates = npts + 3;
    sys = zeros(nstates,2);
    sys(:) = x(:);

if rem(t + 1000*eps, ts) < 10000*eps %t is multiple of ts
    x(1,1) = x(1,1) + 1;
    sys(x(1,1), :) = u(:)';
    div = x(1,1)/npts;
    if (div == round(div))
        blc = blackman(npts);
        ya = [sys(x(1,1)+1:npts+1,1); sys(2:x(1,1),1)];
        ya = ya.*blc;
        yb = [sys(x(1,1)+1:npts+1,2); sys(2:x(1,1),2)];
        yb = yb.*blc;
        ga = fft(ya,npts);
        gb = fft(yb,npts);
        a1 = real(ga); b1 = imag(ga);
        a2 = real(gb); b2 = imag(gb);
        for i=1:length(a1)
            at = atan(b1(i)/a1(i));
        end
        if (a1(i)>0),
```

```

        if (b1(i)>0) ar1(i)=at;
        elseif (b1(i)<0) ar1(i)=2*pi+at;
        else ar1(i)=0;
        end;
    elseif (a1(i)==0),
        if (b1(i)>0) ar1(i)=pi/2;
        elseif (b1(i)<0) ar1(i)=3*pi/2;
        else ar1(i)=0;
        end;
    elseif (b1(i)~=0), ar1(i)=at+pi;
    else ar1(i)=pi;
    end;

        at = atan(b2(i)/a2(i));
    if (a2(i)>0),
        if (b2(i)>0) ar2(i)=at;
        elseif (b2(i)<0) ar2(i)=2*pi+at;
        else ar2(i)=0;
        end;
    elseif (a2(i)==0),
        if (b2(i)>0) ar2(i)=pi/2;
        elseif (b2(i)<0) ar2(i)=3*pi/2;
        else ar2(i)=0;
        end;
    elseif (b2(i)~=0), ar2(i)=at+pi;
    else ar2(i)=pi;
    end;    % if

        dfi(i) = ar1(i) - ar2(i); % 0 <= dfi <= pi
    if ((dfi(i) < -pi)|(dfi(i) > pi)), dfi(i) = 2*pi - abs(dfi(i)); end;
    if ((dfi(i) >= -pi)&(dfi(i) < 0)), dfi(i) = abs(dfi(i)); end;
    end;    % for dfi

        sys(nstates,2)=mean(dfi);
        tact=~tact;
    end;

        if sys(1,1) == npts
            x(1,1) = 1;
            end
        sys(1,1) = x(1,1);
    end;

        sys = sys(:);

