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Marine turbine system directly connected to electrical grid: Experimental implementations using a nonlinear and robust control

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ABSTRACT

This paper deals with real-time implementations of a nonlinear and robust control applied on a marine turbine system. For the experimental validation which uses real data from Raz de Sein site (Brittany, France), the DC motor drives a wound rotor synchronous generator. A computer pilots this DC motor in order to stand in for the marine turbine behavior. Experimental results show the control successful of both outputs (terminal voltage and speed) making possible direct connection to electrical grid. In addition, we verify the robustness properties of the complete system under hard mechanical and electrical perturbations. Finally, a comparative study highlight the proposed control performances compared with conventional AVR-PSS which is one of the most widely adopted controller in industry for electrical grid stabilization.

1. Introduction

Among all renewable energies, marine currents became really attractive recently due to their worldwide energetic potential which is estimated at 100 GW (Ben Elghali, 2008). Marine turbines use part of marine currents in order to extract mechanical energy to produce electrical energy (via synchronous generator) and supplement conventional energy sources. Moreover marine currents are regular, predictable and vary slowly. This behavior is a significant advantage for marine turbines compared to other renewable energy production systems (Dansoko et al., 2014). But their connection to electrical grid adds complexity to regulators design. Indeed, in electricity production, terminal voltage and frequency regulation are required to establish a direct connection. In addition, coupled renewable energy systems must be robust against electrical and mechanical perturbations. In this context we need to develop a robust control taking into account nonlinear specifications of the synchronous generator and simultaneous regulation of terminal voltage and frequency. It is obvious that nonlinear controls operate effectively in wide range while linear controls are efficient only around an equilibrium point. The conservation of nonlinearity properties will improve the transient regimes stability and increase robustness properties. The system will remain stable regardless system perturbations and grid faults without loss of equilibrium point.

Despite the significant number of industrial and academic researches carried out recently on marine turbines systems, most of these investigations are limited to numerical simulations (Ben Elghali, 2008, 2010, 2012; Dansoko et al., 2013, 2014; Ben Elghali et al., 2007; Toumi et al., 2014; Myers and Bahaj, 2005; Bahaj and Myers, 2003). Most of the time, studies can show successful numerical simulations while their experimental validation can produce unsatisfactory results because of simplifications considered during system modeling. Moreover, it may be impossible to achieve the experimental validation of some theoretical models due to unmeasurable variables of model. Very recent works (Toumi et al., 2017; Guangxing et al., 2017) are also limited to numerical simulations. Authors of (Toumi et al., 2017) use a classical controller PI (Proportional Integral) in order to study marine turbine system behavior under faulty rectifier conditions. In paper (Guangxing et al., 2017), the authors study the marine turbine behavior under sudden load variation. In addition, they design turbine generator interface on Visual C++ which communicates with SUPERSIMS platform in order to train mariners and teach schoolchild. Authors of (Yin et al., 2014, 2015a, 2015b, 2015c, 2016) have obtained satisfactory results on pitch angle control and control strategy development for wind turbines. These controls do not regulate terminal voltage and frequency simultaneously. In this condition, it is impossible to envisage a direct connection to electrical grid.

Only two authors were interested in experimental validations of

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marine turbine system so far (Andreica et al., 2008; Ben Elghali et al., 2011). In paper (Andreica et al., 2008), the authors implement a marine turbine system using Permanent Magnet Synchronous Generator (PMSG). In this context, it is impossible to regulate terminal voltage and frequency simultaneously. To achieve the connection to electrical grid (not direct), authors use a controlled converter with two linear regulators PI. These regulators are less efficient and less robust than nonlinear controller against perturbations. In paper (Ben Elghali et al., 2011) the authors also experiment a marine turbine system using PMSG which can't be directly connected to the electrical grid. Here, the authors implement a control to regulate the frequency of marine turbine system without taking into account the voltage regulation, which makes impossible the connection to electrical network. The main drawback of this system (marine turbine using PMSG) is the necessity to use an electronic power system to obtain the electrical grid connection, which increases the technical complexity and economic costs compared with direct grid connection. In marine environment, because of technical constraints (installation, waterproofness of power electronic system and its replacement in fault case), it is necessary to envisage the direct grid connection. To achieve this objective, the control development has to take into account system nonlinear specifications, thus helping to avoid the stall phenomena during severe perturbations. In addition, none of the two authors has experimented a marine turbine system in direct connection. Moreover, no robustness test is performed in order to evaluate the efficiency of the proposed models and no multivariable nonlinear controller (voltage and frequency regulation) is implemented.

