PERFORMANCE ANALYSIS OF GRID-CONNECTED WIND TURBINES

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The development of wind turbines (WT) and the capacities of wind power plants have increased significantly in the last years. Wind power plants (WPP) must provide the power quality required by new regulations and the reliability of the power system that is interconnected to. It is very important to analyze and understand the sources of disturbances that affect the power quality. In this paper is analyzed the performance of three different popular wind generators that are connected to the power system. Based on this analysis was made a comparison for the three wind turbines studied that are: the squirrel-cage induction generator (SCIG), the doubly-fed induction generator (DFIG), and the permanent-magnet synchronous generator (PMSG). The fixed speed system is more simple and reliable, but severely limits the energy production of a wind turbine and power quality. In case of variable speed systems, comparisons shows that generator of similar rating can significantly enhance energy capture as well as power quality. Moreover, performance of their output power leveling is validated by a new method numerically as maximum energy function and leveling function. The performances of these wind turbines and their characteristics are analysed in steady-state. Wind turbines systems are modeled in Matlab/Simulink environment. Simulation results matched well with the theoretical turbines operation.

Keywords Doubly-fed induction generator; Permanent-magnet synchronous generator; Power quality; Squirrel-cage induction generator; Wind turbines.

1. Introduction

As a results of the high increase in the environmental worry, the installed capacity of grid-connected renewable energy sources are concerned up to date that minimized the impact of conventional electricity generation on the environment. For example, the average annual growth rate of wind turbine installation is around 30% during last decade [1, 2, 3]. This leads to large rapid changes in non-programmable sources can cause a significant reduction in reliability, power quality and

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economy. In refs. [4, 5], a planning the connection or disconnection of renewable energy based on forecasting is presented in order to increase in reliability of renewable energy.

The question that needs to be raised is how new renewable sources systems will affect the whole grid. A part of the answer must be obtained from the impact that they have on the power quality. The main impact of the wind turbines on the grid, concerning power quality that is affected by the sources of disturbances [6] is related to voltage dips and fluctuations, harmonic content.

There are currently three main types of generator systems for large wind turbines exist as shown in Figure 1 [7], [8]. The first type, shown in Figure 1a is a fixed-speed wind turbine system using a gearbox and a standard SCIG, directly connected to the grid. The second type, shown in Figure 1b is a variable speed wind turbine system with a gearbox and a DFIG, where the power electronic converter feeding the rotor winding has a power rating of $\sim 30\%$ of generator capacity, the stator winding of the DFIG is directly connected to the grid. The third type, shown in Figure 1c is also a variable speed wind turbine, but it is a gearbox with a smaller low speed PMSG and a full-scale power electronic converter are used [9, 10]. Although such technologies are well known, there is no consensus on what is the best choice under a wide technical perspective. In Figure 2, it can be seen that since year 1995 until 2009 the PMSG and DFIG are the mostly used types of generators [11].

Various types of power system dynamics simulations exist and the approach depends on the aspect of power system dynamic behavior investigated. A new type known as electromagnetically transient simulations, is studied in reference [12]. This research allow the investigation of the impact of high wind power penetrations on electrical power systems, models of wind turbine generating systems are incorporated in software packages in which the fundamental frequency simulation approach is applied. This paper's results is quite similar to our results, but the results in this paper is converged in fundamental frequency which can not show harmonic distortion related to power quality of variable-speed WT. Moreover, the authors did not also demonstrate the differences between doubly-fed and direct-drive machines as well as including pitch angle control in constant speed generator.

This article introduces the configurations of the above mentioned three general types of wind turbines and presents their mathematical models. Computer simulations of their response related to power quality as well as the efficiency during steady-state are researched. A simulation method numerically is applied to validate wind turbine generators. Finally they are compared and analysed from technical point of view.

