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Fifth harmonic and sag impact on PMSG wind turbines with a balancing new strategy for capacitor voltages

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ABSTRACT

This paper deals with the computing simulation of the impact on permanent magnet synchronous generator wind turbines due to fifth harmonic content and grid voltage decrease. Power converter topologies considered in the simulations are the two-level and the three-level ones. The three-level converters are limited by unbalance voltages in the DC-link capacitors. In order to lessen this limitation, a new control strategy for the selection of the output voltage vectors is proposed. Controller strategies considered in the simulation are respectively based on proportional integral and fractional-order controllers. Finally, a comparison between the results of the simulations with the two controller strategies is presented in order to show the main advantage of the proposed strategy.

1. Introduction

Wind energy conversion (WEC) experienced a significant expansion worldwide [1–3]. Particularly, Europe made significant investments in WECs and most probably in the future will go ahead on developments. Even small European states experienced an expansion on WECs implementation, for instance, Portugal had a significant increase in installed capacity [4,5], which was the second highest share with 18% of wind power in 2010 [6]. A noteworthy day in 2010 was 31 of October with 61% of wind energy in the mixed conversion. High level of wind energy in the mixed conversion threatens the stability and power quality [7–9] in the electric grid. A simulation study is an important contribution required to take into account the behavior of WECs in order to evaluate not only grid stability, but also power quality injected into the grid [10]; anticipating in due course undesired behavior is an important security measure not to be disregarded. This paper in the following of other contributions [11–13] is a new contribution on power quality impact due to a grid voltage decrease and a fifth harmonic content.

A comparison of fixed speed wind turbine stabilization methods and guidelines for selection of a suitable technique for the stabilization of wind energy systems are reported in [14]. Nevertheless, the market share of the fixed-speed wind turbine has decreased in favor of the variable speed concept [15,16] due to the technical advantage in the variable speed for wind energy exploitation. Variable-speed wind turbines can be implemented in what regards power electronic with a partial-scale power converter, using a doubly fed induction generator [17–19], or with a full-scale power converter, using a synchronous generator. Higher costs are to be expected in the implementation with a full-scale power converter, but due to the advantage of performing a smooth grid connection over the entire speed range this implementation is a promising one. Variable-speed wind turbines can be implemented in what regards the direct-drive generators by an excited synchronous generator or by a permanent magnet synchronous generator (PMSG) [20]. Although large permanent magnets are costly, the PMSG has become a very interesting option in what regards the implementation of a variable speed wind generator [21], because of compact size, higher power density, reduced losses, high reliability and robustness [22], requiring no excitation circuit, so no additional DC supply. Moreover, a PMSG is almost maintenance free, because of the no need for slip rings usually requiring significant downtime maintenance. Also, due to the low rotational speed of synchronous generators the gearbox is not required. This is important not only due to less space need, but also for reducing the downtime failure [23,24] and because the gearbox

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Nomenclature

A_n	magnitude of the n eigenswing	ω_g	generator rotor speed
ω_n	eigenfrequency of the n eigenswing	J_g	generator moment of inertia
g_{nm}	distribution of the harmonic m in the n eigenswing	T_{dg}	generator bearing resistant torque
a_{nm}	normalized magnitude of g_{nm}	T_{ag}	airflow resistant torque in the generator
h_n	modulation of the n eigenswing	T_g	electric torque
φ_{nm}	phase of the harmonic m in the n eigenswing	i_f	equivalent rotor current
P_t	mechanical power of the wind turbine	M	mutual inductance
P_{tt}	mechanical power captured by the wind turbine without dynamic influences	p	number of pairs of poles
θ_i	pitch angle on blade $i \in \{1, 2, 3\}$	i_d, i_q	stator dq currents
ω_t	wind turbine rotor angular speed.	L_d, L_q	stator inductances
J_t	wind turbine moment of inertia	R_d, R_q	stator resistances
T_t	mechanical torque	v_d, v_q	stator voltages
T_{dt}	wind turbine bearing resistant torque	R_k	resistance of the electric grid
T_{at}	airflow resistant torque in the hub and blades	L_k	inductance of the electric grid
T_{ts}	stiffness torsional torque	v_{fk}	voltage at the filter
		v_k	voltage at the electric grid