In this paper, we study a marine turbine system which is directly connected to an electrical grid. Then, we implementt in real-time a Nonlinear Sliding Mode Control (NSMC) in order to avoid the stall phenomena during the robustness tests (electrical and mechanical perturbations). The choice of this control technique is due to its great robustness and its convergence rapidity. The major advantage of this control law consists in simultaneous regulation of both outputs, terminal voltage and speed, through a single input, the synchronous generator excitation. This double regulation makes possible the direct connection to grid. This nonlinear control design, inspired by the one described in (Kenné et al., 2010a) is improved by using sliding mode techniques in order to increase the robustness properties. In addition, the DC motor, which drives the synchronous generator, is controlled in order to reproduce the marine turbine behaviors. The experimental setup includes a monitor (PC) which controls all devices via a conversion board *DSP RTI 1103.*

The model of marine turbine system is described in section “Marine turbine system modeling”. The synthesis of the proposed control law is detailed in section “Control strategy description”. The results of simulation are presented in section “Simulation results” in order to highlight the robustness properties of the proposed control scheme compared with AVR-PSS. The validation of these results are illustrated in section Experimental validation”. Finally, some concluding remarks are made in section “Conclusion”.

1.1. Marine turbine system modeling

In this study, the electrical generator is driven by a three-blade marine turbine with horizontal axis. The blades profile, inspired from National Advisory Committee for Aeronautics (NACA 44) is based on BEM theory. Up to date, this profile is the best in blades design and it is given in more details in (Ben Elghali et al., 2007). The mechanical power $P_m$provided by the marine turbine is given as follows (Ben Elghali et al., 2012; Dansoko et al., 2013, 2014; Toumi et al., 2014):

$$P_m = \frac{1}{2}\rho C_p S V_t^3 \tag{1}$$

$\rho,\ S$are respectively the water density and the cross-sectional area of the marine turbine. The mechanical power is maximized by using the Maximum Power Point Tracking (MPPT) strategy. $C_p$is the coefficient of power extraction and its approximation model that we have used is represented by equation (2). The reasons of this choice are given in further details in paper (Dansoko et al., 2013, 2014).

$$C_p = a\lambda^4 - b\lambda^3 + c\lambda^2 + d\lambda + e \tag{2}$$

with$\lambda = \frac{R\omega}{V_t}$ and *a, b, c, e* real numbers such:

$$a \simeq 1.9210^{-4};\quad b \simeq 5.210^{-3};\quad c \simeq 2.4410^{-2};\quad d \simeq 5.7910^{-2};\quad e \simeq 1.3810^{-4}.$$

$R,\ \omega$ are respectively radius and rotation speed of marine turbine. $V_t$is a speed tide and the chosen model (Ben Elghali et al., 2010, 2012; Guangxing et al., 2017) is actually the most used in the study of marine turbine systems.

$$V_t = V_{nt} + \frac{C-45}{95-45}(V_{st} - V_{nt}) \tag{3}$$

$V_{st},\ V_{nt},$ are respectively the spring and neap tide current velocities of the site separated by an interval of 6 h. *C* is the tide coefficient of the site which varies between 20 and 120. Values 95 and 45 respectively represent the medium tide coefficients which correspond to spring and neap water.

In order to convert mechanical energy into electricity, synchronous generators are more advantageous than asynchronous generators in marine turbine applications (Ben Elghali et al., 2010, 2012). This synchronous generator advantage is due to their better conversion efficiency and their better operation capacity in marine environment (Ben Elghali et al., 2010, 2012). Moreover there are two types of synchronous generators: Wound Rotor Synchronous Generator (WRSG) and Permanent Magnet Synchronous Generator (PMSG). The WRSG, well-regulated, can be directly connected to electrical grid while the PMSG must inevitably use power electronic interface to ensure the grid connection (Dansoko et al., 2013, 2014). This fact is a technical and economic advantage for the use of WRSG. Indeed, it is not necessary to use electronic power interface in these conditions. For this reason, we have chosen the WRSG generator in this study. The dynamics of this generator connected to infinite bus system are presented by the following third order model (Kenné et al., 2010a, 2010b; Damm et al., 2004):

$$\begin{cases} \dot{\delta} = \omega \\ \dot{\omega} = -\dfrac{D}{H}\omega - \dfrac{\omega_s}{H}(P_e - P_m) \\ \dot{P}_e = -\dfrac{X_{ds}}{X'_{ds}T'_{d0}}\left(P_e - \left\{\dfrac{V_s}{X_{ds}}\sin\delta\left[E_f + T'_{d0}(X_d - X'_d)\dfrac{V_s}{X'_{ds}}\omega\sin\delta\right] + T'_{d0}\dfrac{X'_{ds}}{X_{ds}}P_e\omega\cot\delta\right\}\right) \end{cases} \tag{4}$$