2. Fundamentals about three most important WT

2.1. SCIG

The first concept consists of a rotor coupled to a SCIG through a gearbox. The gearbox is required as the optimal rotor and generator speed ranges are different. The generator is directly coupled to the grid. Therefore, rotor speed variations

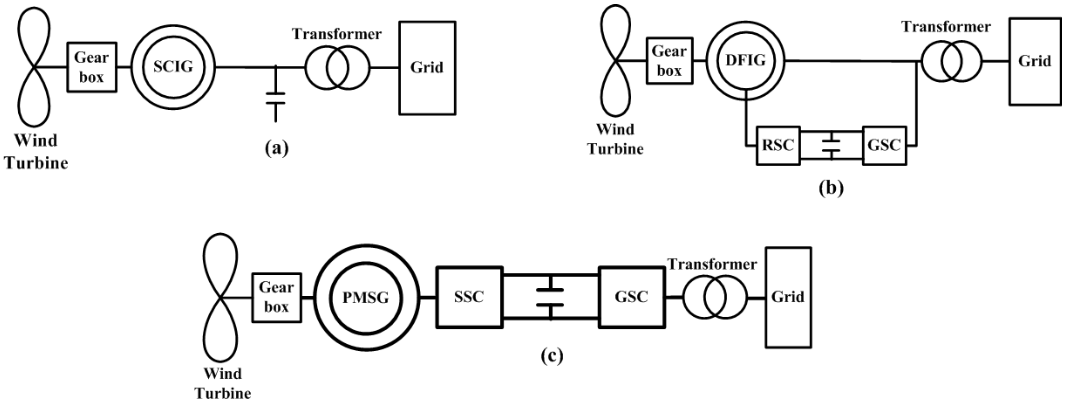

Fig. 1. General structures of three different types of wind turbines.

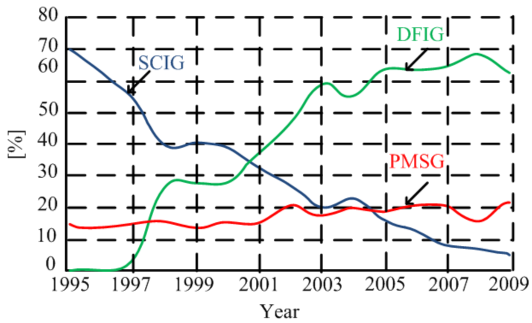

Fig. 2. Annual development of wind generator types.

are very small as the only speed variations that can occur are changes in the rotor slip. Due to speed variations are very small, the turbine is normally considered to operate at constant speed. A SCIG consumes reactive power and behaves similarly to induction motors during a system contingency [13] and [14]. Therefore, the capacitors are added to generate the induction generator magnetizing current, thus improving the power factor of the system. The power extracted from the wind needs to be limited, because otherwise the generator could be overloaded or the pullout torque could be exceeded, leading to rotor speed instability. In this notion, this is often done by using pitch angle [15]. The system is described in Figure 1a.

2.2. DFIG

The second concept is a wind turbine with DFIG in which a back-to-back voltage source converter feeds the rotor winding (Figure 1b). A gearbox is necessary to couple the rotor to the generator like the previous case, because of the difference in the rotor and generator speed ranges. The stator winding of the DFIG is coupled to the grid, the rotor winding is coupled to rotor-side converter (RSC). Meanwhile the other side of back-to-back voltage source converter namely grid-side converter

(GSC) that feeds the rotor winding is coupled to the grid. Moreover, a DC-link are added to decoupled RSC and GSC. Obviously, the converter decouples the electrical grid frequency and the mechanical rotor frequency, thus enabling variable speed operation of the wind turbine. Because of the limited capacity of the converter, the voltage control capability of a DFIG can not match that of a synchronous generator. Normally, the back-to-back converter has current control loops, the ability to control the rotor current substantially contributes to the controllable of the wind turbine. The grid-side of the converter is normally operated at unity power factor, thus not taking part in the reactive power exchange between the generator and the grid [16]. The generator and converter are prevented from being overloaded in high wind speeds by controlling the back-to-back voltage source converter such that the nominal power of generator and converter is not exceeded. To limit the rotor speed, the blades are pitched, thus reducing the mechanical power extracted from the wind and restoring the balance between mechanical power and electrical power. In this way, the rotor speed is prevented from becoming too high.

