A Peak Power Tracker for Low-power Permanent-magnet-synchronous-generator-based Wind Energy Conversion Systems

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Abstract: - This paper presents the results of experimental investigation of a low-power wind energy conversion system (WECS), based on a permanent-magnet synchronous generator (PMSG) connected directly to the turbine. A test rig was built in order to carry out the experiments; its detailed description is also provided. The experimental results show that the performance of a low-power multi-polar-PMSG-based WECS is strongly determined by the generator’s behaviour. Two optimal regimes characteristics (ORC) are defined in this paper: the first one represents the mechanical power versus the rotational speed (ORC_m) and the second one is the electrical power delivered to a load versus the rotational speed (ORC_e). An optimal control loop aiming to maximize the delivered electrical power is designed, namely its reference is computed based on the ORC_e. In this way, the global efficiency of the energy conversion is maximized. The effectiveness of the proposed optimal control loop is illustrated by experimental results.

Key-Words: - wind system, optimal control, permanent-magnet synchronous generator, hardware-in-the-loop simulation, maximum power point tracking.

1 Introduction
Nowadays, multi-polar permanent-magnet synchronous generators (PMSG) represent an important solution to the design of wind energy conversion systems (WECS), offering some advantages versus the asynchronous generators, e.g., a simpler mechanical structure. The maximum power point tracking control of such systems is analyzed in [1], [2], [3]. WECS optimization with an energy criterion is dealt with especially for high-power WECS. In the case of low-power WECS, PMSG are widely used because they allow the generator be coupled directly to the wind turbine shaft. The optimal control of these systems is treated in two distinct situations. The first is when the WECS delivers power to a battery, by means of a charge regulator [4], [5], [6]. This regulator imposes operation constraints which do not allow rigorous tracking of the optimal regimes characteristic (ORC). In the second situation the WECS operates on the ORC, but in [7], [8], [9], [10] only numerical simulation results are reported.

Detailed analysis of PMSG, including experiments, has led to the necessity of taking into account the features of this kind of generator in its various applications. In [11] one can find experimental results illustrating the behaviour of a medium-power PMSG ($S_n = 125$ kVA). For lower power (e.g., $S_n = 2.5$ kVA in [12]), the issue of considering the influence of PMSG characteristics on the autonomous WECS becomes even more important.

In this paper are presented experimental results concerning the properties of a low-power PMSG-based WECS with direct coupling between the generator and the turbine shaft. Two optimal regimes characteristics (ORC) are defined: the first one represents the mechanical power versus the rotational speed (ORC_m) and the second one is the electrical power delivered to a load versus the rotational speed (ORC_e). For the low-power PMSG-based wind energy systems, the ORC_e is not obtained from ORC_m by a simple sub unitary coefficient (PMSG’s efficiency). Instead of maximizing the aerodynamic efficiency, as in most of the works in the literature, a new optimal regimes characteristic is defined, which passes through points of ORC_e. Experimental results are discussed, that suggest the effectiveness of the approach.

The rest of the paper is organized as follows. The next section describes the experimental rig used to carry out the real-time tests. The third section presents the WECS steady-state characteristics, whereas the fourth section discusses the main results.
of maximum power point tracking control. The last section is dedicated to conclusions.

2 Experimental Rig
The experimental rig that was built is composed of two subsystems:
- an electromechanical wind turbine simulator;
- a load adaptation circuit in order to ensure operation on the ORC.

The hardware/software support of the whole rig is ensured by the dSPACE board DS 1103.

The electromechanical wind turbine simulator is built based upon the hardware-in-the-loop simulation concept [13]. This simulator provides a "wind shaft" where the steady-state and dynamic characteristics of a given turbine can be replicated. The simulator is composed of:
- a closed-loop servo-system, consisting of a Danfoss VLT 5005 Flux inverter, which controls an asynchronous motor with 960 rot/min rated speed and 3 kW rated power. This means that wind turbines of 3 kW maximum rated power can be simulated;
- a real-time software simulator (RTSS), implementing the turbine dynamic model and the wind speed model [14], [15], [13].

The servo-system can be controlled by the RTSS in two ways:
- by means of a speed control loop: the RTSS imposes a speed reference to the servo-system and this one responds by sending back the estimated electromagnetic torque of the asynchronous motor as "response variable";
- by means of a torque control loop, when the servo-system receives a torque reference and responds by sending back to the RTS the shaft rotational speed measured.

The results presented in the following have been obtained by controlling the speed of the simulator. This solution has been chosen as it is less affected by noise.

The wind turbine shaft is directly coupled to a Southwest Windpower® Whisper WHI 200 PMSG, having 1 kW rated power.

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Fig. 1. Block diagram of the experimental rig

The most important wind turbine characteristic implemented in the RTSS is that of the torque coefficient, $C_T(\lambda)$, where $\lambda$ is the tip speed ratio of the considered wind turbine. Three situations can be encountered when choosing this characteristic:
a – $C_T(\lambda)$ is considered known (given);
b – a generic $C_T(\lambda)$ curve is adopted, which is parameterised such that the optimal tip speed, $\lambda_{opt}$, to be adjusted within narrow limits ($\lambda_{opt} = 6..8$), without modifying the general form of the curve;

c – $C_T(\lambda)$ is obtained starting from the constructive dimensions of the simulated wind turbine. In this case, the constructive features of blades (chord variation along the blade, pitch angle variation, number of blades, etc.) are established in a preliminary stage, then a software program is used to generate the $C_T(\lambda)$ curve based upon the blade element method [16].

