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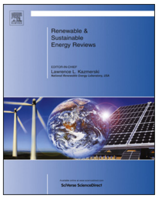

Grid-integrated permanent magnet synchronous generator based wind energy conversion systems: A technology review

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ABSTRACT

The growing trends in wind energy technology are motivating the researchers to work in this area with the aim towards the optimization of the energy extraction from the wind and the injection of the quality power into the grid. Over the last few years, wind generators based on permanent magnet synchronous machines (PMSMs) are becoming the most popular solution for the modern wind energy conversion systems (WECSs). This paper presents a concise review of the grid-integrated WECSs employing permanent magnet synchronous generators (PMSGs). It reviews the trends in converter topologies, control methodologies, and methods for maximum energy extraction in PMSG based WECSs, which have been reported in various research literatures primarily in reputed research journals and transactions during last few years. It also presents an overview to the grid interconnection issues related to output power smoothing and reactive power control in addition to fault-ride-through (FRT) and grid support capabilities of PMSG based WECSs. This review article will serve the researchers working in the area of grid-integrated PMSG based WECSs in the exploration of trends, developments and challenges in the past research works and in finding out the relevant references for their research work.

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1. Introduction

Recently, the clean energy sources such as solar, tidal and wind energy sources are gaining importance due to their less damaging environmental influences. The wind energy technology is one of the most emerging renewable energy technologies. Over the past few decades, the capacities of wind turbine (WT) units have increased from a few tens of kW power capacity to today's multi-MW level [1]. In view to the steady growth in the power level of the WTs and its increased penetration into the power grid; more advanced generators, power converter systems and control solutions have to be developed so as to make the WT units more suitable to be integrated into the power grid [2].

Any WT generator may operate either at a fixed or variable speed [3,4]. For instance, the squirrel cage induction generators (SCIGs) can be employed both in fixed-speed wind turbines (FSWTs) and in variable-speed wind turbines (VSWTs), while doubly-fed induction generators (DFIGs) and synchronous generators (SGs) usually find their applications in VSWTs [3,5]. An overview of possible wind generator systems along with their comparisons is presented in [3,6]. A fixed-speed SCIG based WECS, even though is simple, reliable and less costly; strictly suffers from the shortcomings of high mechanical stress, reactive power burden on power grid, large power fluctuations and very limited fault-ride-through (FRT) ability [7]. When compared with FSWT, the VSWT can extract maximum power from the wind at different wind speeds and therefore, reduces the mechanical stress on WT by absorbing the wind-power fluctuations [8–11]. This way, the variable-speed operation of WT yields more power than the fixed-speed operation of the same, resulting in the maximization of aerodynamic efficiency of the WT [7,10,12]. A mechanical gear box, which is generally employed in VSWT in order to match the low-speed operation of the WT with the relatively high-speed operation of the generator, not only increases the manufacturing cost and maintenance requirements but also reduces the aerodynamic efficiency of the WT [5]. The efficiency of VSWT may increase further if the mechanical gear box could be eliminated [13]. Therefore, several WT manufacturers have adopted the direct-drive PMSG concept so as to eliminate the gear box [14], and a list of such manufacturers is made available in [5]. A comparison of direct-drive and geared generator concepts for WTs is presented in [15] and a review of generator systems for direct-drive WT applications is presented in [16].

Modern VSWT systems, usually based on DFIGs with partial-scale power electronic interfaces or PMSGs with full-scale power electronics interfaces, are popular among others [7,17–23]. The DFIG based VSWT system requires a multi-stage gearbox and also needs for excitation current [23–25]. Different from the DFIG based WECSs, those based on PMSGs with full-scale power electronic interfaces are becoming more popular due to the number of advantages such as high energy density, simple control methodology, low maintenance cost, self excitation system and possibility to direct coupling to a WT with elimination of the gearbox; except initial installation costs [5,8,9,14,15,26–50]. Furthermore, other features such as complete decoupling from the grid, full controllability of the system for maximum wind power extraction, high performance, high efficiency, high precision, high reliability, wide operating range, and improved FRT capability make WECSs based on PMSGs even more attractive; though power converter losses increase [5,16,23,24,35,51–56]. The advantages and disadvantages of different VSWT generators are outlined in [5].

2. Variable speed wind turbines based on permanent magnet synchronous generators

It has been recognized that the PMSG based WECS is an important trend in the development of wind generation systems [57–59]. The PMSG allows a small WT blade diameter and, therefore, is preferred in small-scale turbine designs also [24,60]. Besides, the direct-drive PMSG concept has nowadays been adopted by many WT manufacturers [14]. A general model, that can be used to represent all types of VSWT in power system dynamics simulations, is presented in [19] to facilitate the analysis of the impact of large penetration of WTs on the behaviour of an electric power system. The modelling of WT systems based on PMSGs has widely been discussed in [17,19,22,61–65] which can be used in computer simulations and analyses.

2.1. Wind turbine and drive train

The output power of the wind turbine is expressed as

$$P_m = 0.5\rho C_p A V_\omega^3 \tag{1}$$

where P_m is the turbine output power, ρ is the air density, C_p is the power coefficient, $A(=\pi R^2)$ is the swept area, R is the radius of the turbine blades and V_ω is the wind speed.

One of the generic equations used to model C_p, which is a function of tip-speed ratio λ and pitch angle θ, can be expressed as follows

$$C_p(\lambda,\theta) = 0.73\left[\frac{151}{\lambda_i} - 0.58\theta - 0.002\theta^{2.14} - 13.2\right]\exp\left(-\frac{18.4}{\lambda_i}\right) \tag{2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1} \tag{3}$$

$$\lambda = \omega_r R / V_\omega \tag{4}$$

where ω_r is the turbine rotational speed.

Fig. 1(a) shows the C_p vs. λ curve from which it is noticeable that if the system operates at the maximum power point (MPP) of the curve irrespective of the wind speed, the power captured from the wind would be maximum. Hence, the turbine speed should be adjusted in such a way that λ corresponds to MPP. Fig. 1(b) shows the non-linear power-speed curves of the WT. Each power–speed curve is characterized by a unique turbine speed corresponding to the MPP for that wind speed.

In a number of research studies, the drive-train model in WTs has been considered as one-mass mechanical subsystem. However, in order to correctly illustrate the dynamic impact of WTs on the grid, it is essential to represent the drive-train model as two-mass mechanical subsystem [66]. The dynamic performance of the PMSG based WECSs has been investigated in [12,67] considering two-mass drive-train model. Ref. [12] presents a dynamic model of a gearless VSWT with power electronic interface for simulation study so as to evaluate the control scheme, output performance and impacts of WT on power system at planning or designing stage.