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Analysis and Performance Evaluation of DFIG and PMSG Based Wind Energy Systems

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Abstract: Wind energy generation systems are confronted with growing demands for power quality and active power control. With the advances in power electronics technology, the quick growth of variable speed WECS is now witnessed. This paper explains the control of a grid tied wind energy conversion system (WECS) using Doubly Fed Induction Generator (DFIG) with partial scale converter and Permanent Magnet Synchronous Generator (PMSG) with full scale converter. Modeling of control strategies for both systems are explained clearly. The maximum power point extraction of the wind turbines along with unity power factor operation of the system is also presented. The comparison aims to present the aspects of power quality (PQ) at the point of grid connection, harnessed power from both WECS at various wind velocities and converter ratings. Vector control strategy is being in employment for both the systems. Maximum power point tracking (MPPT) has also been implemented to extract maximum available power for a given wind velocity in both the systems. The performance comparison of both systems with the control strategies are presented using MATLAB/SIMULINK.

Keywords: Permanent Magnet Synchronous Generator (PMSG),Maximum Power Point Tracking (MPPT),Doubly Fed Induction Generator (DFIG), Wind Energy Conversion Systems (WECS), Rotor Side Converter (RSC) and Grid Side Converter (GSC).

1. INTRODUCTION

Renewable energy is the possible solution to minimize pollution, slow global warming and to meet the growing need for electrical energy demand. Wind energy is the fast growing renewable source and has the potential to supply a considerable portion of electrical demand. The generation of electricity with the help of wind turbine is the superior solution when compared to the generation by the solar power [1]. Wind energy technology has made rapid progression in the last three decades. The major differences in WECS technologies are in its design of controller and control of the machine. Presently, there exist three types of Wind Energy Systems for large windturbines [2]. Firstly, fixed speed WECS operating with narrow speed range around the synchronousspeed and directly tied to the grid. Fixed speed WECS provided with Squirrel Cage Induction Generator (SCIG), soft starter, multi stage gear box and capacitor bank. At present fixed speed SCIGs are utilised in several WECS productively and systematically, due to their rugged nature, lowcost, little maintenance and suppleness. High Fatigue and mechanical stress on the system, Larger gear box requirement, absence of voltage support to grid and absence of efficient optimization of aerodynamics are the disadvantages of the system [3, 4].The second one is a variable speed WECS with which variable speed operation is carried over a large range of speed, but within the limited range. In this type of WECS, a Doubly FedInduction Generator (DFIG) with the stator windings connected to the three phase constant – frequency grid and the rotor windings are connected to a reduced capacity back-to-back converter. A gear box with multiple stages is needed in this drive. This type of WECS offer smoother grid connection, high controllability, reactive power compensation and maximum power extraction using back to back power converters ofrating near to 25-30% of the generator capacity [3, 4]. The last category is also a variable speed WECS which uses full scale power converter whose rating is equal to the rating of the generator. Either an SCIG or a synchronous generator can be used in this type of WECS. The synchronous generator can be either an electrically excited synchronous generator (EESG) or a Permanent Magnet Synchronous Generator (PMSG). Gear Box can be eliminated with PMSG by using large number of poles which allows higher

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efficiency. However, this PMSG based WECS may cause problems during start-up, synchronization and voltage regulation [4, 5].

Variable speed WECS are discussed comprehensively in literature. A comparison study of different generator systems, including PMSG and DFIG, for WECS is presented [6]. DFIG with three stage gear box is the light weight, less cost outcome with high grade components and it is used commercially in large scale. The direct drive PMSG is costlier but a better solution because of its greater efficiency and low wear and tear, compared to other generators with gear box. The complete modelling and simulation of a grid interfaced WECS based on DFIG; using dynamic vector approach is presented in [6, 7, 8]. Two number of PWM voltage source inverters are used with the rotor side converter (RSC) for excitation control and grid side converter (GSC) for power flow control. WECS modelling and simulation using DFIG with partial scale converters is presented in this paper. The converters are controlled using vector control strategy to exploit maximum available power from the wind. The paper is organized as follows: Section I presents an introduction along with objectives of the present work. System configuration and proposed strategy for DFIG is presented in section II. Control of PMSG based WECS is explained in Section III. Results and analysis of both systems is explained and compared in Section IV. The conclusions drawn from these results are finally summarized in Section V.