elseif flag == 3
    sys(1) =x(length(x)) ;
    sys(2) =tact ;
elseif flag == 4
    ns = t/ts; % Return next sample hit
    % Number of samples
    sys = (1 + floor(ns + 1e-13*(1+ns)))*ts;
else
    % Other flag options ignored
    sys = [];
end
end

```

- limit-values used for aerodynamic efficiency and tip speed normalisation: $\lambda_{max} = 15$, $C_{p_{opt}} = 0.5$;

• the average phase shift θ is processed as in figure 4.8b). The information concerning the OP position in the optimal one's (OOP) neighbourhood is linearly approximated: $m \cdot \left(\theta - \frac{\pi}{2} \right) + \frac{\pi}{2}$. For the concerned simulations, the slope has been chosen as $m=1.2185$. Smaller values of m induce smoother behaviour around the OOP;

- speed reference conditioning: rate limit $\pm 10 \text{ rad/s}^2$, filtering: $\frac{1}{0.2s+1}$;
- integrator coefficient variation range is: $k \in [0.005; 0.5]$;
- Simulink implementation in figure A.4.

Appendix E

SPECIFICATIONS OF THE SLIDING MODE CONTROLLER

The Simulink implementation of the control structure used for off-line simulations, as described in §5.3, is presented in figure A.5. Parameters used within belong to the SCIG based rigid DT WECS whose parameters are given in appendix A. Measurements of wind speed, Ω_h and Γ_G – with filtering – are necessary.

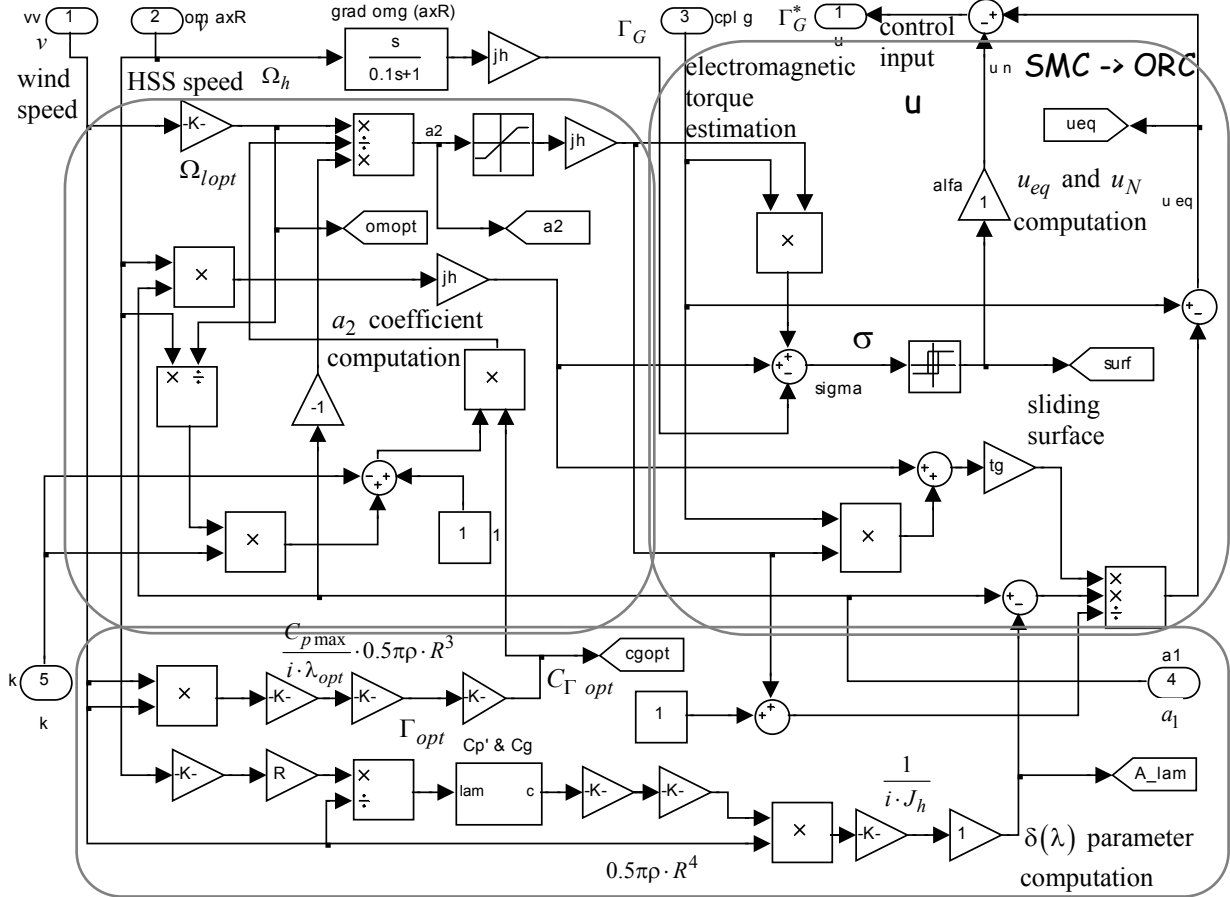


Fig. A.5 Simulink implementation of the sliding mode control law – off-line simulations

The multiplying correction of value Γ_{opt} , η_{em} , has a variation with the wind speed, as given in figure A.6 [MUNT 05c], which was experimentally obtained for the EMS described in appendix C.

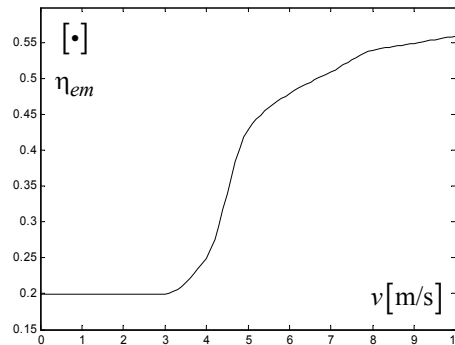


Fig. A.6 Torque correction coefficient versus the wind speed

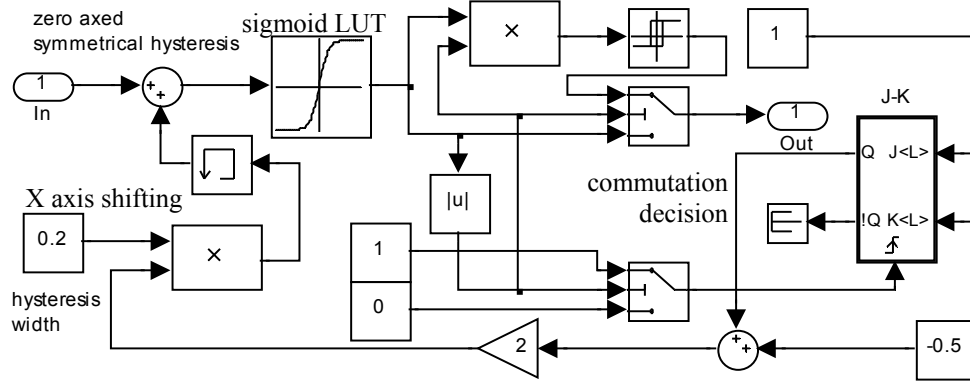


Fig. A.7 Simulink construction of the sigmoid based hysteresis

Figure A.7 outlines the method used for implementing the sigmoid (hyperbolic tangent) hysteresis. A look-up table has been used for obtaining the sigmoid curve. Also, the x-axis of the sigmoid curve had to be shifted with respect to the input gradient and position. A J-K flip-flop has been used for implementing the decision of shifting the curve.

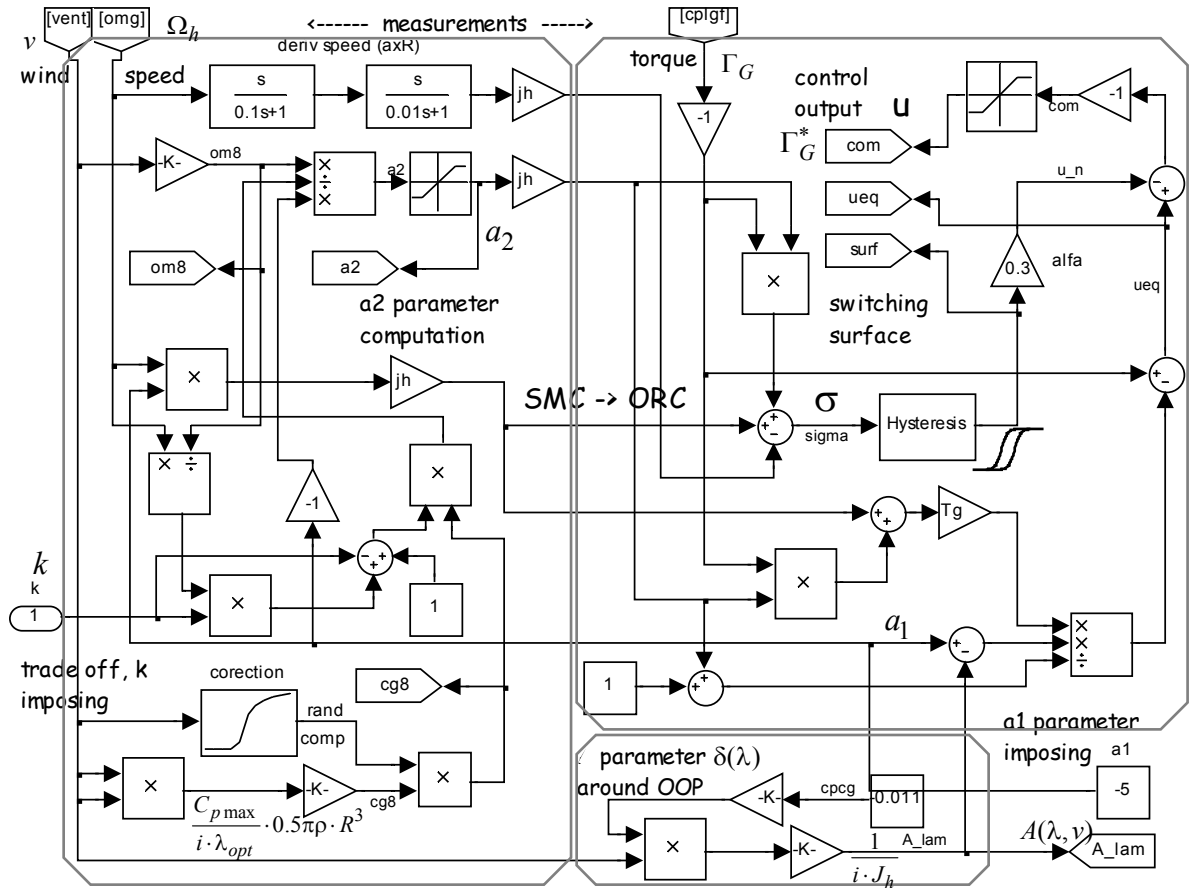


Fig. A.8 Simulink implementation of the sliding mode control law – real-time simulations

Figure A.8 shows the differences brought to the control law in order to perform real-time experiments on the wind turbine simulator exposed in chapter 3 and in appendix C, according to the remarks made in §5.4.1.

Remarks:

Experiments/simulations have been conducted using the following:

- WECS parameters from appendices A and C,
- value of parameter $A(\lambda, v)_{\text{OOP}}$ of -0.011 (after calculi),
- hysteresis width $\Delta\sigma = 0.2$ and the u_N amplitude domain: $0.1 \div 1$,
- the imposed sliding mode dynamic is $T_{sm} = 0.2$ s, therefore $a_1 = -5$,
- HSS rotational speed gradient has been estimated using the transfer function $\frac{s}{(0.1s + 1) \cdot (0.01s + 1)}$, such

to alleviating the noise produced by the speed transducer (encoder),