2.3. PMSG

This configuration may respond to a variable speed wind turbine with a permanent-magnet synchronous generator connected to the grid through a full-scale power converter (Figure 1c). The converter system consists of two IGBT-based back-to-back voltage source converters including stator-side converter (SSC) and grid-side converter (GSC) connected via a DC link. Due to the converter system decouples the generator from the grid, the electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged [17]. The rating of the converter system in this type corresponds to the rated power of the generator plus losses. The stator-side converter controls the operation of the generator to extract maximum power from the prevailing wind velocity [18]. The grid-side converter is controlled to maintain the DC-link voltage at the reference value by exporting active power to the grid and also controls reactive power flow to the network [19].

3. The Wind Energy Conversion Systems Modelling

There are three types of machines used in wind energy conversion systems that is mentioned timely in reference [20].

3.1. Wind Modeling

The captured aerodynamic power is given by:

$$P_{wt} = \frac{1}{2}\rho\pi R^2 V^3 \tag{1}$$

where P_{wt} is the power, ρ is the air density [kg/m^3], R is the blade radius [m] and V is the wind speed [m/s]. The turbine mechanical power which a wind turbine can extract depends on the power coefficient C_p is given by:

$$P_{mec} = C_p P_{wt} = \frac{1}{2} C_p \rho \pi R^2 V^3 \tag{2}$$

3.2. Drive Train Modeling

The shaft dynamic equations are [21]:

$$T_{IN} = J_T \frac{d\omega_T}{dt} + k\Delta\vartheta + B\Delta\omega \tag{3}$$

$$k\Delta\vartheta + B\Delta\omega = J_G \frac{d\omega_G}{dt} + T_e \tag{4}$$

$$\Delta\omega = \omega_T - \omega_G \tag{5}$$

$$\Delta\vartheta = \vartheta_T - \vartheta_G \tag{6}$$

where J_T $(kg.m^2)$ is the turbine moment of inertia, J_G $(kg.m^2)$ is the generator moment of inertia, k $(kg.m^2.s^{-2})$ is the stiffness of the shaft, B $(kg.m^2.s^{-1})$ is the absorption of the shaft, T_{IN} $(N.m)$ is the input torque, T_e $(N.m)$ is the generator electromagnetic torque, ω_T, $\omega_G (rad/s)$ are the angular speed of the turbine and of the generator, respectively, and ϑ_T, ϑ_G (rad) are the angle of the turbine and of the generator, respectively. All quantities are referred to the high-speed of the gearbox.

3.3. Generator Modeling

3.3.1. *Asynchronous Generator.* Stator voltage is given by Refs. [20] and [22] :

$$v_{ds} = R_s i_{ds} + \frac{d\Psi_{ds}}{dt} + \omega_s \Psi_{qs} \tag{7}$$

$$v_{qs} = R_s i_{qs} + \frac{d\Psi_{qs}}{dt} + \omega_s \Psi_{ds} \tag{8}$$

Rotor voltage is given by:

$$v_{dr} = R_r i_{dr} + \frac{d\Psi_{dr}}{dt} - s\omega_s \Psi_{qr} \tag{9}$$

$$v_{qr} = R_r i_{qr} + \frac{d\Psi_{qr}}{dt} + s\omega_s \Psi_{dr} \tag{10}$$

Flux linkage is given by:

$$\Psi_{ds} = L_m i_{dr} - L_{sl} i_{ds} \tag{11}$$

$$\Psi_{qs} = L_m i_{qr} - L_{sl} i_{qs} \tag{12}$$

$$\Psi_{dr} = -L_m i_{ds} - L_{rl} i_{dr} \tag{13}$$

$$\Psi_{qr} = -L_m i_{qs} - L_{rl} i_{qr} \tag{14}$$

Electromagnetic Torque is:

$$T_{el} = \Psi_{qr} i_{dr} - \Psi_{dr} i_{qr} \tag{15}$$

where v_s, i_s and Ψ_s are stator voltage, current and flux respectively; v_r, i_r and Ψ_r are rotor voltage, current and flux respectively; ω_s is the angular velocity of the chosen frame of reference; d and q represent direct and quadrature axis components, respectively. L_m is the mutual inductance; L_{sl} and L_{rl} are the stator and rotor leakage inductance.