An important function of the RTSS is the real-time wind speed generation. The subsystem achieving this function can ensure three distinct regimes:

a – constant speed regime, adjustable in real time through the ControlDesk® interface accompanying the dSPACE board;

b – turbulent wind regime, where the average wind speed is adjustable in real time through the ControlDesk® interface. The wind speed turbulence component depends of the current average wind speed and is obtained with a second-order rational shaping filter by imposing a desired value of the turbulence intensity, $I_t$:

$$I_t = \frac{\sigma_t}{\bar{v}},$$

where $\sigma_t$ is the standard deviation of the turbulence component and $\bar{v}$ is the average wind speed. The turbulence intensity is established upon von Karman’s or Kaimal’s expressions of the spectral density function by using computation relations according to some usual standards: IEC 1400-1, Danish standard DS 472, etc. These relations have as parameters the ground surface roughness and the height from the ground [17], [18]. The transfer function of the rational shaping filter using von Karman’s model of turbulence is:

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

where $m_1 = 0.4$, $m_2 = 0.25$ and turbulence parameters $K_F$ and $T_F$ are computed in function of the average wind speed [19], [18].

The load adaptation circuit, coupled at the PMSG output, is composed of a rectifier and a chopper embedded in the power optimal control loop (Fig.1). The sampling time of the real-time application is 0.2 ms.

3 Experimental steady-state characteristics of WECS

The steady-state characteristics of WECS have been determined when the PMSG delivers power to the load resistance through the rectifier (switches $K_1$ and $K_2$ turned on in Fig.1). In Fig.2 we can see the following curves:

a – mechanical power versus rotational speed, $\Omega$, and wind speed, $v$ – this curve is denoted by $P_m(\Omega, v)$ and drawn with dashed line;

b – electrical power, denoted by $P_e(\Omega, v)$, drawn with solid line.

The circles in graphs from Fig.2 denote the points obtained experimentally. One can note sensible differences between the two curve families.
As expected, values of electrical power, \( P_e \), are below the corresponding values of mechanical power, \( P_m \), because of the low efficiency of low-power multi-polar PMSG. But an expected result is that the \( P_e(\Omega, v) \) curves are drifted to the right in relation to the \( P_m(\Omega, v) \) curves. Therefore, there are in fact two optimal regimes characteristics that can be defined when the wind speed varies, namely:
- ORC\(_m\), i.e., the locus of maximum mechanical power points;
- ORC\(_e\), i.e., the locus of points of maximum electrical power delivered to the load.

When formulating the WECS optimal control problem the interest is obviously focused on the ORC\(_e\). This problem requires a control solution that is modified in relation to that employed for high-power WECS.

4 Results concerning the Maximum Power Point Tracking Control

In the case of high-power WECS, the optimization control loop is achieved by tracking an optimal power reference, which in turn depends on the maximum mechanical power, that is [13]:

\[
P^*_{opt} = K \cdot \Omega^3,
\]

with:

\[
K = 0.5 \cdot C_p(\lambda_{opt}) \cdot \rho \pi R^2 / \lambda_{opt}^3,
\]

where \( C_p(\lambda) \) is the power coefficient of the turbine and \( \lambda_{opt} \) is the optimal tip speed ratio. It is considered that the mechanical to electrical energy conversion efficiency is close to 1, whereas the theoretical efficiency of the wind to mechanical energy conversion is given by the Betz limit, \( C_{P_{max}} = 0.59 \) [17].

Unlike the high-power WECS (including those with PMSG), the low-power multi-polar PMSG-based WECS have quite reduced mechanical to electrical conversion efficiency. Hence, the ORC\(_e\) differs from the ORC\(_m\) in a non-negligible degree.

In order to obtain the reference of the electrical power loop, the ORC\(_e\) given in Fig.2 has been parameterised by polynomial regression. Thus, the optimal electrical power that has been imposed to the tracking loop is:

\[
P^*_{e_{opt}} = 0.0081356 \Omega^3 - 0.555 \Omega^2 + 18.6 \Omega - 179.1
\]

The experimental results illustrating the optimal operation of WECS can be seen in the ControlDesk\textsuperscript{®} captures shown in Fig.3 and 4. In Fig.3 one can see how the optimized WECS evolves in a pseudo-steady-state regime ensured by a slow ramp variation of the wind speed. One can see that, once the starting regime was finished, the optimal tip speed slightly differs from its optimal value that corresponds to the wind to mechanical energy conversion (in this case, \( \lambda_{opt} = 7 \)).

Fig.3. Response of the optimized WECS to a ramp change in the wind speed
Among the variables displayed in Fig. 3 one can see the error of the optimal power tracking loop. In the \( C_T - \Omega \) plane the wind torque – rotational speed curve is obtained for the initial value of the wind speed, \( v = 4 \) m/s, during the starting regime, then the ORC\(_e\) is obtained as the wind speed increases slowly with constant gradient.

Fig.4 illustrates the operation of the optimized WECS as the wind speed varies stochastically. One can see how the optimal operating point evolves around the ORC\(_e\). Moreover, the dynamical errors of tracking the power reference (5) are small versus the reference value.

5 Conclusion
This paper has approached the problem of maximizing the global efficiency of a low-power multi-polar-PMSG-based wind energy conversion system. Two optimal regimes characteristics (ORC) can be defined: the first one represents the mechanical power versus the rotational speed (ORC\(_m\)) and the second one is the electrical power delivered to a load versus the rotational speed (ORC\(_e\)). An optimal control solution is proposed as tracking the ORC\(_e\) by means of a power loop using the measured rotational speed. The reference of this loop is computed by modelling the ORC\(_e\) as a polynomial curve. The proposed solution is validated by experimental results on a dedicated experimental rig.

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