- k coefficient, imposing the sliding surface position versus the ORC, therefore the OP excursion around these characteristics, has a domain of $0.15 \div 15$. Outside this domain, smaller values have proven totally inefficient, the regime of the generator is chaotic, even motoring regimes are possible. On the other hand, larger values have induced significant supplementary stress in the electromechanical subsystem, EMS.

More simulation results and comments concerning the sliding mode structure presented in chapter 5 and the wind turbine simulator used for experimentations can be found in [MUNT 05c].

Appendix F

SPECIFICATIONS OF THE STEADY-STATE OPTIMISATION FROM CHAPTER 7 (LFL)

These specifications concern mainly section §7.2 of this work, more specific the WECS low frequency loop (LFL) design. However, some of the presented elements apply also for chapter 8. The control purpose is to zeroing the difference $\bar{\lambda} - \lambda_{opt}$, so the LFL controller is called TSC – tip speed controller.

LFL using PI control

The associated Simulink structure is given in figure A.9 and has the following main parameters:

- 4th order Butterworth low-pass filter, 0.1Hz cut-off frequency, band stop attenuation $a = 80$ dB ;
- stationary wind speed generated according to figure 2.9;
- PI controller structure: antiwindup Ziegler-Nichols tuned: $H(s) = \left(10 + \frac{50}{s}\right)$, control output limitation at

–40 Nm.

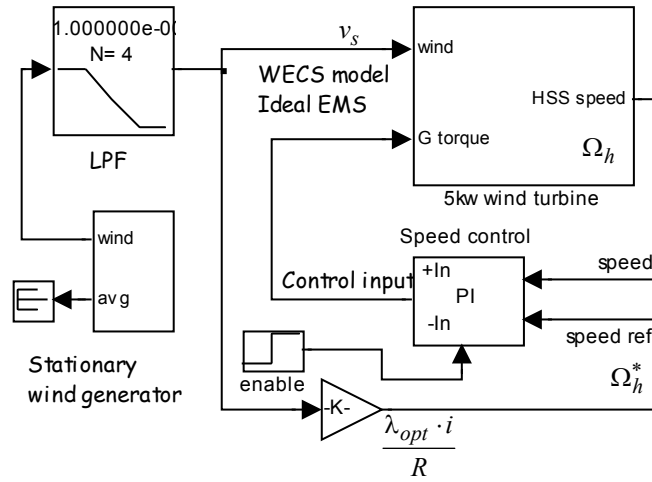


Fig. A.9 Simulink implementation for LFL/PI

Ziegler-Nichols procedure for PI control tuning implies to zeroing the integral action $K_I = 0$ in open loop condition, then raising the proportional action K_P , until one obtains self-oscillations; using the oscillations' period, T_0 , and the critical gain, K_C , one obtains the PI controller coefficients as: $K_P = 0.6K_C$, $T_I = T_0/2$ and $K_I = 1/T_0$.

LFL using on-off control

The general control structure, implemented in Simulink, is to be seen in figure A.10. The LPF parameters are the same as in the previous case and a non stationary wind speed has been used, generated according to figure 2.7 (second approach in §2.2.1). The on-off TSC parameters (figure A.11) are:

- S&H element has $T_e = 0.01$ s, implying a parameter $T_1 = 0.0054$ s used in oscillations analysis;
- amplitude of the alternate component u_N is $\beta = 3$ Nm ;
- aerodynamic WECS parameters (appendix A) imply a factor $C \approx 0.25$ (multiplying the wind speed squared);
- time constant of the averaging filter used for the modified control law is 5 s, its gain is 20.

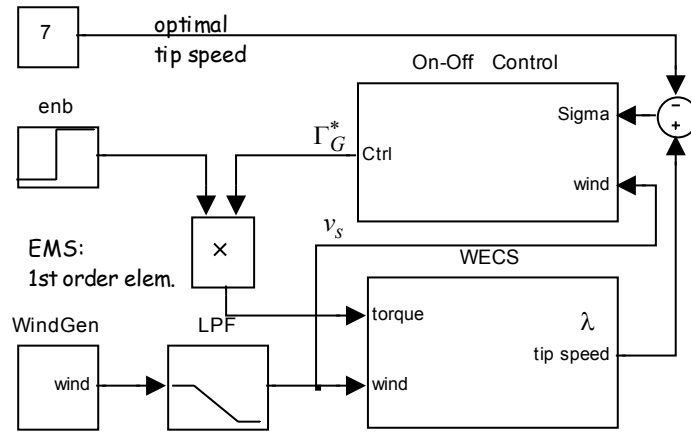


Fig. A.10 Simulink implementation for the on-off TSC based LFL

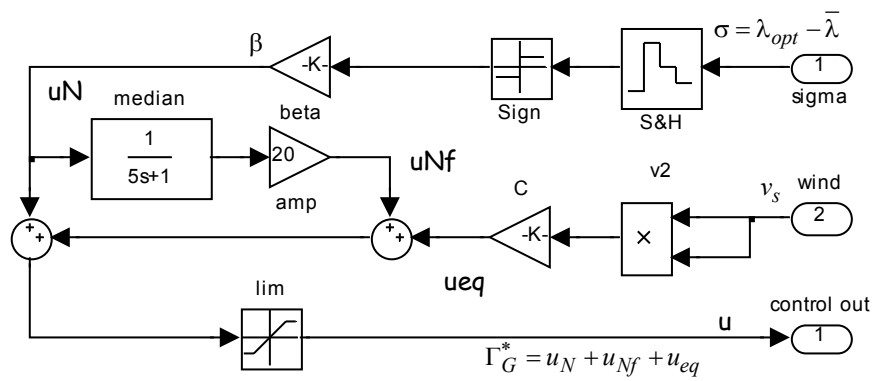


Fig. A.11 On-off TSC in the LFL

Appendix G

SPECIFICATIONS CONCERNING THE 2LFSP METHOD APPLIED TO RIGID DRIVE TRAIN WECSs

Off-line simulations

The linearized model parameters (relation (7.10)) have been computed using the following Matlab code for an operating point in the middle of the control domain, $\bar{v} = 7$ [m/s] ($\gamma = -1.06$) [MATL 00]:

```
%initializations
eta=1.25; Lt=150; R=2.5; jt=3; lambda_opt=7;
cg=[-4.54e-7 1.3027e-5 -6.5416e-5 -9.7477e-4 0.0081 -0.0013 0.0061];
cp=[cg 0];
for i=1:length(cg),
    cpd(i)=cg(i)*(length(cg)-i+1);
end;
gamma=polyval(cpd,lambda_opt)*lambda_opt/polyval(cp,lambda_opt)-1;

% Obtaining the position on the CRO:
wmax=60; wquant=0.05; w=0:wquant:wmax;
for ind=1:length(w)
% relative speed
u=w(ind)*R/vs;
% torque coefficient
cc=polyval(cg,u);
c(ind)=0.5*pi*1.25*vs*vs*(R^3)*cc;
p(ind)=c(ind)*w(ind);
end;

vbar
% maximal power at the given speed vbar
[pmx,poz]=max(p); pmx
% rotational speed associated to the maximal power (OOP)
mgs=w(poz)
% wind torque associated to the maximal power (OOP)
cpls=c(poz), JT=jt*omgs/cpls, Tw=Lt/vs
```

System matrices are:

```
A =
      0      1.0000
-0.0496 -1.1798

B =
-1.0654
 1.1331
```

The code used for computing the LQG controller parameters is:

```
A=[0 1;gamma/Tw gamma/JT-1/Tw];
B=[-1/JT; -gamma/JT];
Calf=[2/(2-gamma) -1/(2-gamma)]*sqrt(pdr); %pdr is the trade off parameter
D=[0];
Q=Calf'*Calf;
R=[1];
N=[0; 0];