3.**3**.2. *Synchronous Generator.* The permanent-magnet synchronous generator can be expressed by the following equations in Refs. [20] and [22]:

$$v_{ds} = -R_s i_{ds} - L_s \frac{di_{ds}}{dt} + L_s \omega_r i_{qs} \tag{16}$$

$$v_{qs} = -R_s i_{qs} - L_s \frac{di_{qs}}{dt} - L_s \omega_r i_{ds} + \omega_r \Psi \tag{17}$$

where L_s and R_s are the generator inductance and resistance stator, respectively, ω_r is the generator rotor speed, and Ψ is the magnet flux. The electromagnetic torque is given by:

$$T_e = \frac{3}{2} p \Psi I_{qs} \tag{18}$$

where p is the number of pair poles.

3.**4**. **Converter Modeling**

3.**4**.1. *DFIG converter.* From Refs. [20] and [22], the power at the rotor side is given by:

$$P_r = v_{dr} i_{dr} + v_{qr} i_{qr} \tag{19}$$

$$Q_r = v_{qr} i_{dr} - v_{dr} i_{qr} \tag{20}$$

and the power at the stator side is given by:

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \tag{21}$$

$$Q_s = v_{qs} i_{ds} - v_{ds} i_{qs} \tag{22}$$

So the total output power is:

$$P = P_s + P_r = v_{dr} i_{dr} + v_{qr} i_{qr} + v_{ds} i_{ds} + v_{qs} i_{qs} \tag{23}$$

$$Q = Q_s + Q_r = v_{qs} i_{ds} + v_{qr} i_{dr} - v_{ds} i_{qs} - v_{dr} i_{qr} \tag{24}$$

3.**4**.2. *PMSG converter.* All the power produced by the generator is transmitted from the stator and flows through the converter is given by [20] and [22]:

$$P = \frac{3}{2} v_d i_d \tag{25}$$

$$Q = \frac{3}{2} v_d i_q \tag{26}$$

3.5. The Case Study

The system simulated is shown in Figure 3. Each type of wind turbine is connected one at a time directly to the respective 34.5 kV lines. The WT is equipped with a power transformer 0.69/34.5 kV. The 34.5 kV lines are interconnected through a power transformer 34.5/110 kV to the 110 kV transmission line in the PCC.

4. The Simulation Results

The performance of each type of wind turbines was evaluated with Matlab/simulink simulation for a wind turbine containing a 3 MW ones. From Ref. [12], a research related to the real wind speed in Figure 4a and its relative measured value in Figure 4b that was developed at RISO National Laboratory have been used to assess the performance of the wind turbines in this research. The characteristic data of the simulated asynchronous and synchronous wind generators are reported in Table. 1.

Steady-state voltage profile of the system with SCIG, DFIG or PMSG type wind turbine is shown in Figure 5. The integration of SCIG wind turbine decreases the terminal voltage due to the reactive power absorbed from the grid. DFIG and

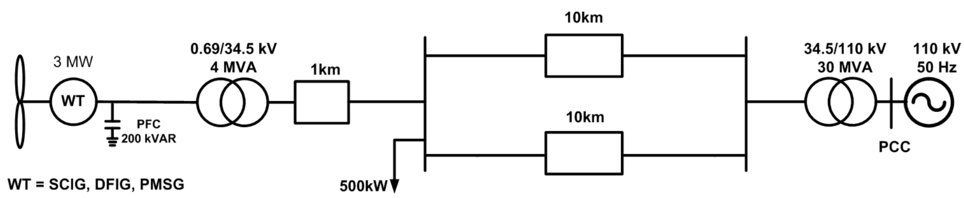

Fig. 3. Coupled each of SCIG, DFIG and PMSG based WPP with the same PCC.