usually requires significant maintenance. Power electronic efficiently compatibilize different electric power, plays an important role in WECs [25]. The three-level converters have emerge as a promising power converter interface [26] for WECs [27], allowing conversion in the megawatt range which is the current range for eolic turbines. However, three-level converters are limited by the following drawbacks: voltage unbalances, high component count, and increased control complexity [28]. A critical issue in multi-level converters, namely three-level converters, is related with the DC-link capacitors unbalance in the voltage, which may produce control malfunctions. A contribution in order to mitigate this critical issue is proposed for the three-level converters in this paper and considered in the simulation studies carried out in order to assess the effect on the electric current injected due to the presence of a grid voltage decrease and a fifth harmonic content. Although not imposed for WECs, the IEEE-519 imposes a total harmonic distortion (THD) not exceeding 5%, this THD is followed as a guideline for evaluation purpose of the performance achieved with the power electronic converters.

The rest of the paper is organized as follows. Section 2 presents the mechanical modeling, taking in consideration the dynamic associated with the action excited by wind on all physical structure and assuming a two-mass modeling for the rotor of the wind turbine and generator. Section 3 presents the electric modeling, considering PMSG with two converter configurations, respectively, two-level and three-level converter, and the modeling for the new balancing strategy in capacitors voltage. Section 4 presents notions about fractional calculus. Section 5 presents the controller modeling, using a classic PI and a fractional-order PI^{μ} controllers, and a new control strategy for the unbalancing in capacitors voltage. Section 6 presents two case studies using Matlab/Simulink language and respectively considering: grid ideal sinusoidal voltage or grid non-ideal voltage with decrease and fifth harmonic content. Finally, concluding notes are provided in Section 7.

2. Mechanical modeling

The wind speed is modeled by a finite sum of harmonic terms with frequencies range in 0.1–10 Hz and the mechanical power of the wind turbine is modeled taking in consideration three influences of the dynamic associated with the action excited by wind on all physical structure [29]. The mechanical power is given by:

$$P_t = P_{tt}\left[1 + \sum_{n=1}^{3} I_n(t)\right] \quad (1)$$

where

$$P_{tt} = \frac{1}{2}\rho\pi\, R^2\, u^3 c_p \quad (2)$$

The mechanical power in (1) is computed by a multiplicative term (2) given by the well-known formula for the mechanical power captured by the wind turbine without dynamic influences [11]. The influences considered are three, respectively: I_1 the asymmetry in the turbine, I_2 the vortex tower interaction and I_3 the eigenswings in the blades. Both influences are modeled by a sum given by:

$$I_n(t) = A_n\left(\sum_{m=1}^{2} a_{nm} g_{nm}(t)\right) h_n(t) \quad (3)$$

where

$$g_{nm}(t) = \sin\left(\int_0^t m\omega_n(t')dt' + \varphi_{nm}\right) \quad (4)$$

The dynamic associated with the asymmetry in the turbine is assessed considering the following data: $A_1 = 0.01$, $a_{11} = 4/5$, $a_{12} = 1/5$, $\omega_1(t) = \omega_t(t)$, $\varphi_{11} = 0$, $\varphi_{12} = \pi/2$. This influence is shown in Fig. 1

The dynamic associated with the vortex tower interaction is assessed considering the following data: $A_2 = 0.08$, $a_{21} = 1/2$, $a_{22} = 1/2$, $\omega_2(t) = 3\omega_t(t)$ $\varphi_{21} = 0$, $\varphi_{22} = \pi/2$. This influence is shown in Fig. 2.

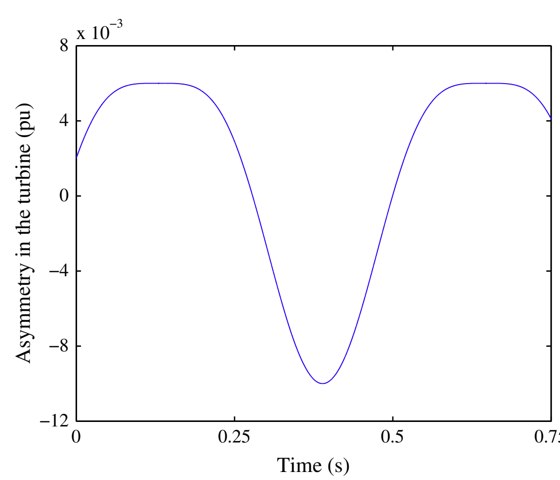

Fig. 1. Asymmetry in the turbine.