SUPERVISORY CONTROL OF GRID CONNECTED WIND POWER SYSTEMS TO GUARANTEE SAFE OPERATION

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Abstract: This article proposes a supervisor synthesis for a two level hierarchical control structure of a grid connected wind power system to ensure its safe and optimal operation. The global hybrid dynamics may roughly be captured into a hybrid automaton. The optimization tasks, specific to different operating regimes, are performed by the low level continuous controllers. A supervisor placed on a higher level must guarantee the safe transition from an operating regime to another, triggered by some discrete events. The interest is focused on the design problem on the higher level: the discrete event modelling and the supervisor design in the supervisory control framework.

Keywords: safety, supervisory control, discrete event dynamic systems, automata theory, hierarchical control.

1. INTRODUCTION

Wind power systems (WPS) technology is a rapidly growing domain, the installed generation capacity was increasing averagely with 32% every year from 1998 to 2003. The modern technology has allowed the production costs reduction with more than 80% in the 1980s, so that the wind energy represents now a stable segment of the electrical energy market, supported by a mature technology (Burton, *et al.*, 2001; Bathurst, *et al.*, 2002). The wind energy conversion problem has a unitary-systemic character, imposing a global control approach, to ensure the system's functionality and viability, as well as the provided energy quality. These requirements result from the exploitation experience and grid integration. The global WPSs' performance (economical efficiency and integration capacity into energy grids) is presently aimed at, as briefly discussed next.

Modelling of the exogenous signal, namely the *wind*, as a 3D non stationary random process, result in spectral models, allowing to identify two components in the wind speed: the *steady-state*, low frequency one, and the *turbulent*, high frequency one (Van der Hoven model – Nichita, *et al.*, 2002). The steady-state speed determines the available energy of a wind site. Dedicated spectral models (i.e. von Karman and Kaimal – Nichita, *et al.*, 2002) exist for the turbulent component, the one inducing fatigue loads and rapidly cyclic aerodynamic and possibly damaging phenomena.

Modelling of the WPSs in different regimes has as purpose the simulation analysis of their dynamic behaviour (Wilkie, *et al.*, 1990), aiming further at solving the associated control problems (Novak and Ekelund, 1994; Welfonder, *et al.*, 1997). The static operation of a wind turbine, depending on the average (steady state) wind speed, exhibits four zones (figure 1): I) for wind speeds smaller than the starting threshold (v_S), the wind energy is not sufficient to move on the turbine (the provided power is zero); II) in the *partial load* zone – speeds larger than the start one, but smaller than the nominal one (v_n) – the extracted power is proportional to the wind speed cubed (this zone is also called *parabolic*); III) in the *full load* zone – speeds larger than the nominal one (v_n) and smaller than the safe functioning limit (v_M) – the harvested power is limited at its nominal value (P_n); IV) for wind speeds larger than the maximal operation speed the provided power becomes zero.

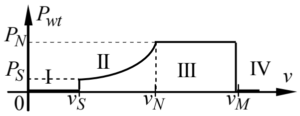

Fig. 1. Power captured by a wind turbine versus average wind speed.

Zones from figure 1 roughly correspond to the *operating regimes* (operational states) of a wind turbine. For the productive regimes – the partial and the full load zones – sufficiently good performing models are available. The normal operating regime is practically superposed on the *partial load zone*, for which multiple *control objectives* may be defined (Leithead, *et al.*, 1991), in general cast into continuous optimal control problems, aiming at maximizing the conversion. The aerodynamic efficiency is expressed by the power coefficient, C_p, depending on the tip speed ratio, λ (the ratio between the peripheral blade speed and the wind speed). In figure 2a) a typical C_p curve for a horizontal axis wind turbine (HAWT – Wilkie, *et al.*, 1990) is shown, presenting a maximum for a well determined value of the tip speed, λ_{opt}. The power characteristics (figure 2b)) have a maximum for each value of the wind speed; all these maxima form the so called *optimal regime characteristic* (ORC, figure 2b)).