Table 1

Parameters of simulated asynchronous and synchronous generator

Parameters	SCIG	DFIG	PMSG	Unit
Rated power	3	3	3	MW
Rated speed	12	12	12	m/s
Cut in wind speed	5	5	5	m/s
Cut out wind speed	20	20	20	m/s
Rated Voltage/Frequency	690/50	690/50	690/50	V/Hz
R_s/R_r	0.004/0.005	0.004/0.005	0.02/-	pu
$L_{ls}/L_{lr}/L_m$	0.092/0.099/3.952	0.092/0.099/3.952	-	pu
$X_d/X_q/X_l$	-	-	0.296/0.474/0.18	pu
Q_{pf}	200	-	-	kVAR
V_{DC}	-	1000	1000	V

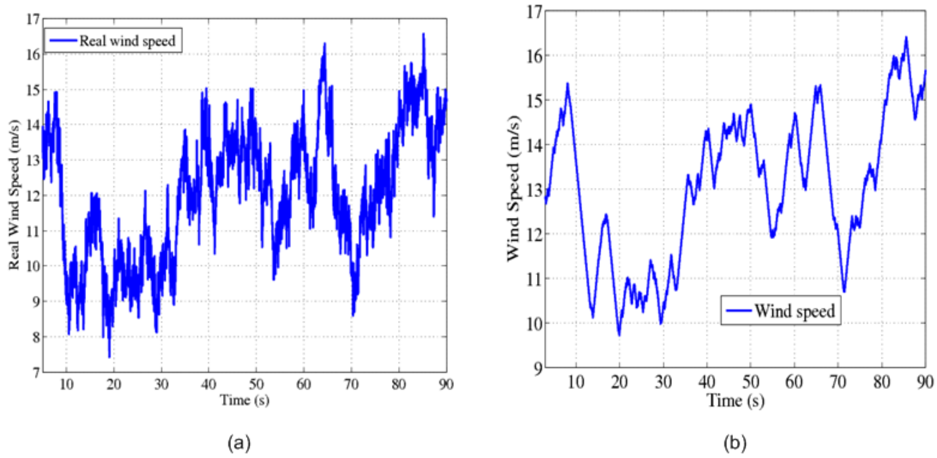

Fig. 4. Real and filtered wind speed variations.

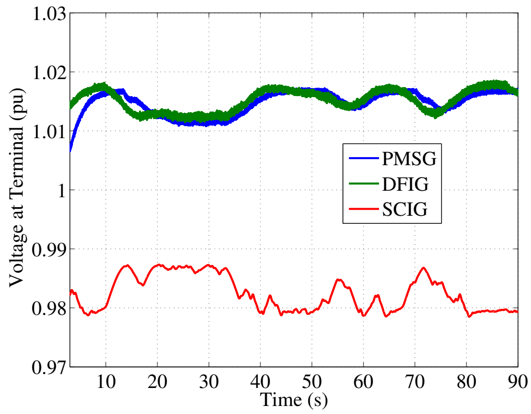

Fig. 5. The voltage at generator terminals.

PMSG operated in voltage control mode causes voltage rise (more than 1.0 pu) in terminal voltage. It is seen that voltage at terminal is well maintained with voltage control mode of DFIG and PMSG. The voltage profile is within the permissible limits ($\sim$ 6%). When the wind speed varies, the variation of the SCIG terminal voltage became larger and voltage fluctuations resulting in flicker can occur, while DFIG and PMSG connecting the the grid keep nearly smooth terminal voltage profile. When more SCIG are connected to power system, the problem due to the wind speed change will became more serious because this wind turbine could be affected the power system stability.