[K,S,E] = LQR(A,B,Q,R,N);
K1=K(1), K2=K(2)
maty=A-B*K;
```

Remarks:

- Simulations have used a stationary wind sequence, obtained according to the method exposed in §2.2.2 (two shape filters applied over two noise sources);

- WECS from appendix A has been integrated;
- filtering blocks have been used for splitting the involved wind and rotational speed components for the two loops; these blocks perform as follows:

- LFL: 4th order Butterworth low-pass filter (LPF), 0.1Hz cut-off frequency, band stop attenuation $a = 80$ dB, outputs the low frequency wind speed component, $v_s(t)$;
- HFL: from total wind speed one subtracts the LPF output and normalizes the result with respect to this latter, obtaining the high frequency wind speed component, $\overline{\Delta v}(t)$;
- LFL has an antiwindup Ziegler-Nichols tuned PI TSC with transfer function $H(s) = -\left(10 + \frac{50}{s}\right)$ and output limitation at -40 Nm;
- HFL: LQG controller parameters are off-line computed for different weighting coefficients; their values must be changed at very large time intervals (e.g., hourly), consequently to changes in wind behaviour or user requirements.

Synthetic results are given in the following table.

α / parameters	K_1	K_2	$\text{eig}(\mathbf{A} - \mathbf{B} \cdot \mathbf{K})$
$\alpha = 0.1$	-0.0858	-0.0327	-0.0494, -1.1848
$\alpha = 1$	-0.5321	-0.1055	-0.0706, -1.5565
$\alpha = 10$	-2.0184	0.2761	-3.5546, -0.0884
$\alpha = 100$	-6.5229	2.3621	-10.7139, -0.0917

Table A.2 Closed loop parameters

More simulation results can be found in [MUNT 04b].

Real-time experiments

Implementations of different structures have been realized using Matlab/SimulinkTM package. Real Time Interface Toolbox has been used for translating the block diagrams and for uploading the resulted code into DS1103 system. Supervision of the controlled WECS has been performed using ControlDesk[®] software.

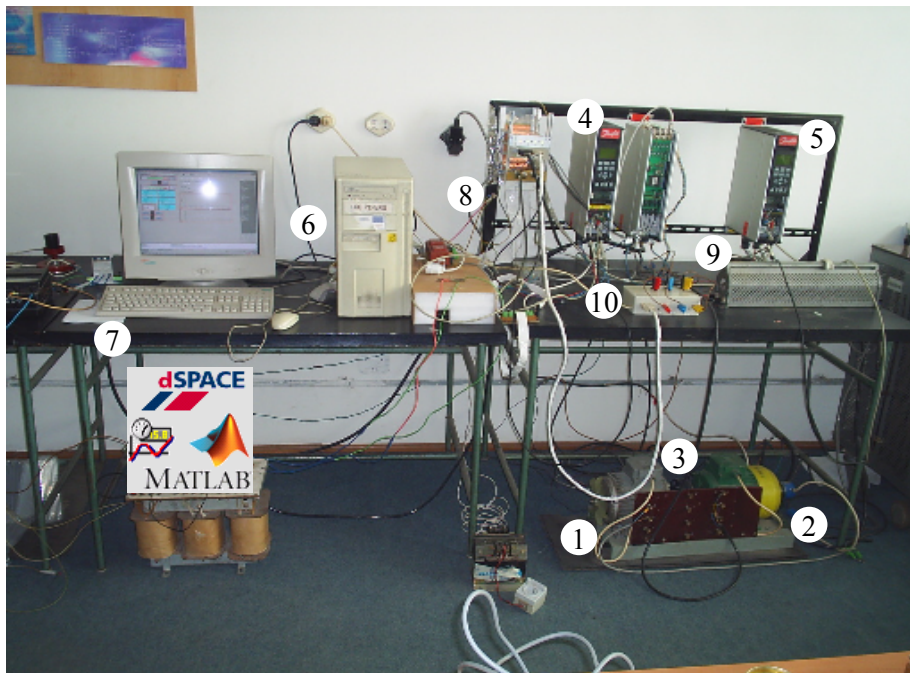


Fig. A.12 Picture of the variable speed WECS experimental test rig used for real-time experiments in chapter 7

Figure A.12 presents a photo of the experimental rig containing a 1:4.66 HIL WECS simulator used for real-time validations in the seventh chapter. It contains the following elements:

1. Squirrel cage induction motor from RTPS (SCIM);
2. Squirrel cage induction generator (SCIG);
3. SCIM-SCIG coupling;
4. Power electronics for driving SCIM;
5. Power electronics for driving SCIG;
6. Personal computer (PC) implementing user interfaces;
7. Simulink & ControlDeskTM interfaces on PC;
8. DSP DS1005 (dSPACE) implementing RTPS, WECS and SCIG control;
9. Brake resistor;
10. Current and voltage sensors.

Figure A.13 presents the Simulink implementation of the control structure used for 2LFSP real-time experiments. On the top of figure A.13 one can see the subsystem associated to the RTSS of the wind turbine (see §3.4.3). On the left/bottom the optimal two loop control structure is visible. The control output, together with afferent computations, is placed on the right/bottom.

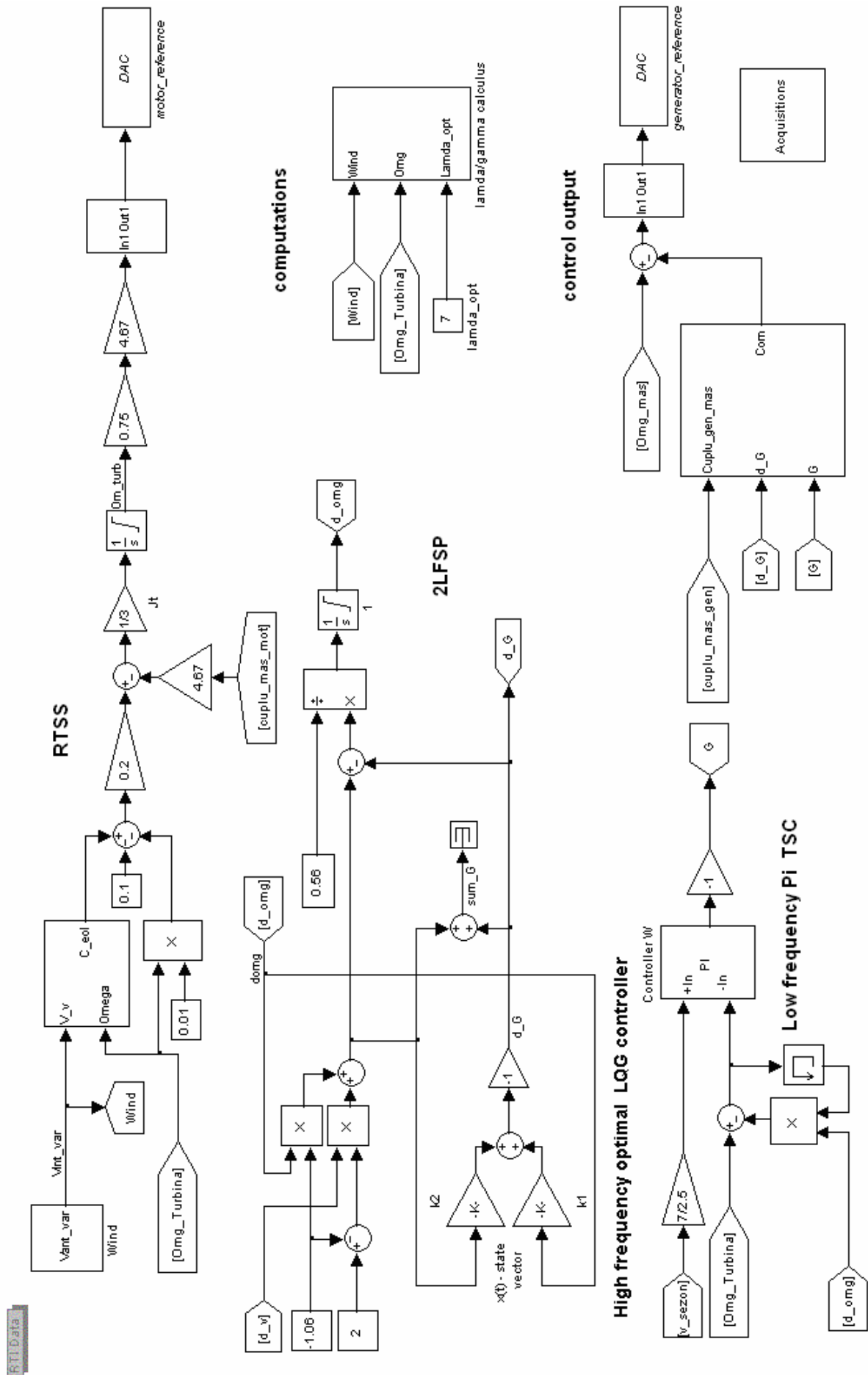


Fig. A.13 Simulation block diagram used for 2LFSP real-time simulation

Appendix H

SPECIFICATIONS CONCERNING THE 2LFSP METHOD APPLIED TO FLEXIBLE DRIVE TRAIN WECSs

Flexible drive train parameters:

- multiplication ratio: $i = 6$;
- average efficiency: $\eta = 1$;
- stiffness: $K_S = 75 \text{ Nm/rad}$;
- damping: $B_S = 0.5 \text{ kgm}^2/\text{s}$;
- the other WECS parameters of interest can be found in appendix A;
- flexible drive train scheme in figure A.14.

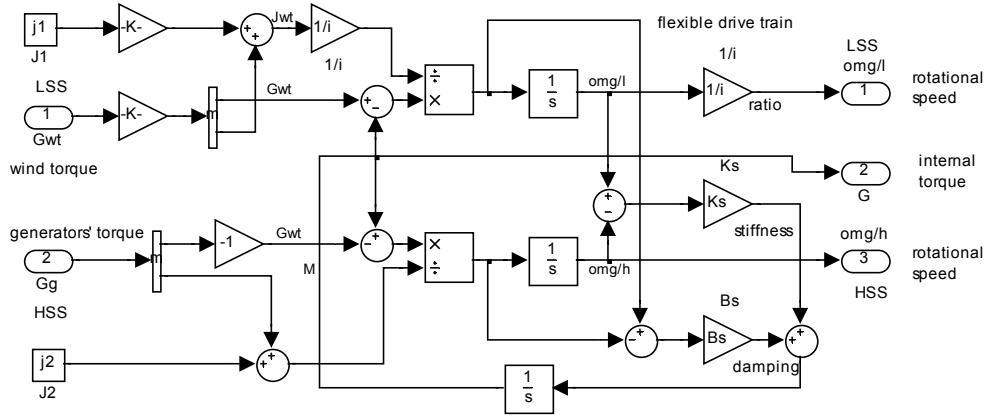


Fig. A.14 Simulink implementation of flexible drive train

High frequency modelling for flexible drive train WECS

Following the assumption from figure 8.2, the two parts of the high-speed shaft, axB and axC, are turning at different speeds, $i \cdot \Omega_l$ and Ω_h respectively; also, the energy accumulations in the elastic coupling yield a new state variable, the internal torque, Γ . If we follow the same idea used in §7.1.2, of embedding the simplified turbulence wind speed model (figure 2.11), a fourth order model is expected to obtain.

The DT model given by relation (8.1) – also referred in literature to as two mass WECS model – can be expressed in normalized variations around the steady-state operating point as follows:

$$(A.1) \quad \begin{cases} \dot{\Delta\Omega_l} = \frac{1}{J_{wt}} \cdot \Delta\Gamma_{wt} - \frac{i}{J_{wt}} \cdot \Delta\Gamma \cdot \frac{1}{\Omega_l} \\ \dot{\Delta\Omega_h} = \frac{1}{J_g} \cdot \Delta\Gamma - \frac{1}{J_g} \cdot \Delta\Gamma_G \cdot \frac{1}{\Omega_h} \\ \dot{\Delta\Gamma} = K_s i \cdot \Delta\Omega_l - K_s \cdot \Delta\Omega_h + \frac{B_s i}{J_{wt}} \cdot \Delta\Gamma_{wt} - B_s \left(\frac{1}{J_B} + \frac{1}{J_G} \right) \cdot \Delta\Gamma + \frac{B_s}{J_g} \cdot \Delta\Gamma_G \cdot \frac{1}{\Gamma} \end{cases},$$

where J_{wt} and J_g have been introduced in §2.3.3 and J_B has been given in §8.1. One can note:

$$(A.2) \quad J_T = \frac{\overline{\Omega_l}}{\Gamma_{wt}} \cdot i^2 \cdot J_B = \frac{\overline{\Omega_l}}{\Gamma_{wt}} \cdot J_{wt}, \quad J_G = \frac{\overline{\Omega_l}}{\Gamma_{wt}} \cdot i^2 \cdot J_g, \quad K_A = K_s \cdot i^2 \cdot \frac{\overline{\Omega_l}}{\Gamma_{wt}}$$