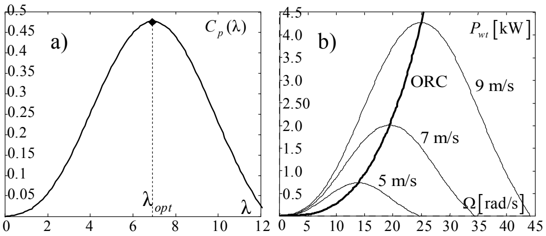

Fig. 2. a) Power coefficient versus the tip speed ratio; b) Power characteristics.

Curves from figure 2, only valuable in the partial load zone, suggest a harvested wind energy maximisation problem formulation: the turbine must ideally operate on the ORC (at the optimal value of the tip speed), irrespectively of the wind speed. To this, one can add the variable fatigue load reduction, to ensure a certain reliability level of the mechanical parts.

Various approaches exist for solving one or many objectives from those above: Maximum Power Point Tracking (MPPT – Datta and Ranganathan, 2003; Wang, 2004), suitable especially under uncertainties, including on the static characteristic; use of the intelligent control techniques (Abo-Khalil, *et al.*, 2004; Zhang, *et al.*, 2004), when there are uncertainties about the static model; sliding mode techniques (De Battista, *et al.*, 2000), when the uncertainties refer to the dynamic model; gain scheduling techniques (Ekelund, 1997; Bianchi, *et al.*, 2005), for adapting the control law depending on the average wind speed; frequency robust control techniques (Rocha and Filho, 2003). Control laws based upon some mixed (energy-reliability) optimisation criteria (Novak and Ekelund, 1994; Ekelund, 1997) can be designed to comply with the fatigue minimisation. *Supervisory control of WPSs* is related to their global, "high-level" operation. Transitions between different operating zones, turbine's functioning in regimes distinct from the normal ones, as well as its behaviour under extreme dynamical loads, are ensured by a supervisor (Burton, *et al.*, 2001). Concerning the design control problem at this level, the literature is however extremely poor in publications. Kana, *et al.* (2001) and Young, *et al.* (2003) present points of view closer to a global control approach. Studies on supervisory control of the WPSs seem to be still at the beginning. The system approached in this paper is an average power (dozens of kW) variable speed fixed pitch asynchronous generator based HAWT, which will be supervised in order to force a set of safe operation specifications to be met. The model used will be a hybrid automaton, whose discrete states are issued by an as exhaustive as possible enumeration of the operating regimes, each of which is equipped with a continuous controller for specific optimization tasks. So, the global control structure has a hybrid dynamic on two decision levels. In this paper the interest is given to the higher level design problem.

The rest of the paper is organised as follows. The second section explains the necessity of a hierarchical control for the approached WPSs. A discrete event model is built in the third section, to be used in the fifth section for designing a supervisor to guarantee the safe operation, using the general framework briefed in the fourth section. The last section is dedicated to conclusion and future work.

2. CONTROLLED GRID CONNECTED WPS AS A HYBRID DYNAMIC SYSTEM

To reduce the wind turbines operation costs requires an automated and remote controlled operation. An appropriate control strategy allows improving the system's reliability, yielding both maintenance costs' reduction and harvested power growth. The reliability can be improved at two levels of action: 1) at *low* level, by controlling the captured power at variable speed, and 2) at a *higher* level, by ensuring the safe operation, regardless from the wind conditions (by rejecting mainly the extreme wind turbulences). The above cited works show that the continuous dynamics of the partial load zone (figure 1) can be controlled for conversion optimization. In the other zones the control subsystems are less complex. Because of the wind's randomness, the WPS may often change the operating point from an operational state to another, potentially affecting the proper operation. One may naturally think of a supervisor to assist the system's *safe* transition among different operational states, equipped with continuous controllers. This one must be placed on a higher level to "see" the system being driven by certain discrete events, which trigger the transitions