Changes is wind speed often result in wind turbine active and reactive power fluctuations. Figure 6a and Figure 6b, compare three kinds of wind turbines, where the output active and reactive power changes with the wind speed. Both wind turbines with DFIG and PMSG could be run at variable speed and control reactive

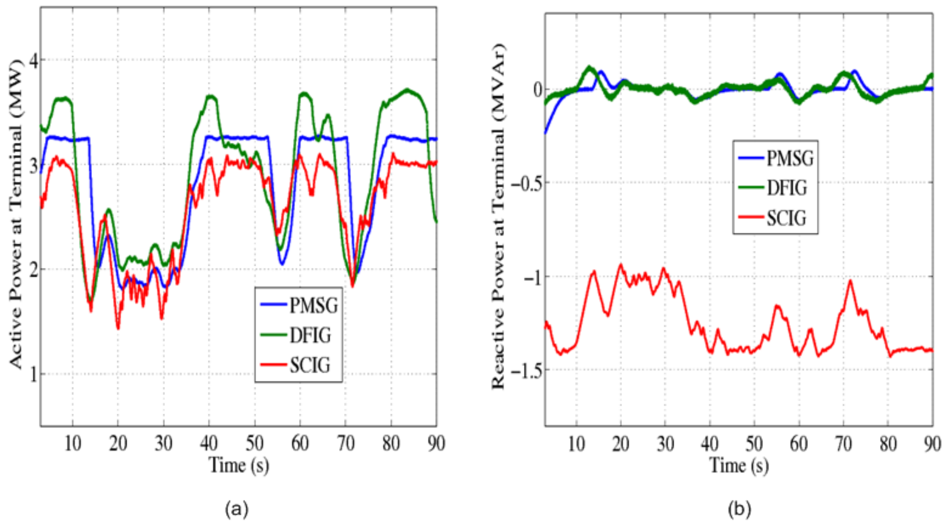

Fig. 6. The active and reactive power at generator terminals.

power. As result, they have much more efficiently and can improve power quality during wind speed variation. From Figure 6b, we can see that the wind turbine with DFIG and PMSG can keep reactive power at terminal nearly zero during steady-state operation, while the fixed-speed wind turbine absorbed a large amount of reactive power from the grid. During steady-state, the different behavior of DFIG and PMSG can also be explained by analyzing the active power exchanged between the generators and the network. In case of DFIG, the active power supply to the grid higher and more oscillatory than PMSG due to smaller in losses associated with converters conversion process and rating of converter. In case of PMSG, it can be noted that the active power injected by generator is lower and smoother than DFIG

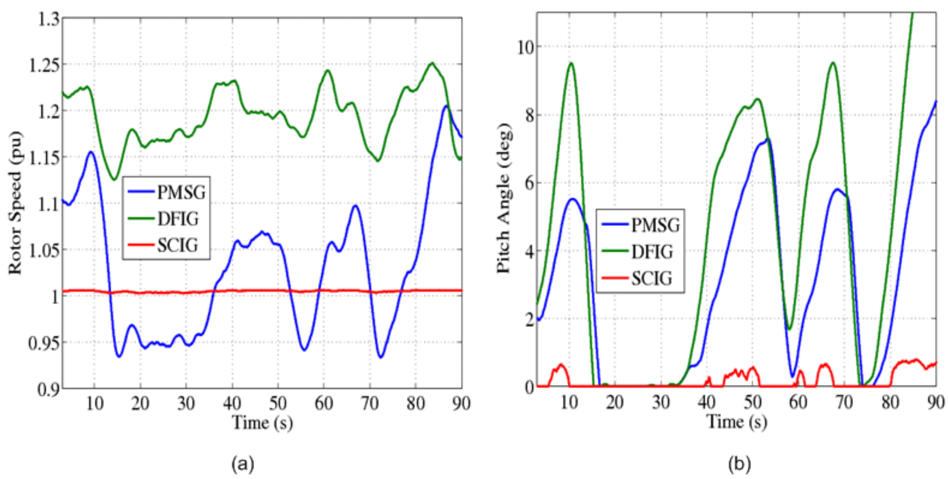

Fig. 7. The rotor speed and pitch angle.