Terms J_T , J_G and K_A depend on the static operating point of the turbines' rotor (or LSS) ($\overline{\Omega_l}$, $\overline{\Gamma_{wt}}$).

Introducing the (linearized) turbulence model in normalized variations, $\dot{\overline{\Delta v}}(t) = -1/T_w \cdot \overline{\Delta v}(t) + 1/T_w \cdot e(t)$, one obtains:

$$(A.3) \quad \begin{cases} \dot{\overline{\Delta \Omega_l}} = \frac{1}{J_T} \cdot \overline{\Delta \Gamma_{wt}} - \frac{1}{J_T} \cdot \overline{\Delta \Gamma} \\ \dot{\overline{\Delta \Omega_h}} = \frac{1}{J_G} \cdot \overline{\Delta \Gamma} - \frac{1}{J_G} \cdot \overline{\Delta \Gamma_G} \\ \dot{\overline{\Delta \Gamma}} = K_A \cdot \overline{\Delta \Omega_l} - K_A \cdot \overline{\Delta \Omega_h} + \frac{B_S}{J_B} \cdot \overline{\Delta \Gamma_{wt}} - B_S \left(\frac{1}{J_B} + \frac{1}{J_g} \right) \cdot \overline{\Delta \Gamma} + \frac{B_S}{J_g} \cdot \overline{\Delta \Gamma_G} \\ \dot{\overline{\Delta v}} = -\frac{1}{T_w} \cdot \overline{\Delta v} + \frac{1}{T_w} \cdot e(t) \end{cases}$$

These relations, coupled with linearized torque characteristic:

$$(A.4) \quad \dot{\overline{\Delta \Gamma_{wt}}}(t) = \gamma \cdot \dot{\overline{\Delta \Omega_l}}(t) + (2 - \gamma) \cdot \dot{\overline{\Delta v}}(t)$$

completely describe the model of the flexible DT WECS in the general modelling assumptions frame. The obtained model is variant, depending on the turbine's operating point, ($\overline{\Omega_l}$, $\overline{\Gamma_{wt}}$).

Lets the state vector be chosen as $\left[\begin{matrix} \dot{\overline{\Delta \Omega_l}} & \dot{\overline{\Delta \Omega_h}} & \dot{\overline{\Delta \Gamma}} & \dot{\overline{\Delta \Gamma_{wt}}} \end{matrix} \right]^T$ and the generator's torque normalized

variation, $\overline{\Delta \Gamma_G}(t)$, be the control input. Relation (2.21) yields (supposing that $\gamma \neq 2$):

$$(A.5) \quad \overline{\Delta v}(t) = \frac{1}{(2 - \gamma)} \cdot \overline{\Delta \Gamma_{wt}}(t) - \frac{\gamma}{(2 - \gamma)} \cdot \overline{\Delta \Omega_l}(t)$$

One can replace $\overline{\Delta v}$ in equation (A.4), obtaining a relation giving the wind torque variations dynamic:

$$(A.6) \quad \dot{\overline{\Delta \Gamma_{wt}}} = \frac{\gamma}{T_w} \cdot \overline{\Delta \Omega_l} - \frac{\gamma}{J_T} \cdot \overline{\Delta \Gamma} + \left(\frac{\gamma}{J_T} - \frac{1}{T_w} \right) \cdot \overline{\Delta \Gamma_{wt}} + \frac{(2 - \gamma)}{T_w} \cdot e(t)$$

By coupling equations (A.3) and (A.6) one obtains the matrix state equation:

$$(A.7) \quad \begin{bmatrix} \dot{\overline{\Delta \Omega_l}} \\ \dot{\overline{\Delta \Omega_h}} \\ \dot{\overline{\Delta \Gamma}} \\ \dot{\overline{\Delta \Gamma_{wt}}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{-1}{J_T} & \frac{1}{J_T} \\ 0 & 0 & \frac{1}{J_G} & 0 \\ K_A & -K_A & -B_S \left(\frac{1}{J_B} + \frac{1}{J_g} \right) & \frac{B_S}{J_B} \\ \frac{\gamma}{T_w} & 0 & \frac{-\gamma}{J_T} & \frac{\gamma}{J_T} - \frac{1}{T_w} \end{bmatrix} \cdot \begin{bmatrix} \overline{\Delta \Omega_l} \\ \overline{\Delta \Omega_h} \\ \overline{\Delta \Gamma} \\ \overline{\Delta \Gamma_{wt}} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{-1}{J_G} \\ \frac{B_S}{J_g} \\ 0 \end{bmatrix} \cdot \overline{\Delta \Gamma_G} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{2 - \gamma}{T_w} \end{bmatrix} \cdot e(t)$$

The output variable is the normalized variation of the tip speed ratio, expressed as function of $\overline{\Delta \Omega_l}$ and $\overline{\Delta \Gamma_{wt}}$ variables (relation (7.11) from §7.1.2):

$$(A.8) \quad \overline{\Delta \lambda}(t) = \frac{2}{(2 - \gamma)} \cdot \overline{\Delta \Omega_l}(t) - \frac{1}{(2 - \gamma)} \cdot \overline{\Delta \Gamma_{wt}}(t)$$

and so, the matrix form of the output equation is:

$$(A.9) \quad z(t) = \underbrace{\begin{bmatrix} \frac{2}{(2-\gamma)} & 0 & 0 & -\frac{1}{(2-\gamma)} \end{bmatrix}}_C \cdot \underbrace{\begin{bmatrix} \overline{\Delta\Omega_l(t)} \\ \overline{\Delta\Omega_h(t)} \\ \overline{\Delta\Gamma(t)} \\ \overline{\Delta\Gamma_{wt}(t)} \end{bmatrix}}_{\underline{x}(t)}$$

Finally, by coupling equations (A.7) and (A.9), one obtains the complete model used for describing the high frequency behaviour of the flexible drive train WECS:

$$(A.10) \quad \begin{cases} \dot{\mathbf{x}}(t) = \mathbf{A} \cdot \mathbf{x}(t) + \mathbf{B} \cdot u(t) + \mathbf{L} \cdot e(t), \\ z(t) = \mathbf{C} \cdot \mathbf{x}(t) \end{cases}$$

where the involved matrices are (see also relation (8.3)):

$$(A.11) \quad \begin{cases} \mathbf{A} = \begin{bmatrix} 0 & 0 & -1/J_T & 1/J_T \\ 0 & 0 & 1/J_G & 0 \\ K_A & -K_A & -B_S(1/J_B + 1/J_g) & B_S/J_B \\ \gamma/T_w & 0 & -\gamma/J_T & \gamma/J_T - 1/T_w \end{bmatrix} \\ \mathbf{B} = [0 \quad -1/J_G \quad B_S/J_g \quad 0]^T \\ \mathbf{L} = [0 \quad 0 \quad 0 \quad (2-\gamma)/T_w]^T \\ \mathbf{C} = [2/(2-\gamma) \quad 0 \quad 0 \quad -1/(2-\gamma)] \end{cases}$$

State observer design

Observer's structure is given in figure A.15.

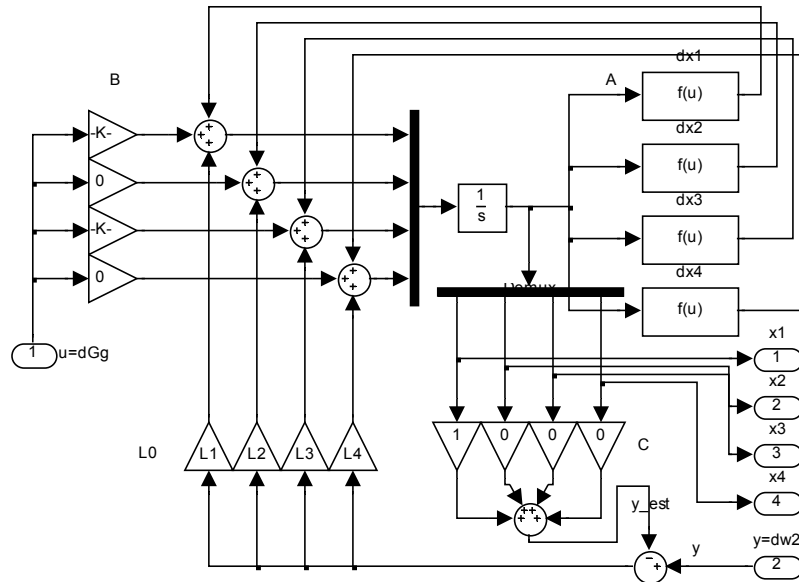


Fig. A.15 Observer's Simulink implementation

The Matlab code for off-line computation of observer's parameters is given below:

```
A=[0 0 1/JG 0; 0 0 -1/JT 1/JT; -KA KA -Bs*(1/JB+1/Jg) Bs/JB; 0 gam/Tw -gam/JT gam/JT-1/Tw];
B=[-1/JG; 0; Bs/Jg; 0]; C=[1 0 0 0]; D=[0];
[m,n]=size(A); poli=eig(A); pc=poly(A);
poli_est=[15*poli(1:3)' 100*poli(4)];
```

```

coef=poly(poli_est);
Lo=(coef(2:n+1)-pc(2:n+1))';
Co=[1 0 0 0];
Ao=[-pc(2:n+1)' [eye(n-1); zeros(1,n-1)]];
omx=obsv(Ao, Co);
omz=obsv(A, C);
P=inv(omz)*omx;
A_est=A-P*Lo*C; C_est=C;
xxl=P*Lo;
Lo1=xxl(1); Lo2=xxl(2); Lo3=xxl(3); Lo4=xxl(4);

```

HF system parameters for different steady-state (optimal) operating points:

parameters / v_s [m/s]	5	7	9
HF model parameters	$\overline{\Omega}_l$ [rad/s] = 13.8500 $\overline{\Gamma}_{wt}$ [Nm] = 52.7526 $P_{wt\ max}$ [W] = 730.6241 $\overline{\gamma}$ = -1.0636 T_w [s] = 30 J_T [s] = 0.7876 J_B [s] = 0.0833 J_G [s] = 0.4726 K_A = 708.8744	$\overline{\Omega}_l$ [rad/s] = 19.4000 $\overline{\Gamma}_{wt}$ [Nm] = 103.3423 $P_{wt\ max}$ [W] = 2.0048e+03 $\overline{\gamma}$ = -1.0636 T_w [s] = 21.4286 J_T [s] = 0.5632 J_B [s] = 0.0833 J_G [s] = 0.3379 K_A = 506.8592	$\overline{\Omega}_l$ [rad/s] = 24.9500 $\overline{\Gamma}_{wt}$ [Nm] = 170.7825 $P_{wt\ max}$ [W] = 4.2610e+03 $\overline{\gamma}$ = -1.0636 T_w [s] = 16.6667 J_T [s] = 0.4383 J_B [s] = 0.0833 J_G [s] = 0.2630 K_A = 394.4491
estimator coefficients	L_1 = 259.5377 L_2 = 9.5145e+003 L_3 = 2.5541e+005 L_4 = 4.9441e+004	L_1 = 273.7256 L_2 = 1.3148e+004 L_3 = 1.8354e+005 L_4 = 6.9408e+004	L_1 = 287.9135 L_2 = 1.6652e+004 L_3 = 1.4358e+005 L_4 = 8.9516e+004

Table A.3 Parameters of the high frequency WECS dynamics

Control structure specifications

Matlab code for off-line computation of controller parameters:

```

A=[0 0 -1/JT 1/JT; 0 0 1/JG 0; KA -KA -Bs*(1/JB+1/Jg) Bs/JB; gam/Tw 0 -gam/JT
gam/JT-1/Tw];
B=[0; -1/JG; Bs/Jg; 0]; C=[2/(2-gam) 0 0 -1/(2-gam)]; D=[0];
Calf=C*sqrt(pdr);
R=[1];

M=[0 0 0 1];
Q=Calf'*Calf+M'*M;
N=M';
[K,S,E] = LQR(A,B,Q,R,N);
K1=K(1), K2=K(2), K3=K(3), K4=K(4)

```

LFL:

- filters on wind speed and rotational speed have the same characteristics: 4th order Butterworth low-pass filter (LPF), 0.1 Hz cut-off frequency, band stop attenuation $a = 80$ dB;

- PI controller: anti-windup Ziegler-Nichols tuned: $H(s) = -\left(10 + \frac{50}{s}\right)$, output limitation at -40 Nm.

HFL:

- filters on wind speed and rotational speed have the same characteristics: high-pass filter (HPF) uses v_s

obtained from the HFL, with turbulence being obtained as $\overline{\Delta v} = \frac{v - v_s}{v_s}$;

- LQG controller parameters are off-line computed for different weighting coefficients; their values must be changed at very large time intervals (e.g., hourly), consequently to changes in wind behaviour or user requirements;

• LQG controller parameters for two stationary wind speeds (6 m/s and 9m/s) and for five weighting coefficients are listed in the tables below:

$\mathbf{K}/\alpha$ at 6 m/s	0.5	1	5	10	50
K_1	-0.0972	-0.1832	-0.6496	-0.9903	-2.0760
K_2	-0.0478	-0.0935	-0.4068	-0.7224	-2.3495
K_3	1.5635e-004	3.2132e-004	0.0019	0.0041	0.0261
K_4	0.9711	0.9494	0.9067	0.9689	1.7557

Table A.4 LQG controller parameters for $v_s = 6$ m/s

$\mathbf{K}/\alpha$ at 9 m/s	0.5	1	5	10	50
K_1	-0.0948	-0.1784	-0.6275	-0.9502	-1.9726
K_2	-0.0503	-0.0984	-0.4289	-0.7625	-2.4531
K_3	3.5547e-004	7.3191e-004	0.0043	0.0095	0.0597
K_4	0.9709	0.9490	0.9042	0.9635	1.7219

Table A.5 LQG controller parameters for $v_s = 9$ m/s

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Contributions to the optimal control of wind energy conversion systems

ABSTRACT

Consistent with the sustained effort of imposing the renewable energy sources in the future's energy landscape, this doctoral dissertation focuses on approaching the wind energy conversion systems (WECS) from a **global dynamic optimization** point of view. Its central idea is coherent with the final scope of ensuring the most suitable service operation in terms of **energetic efficiency, reliability, cost-effectiveness and grid integration compliance**. This involves an extensive use of advanced control methods, the most promising of which have constituted the starting point of the original contributions reported here.

The content of the doctoral dissertation is divided in eight chapters as follows.

In the first chapter a general view on the wind energy conversion and on WECS evolution in the current political and economical context of the market energy is presented; some of the very basic concepts about the wind turbines structures and operating principles and some general objectives concerning their control have also been outlined. The scope of the work is stated and the approached type of systems is fixed: *variable speed fixed pitch horizontal axis asynchronous generator based WECS*.

The second chapter presents the state of the art in

modelling and optimal control of the studied type of WECS in the partial load region and specifies more accurately and more technically the scope of the thesis. Some methodological and practical elements used for a variable speed WECS test rig construction, using hardware-in-the-loop simulation technique, are described in the third chapter. The fourth and fifth chapters present nonlinear robust control approaches used for harvesting the maximum power available in the wind when disposing of poor information about the system, namely the maximum power point tracking and the sliding mode control.

A novel optimal control structure derived from the frequency separation principle and consisting in two loops for separately processing the wind speed components is introduced in the sixth chapter; it needs rich information about the system and constitutes a better alternative to previously developed LQ control. Its applications for variable speed WECS having rigid and flexible drive train are presented in the seventh and the eighth chapter respectively.

The final chapter, the ninth, concludes the work by listing conclusions, contributions and future developments.

The eight accompanying appendices, from A to H, contain technical details about the approaches developed in each of the first eight chapters.

KEYWORDS: wind energy conversion systems, optimal control, integral performance indices, sliding mode control, Maximum Power Point Tracking, hardware-in-the-loop

REZUMAT

Fiind consistentă cu efortul susținut de a impune sursele de energie regenerabilă în peisajul energetic al viitorului, această teză se focalizează pe abordarea sistemelor de conversie a energiei eoliene (SCEE) din perspectiva unei **optimizări dinamice globale**. Ideea centrală este coerentă cu scopul final de a asigura cele mai bune condiții de exploatare în termeni de **eficiență energetică, fiabilitate, cost redus și respectare a cerințelor integrării în rețea**. Aceasta implică utilizarea pe scară largă a metodelor avansate de automatiză, dintre care cele mai promițătoare au constituit punctele de plecare ale contribuțiilor originale raportate aici.

Conținutul tezei se împarte în opt capitole după cum urmează.

În primul capitol se prezintă o vedere generală asupra procesului de conversie eoliană și a evoluției SCEE în contextul politico-economic actual al pieței energiei; sunt de asemenea detaliate câteva concepte de bază privind structura și principiile operării turbinelor eoliene, precum și obiectivele generale ale conducerii lor automate. Se formulează obiectivul demersului și se fixează tipul de sistem care va fi studiat: *SCEE de viteză variabilă, cu unghi de calare fix, bazat pe generator asincron*.

Al doilea capitol prezintă stadiul actual în modelarea și conducerea optimă a tipului fixat de SCEE în regiunea de sarcină parțială și specifică mai precis din

punct de vedere tehnic scopul tezei. În al treilea capitol sunt descrise câteva elemente metodologice și practice utile construirii pe baza conceptului de simulare *hardware-in-the-loop* a unui stand experimental dedicat SCEE de viteză variabilă. Al patrulea și al cincilea capitol prezintă abordări de conducere neliniară robustă, vizând captarea maximului de energie disponibilă în vânt atunci când informația despre sistem este săracă, și anume urmărirea maximului de putere (*Maximum Power Point Tracking* – MPPT) și conducerea în regim alunecător.

Capitolul al șaselea este dedicat introducerii unei noi structuri de conducere optimă a SCEE, derivată din principiul separării în frecvență și constând în două bucle pentru procesarea separată a celor două componente ale vitezei vântului, ca o alternativă mai eficientă la abordările de optimizare liniară pătratică (LQ) anterioare; în acest caz, informația disponibilă este mai bogată. Aplicarea acestei structuri la SCEE de viteză variabilă cu transmisie mecanică rigidă și flexibilă este prezentată în al șaptelea și respectiv al optulea capitol.

Ultimul capitol, al nouălea, conchide lucrarea prin enumerarea concluziilor, contribuțiilor și a direcțiilor de dezvoltare ulterioară.

Cele opt anexe, de la A la H, conțin detalii tehnice referitoare la abordările dezvoltate în fiecare din primele opt capitole ale lucrării.

CUVINTE CHEIE: sisteme de conversie a energiei eoliene, conducere optimă, indici integrali de performanță, conducere în regim alunecător, *Maximum Power Point Tracking*, *hardware-in-the-loop*