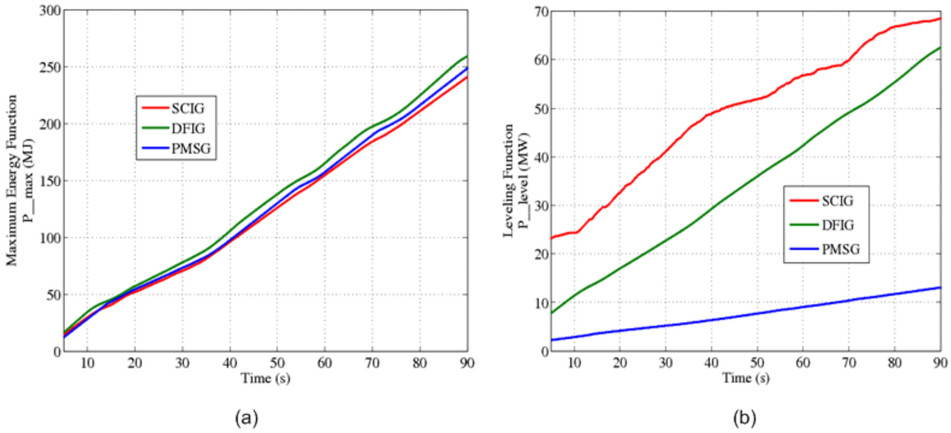

Fig. 8. The maximum and leveling energy.

due to higher in losses and rating of converter. This fact reduces power quality from DFIG compared to PMSG.

Figure 7a presents the dynamic responses of rotor speed among all types. Compared to SCIG, which is constant rotor speed, indirect grid connected wind turbines (DFIG and PMSG) are much more efficiently because they could run at variable speed. This advantage is especially useful for a wide wind speed and a weak electrical grid, a very common occurrence as wind turbines are typically located at remote locations. From simulation results, the PMSG type of wind turbine has the widest rotor speed variation due to converter which is rated to 100% of the wind turbine power, but there is a higher delay because the generator is bigger than other types of wind turbines. Simulated pitch angle behavior of DFIG and PMSG in Figure 7b are similar with respect to the rate of change ($\sim 5\ deg/s$) and the minimum ($\sim 0\ deg$) and maximum ($\sim 6\ deg$). Obviously, the response of the variable-speed wind turbines is similar, which can be explained by noticing their behavior is for the largest part determined by the controllers that does not exist inside fix-speed wind turbines.

Figure 8a and 8b show the validity of the efficiency of wind turbines and the smooth of power output by method numerically. As compared with the SCIG wind turbine, maximum power captured P_{max} by the PMSG and DFIG is higher. Moreover, as compared with the asynchronous generator SCIG and DFIG, with the synchronous generator PMSG leveling function P_{level} drops to about 1/7 compared to SCIG and 1/6 compared to DFIG. Since the slope of P_{level} for the PMSG wind turbine is small compared with SCIG and DFIG, the output power fluctuation of PMSG is smallest, then is DFIG and SCIG is the last with this concept.

5. **Conclusion**

This paper has summarized the most-recent in the field of the WT regarding generators and converters. The three main types of WT that have been used during past 20 years have been evaluated. An extensive study about the impacts determined by the connection of induction and synchronous generator to distribution networks. The objective was determine the main technical differences between these generators. The respond of WT connecting to the grid when wind speed variation are presented during steady-state by view point of power quality. The SCIG are only used by small wind turbines because they lack reactive power controlling, the market share the one has decreased slightly, whereas the variable speed wind turbines increases. Compared with PMSG, the main advantage of DFIG is only 30 % of the generated power passing through the power converter, so that it seems that the most-adopted system is still the DFIG with a back-to-back converter, due to the lower weight and cost even with low cost power electronics in the future. However, the PMSG is the preferred solution that the robustness, the efficiency, and the reliability related power quality are of paramount importance. Moreover, this research also presented maximum power captured and output power leveling of SCIG, DFIG and PMSG for wind speed variations by method numerically. By this method, we can more easier to evaluate efficiency of three popular wind turbines that related to power quality.

To sum up, it was verified that from the view point of a steady-state terminal voltage profile, active and reactive power, rotor speed, the usage of synchronous generator is advantageous and permits to increase the allowable penetration level of distributed generation. However, other factors must be considered to decide what is the best option in global terms, for example, economical and political aspects.

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