2. Control of DFIG based WECS

In this drive the variable voltage and frequency rotor circuit is associated with the constant voltage and frequency grid by a bi-directional BTB connected voltage source converter connected through a DC capacitor. The grid is directly connected to the stator terminals of the DFIG. The overall block diagram showing the DFIG control is shown in figure 1.The converters rating is low as they have to handle slip power only. Since the speed range is limited, when compared to grid voltage the rotor induced voltage is too small, which requires a transformer at the interface of rotor-grid. With the help of vector control technique for the GSC a constant DC link voltage can be maintained irrespective of bidirectional power flow at rotor. The active and reactive powers injected into the grid by the stator are controlled by RSC. Through rotor current vector control (VC) both active and reactive powers are controlled. In this approach current vector is decomposed into stator active and reactive power components in synchronous frame of reference. Grid requirements and maximum power point tracking (MPPT) strategy will determine the reactive and active power references. The performance of the VC depends on stator flux position estimation, which is difficult with voltage distortion or machine parameter variation [9].For the controller synchronization stator voltage oriented frame (SVOF) is used in this paper. The stator active and reactive powers are given by the following expressions.

$$P_s = \frac{3}{2}(V_{sd}i_{sd} + V_{sq}i_{sq}) \tag{1}$$

$$Q_s = \frac{3}{2}(V_{sq}i_{sd} - V_{sd}i_{sq}) \tag{2}$$

v_{sq}becomes zero with SVOF used for synchronization of the controllers and the equations (1) and (2) are simplified as

$$P_s = \frac{3}{2}(V_{sd}i_{sd}) \tag{3}$$

$$Q_s = -\frac{3}{2}(V_{sd}i_{sq}) \tag{4}$$

With the synchronous frame stator flux equations [10], the stator currents represented as

$$i_{sd} = \frac{-L_m}{L_s}(i_{rd}) \tag{5}$$

$$i_{qs} = \frac{-L_m}{L_s}(i_{rq} + \frac{V_{sd}}{\omega_s L_m}) \tag{6}$$

With the substitution of (5) and (6) in (3) and (4), one can conclude that, stator active and reactive powers are controlled using i_{rd} and i_{rq} respectively.

$$P_s = \frac{-3L_m}{2L_s}(V_{sd}i_{rd}) \tag{7}$$

$$Q_s = \frac{3L_m}{2L_s}V_{sd}(i_{rq} + \frac{V_{sd}}{\omega_s L_m}) \tag{8}$$

In order to maintain a constant dc-link voltage and to improve the power factor of the rotor side, grid voltage oriented vector control scheme is used on the grid side.Vector control is achieved by aligning the direct axis of the reference frame with the direct axis component of the grid with that the quadrature-axis voltage vector is made zero. Rotor reactive power flow can be controlled by the quadrature axis current on the grid side.

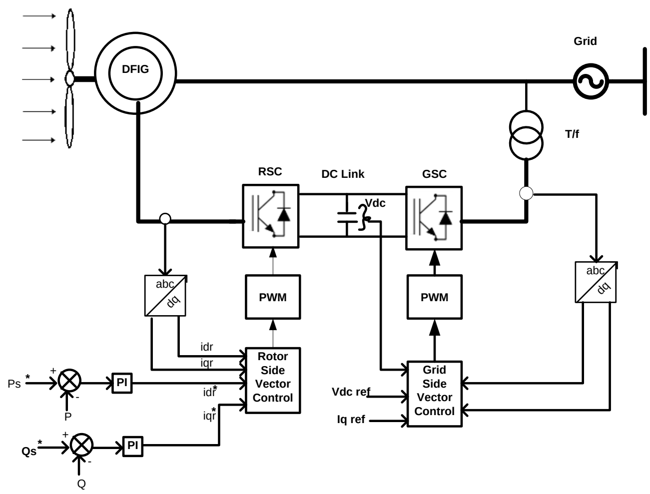

Figure 1. Block diagram of DFIG based Wind Energy Conversion System

A. Vector Control of RSC

The active and reactive powers injected by the stator of the DFIG to the grid are controlled by RSC. The control block diagram is composed by two-controller stages.The actual active power is compared with the reference active power and the resultant erroris feed to the PI controller to assess the reference value for the q-axis rotorcurrent. This signal is then compared to its actual value and the error is passed througha second PI controller determining the reference voltage for the q-axis component.The d-axis is used to control the reactive power exchanged with the grid, which innormal operation is set to zero in order to operate with unity power factor. Similar to the control strategy for the q-component, when the sensed reactive power is compared with the reference reactive power, an error is produced on processing through the PI controller, computes the reference d-axis component of the rotor current. This signal iscompared to the d-axis current value and the error is sent to a second PI controller which determines the reference voltage for the d-axis component. Finally, the dq reference voltages are passed through the PWM module and the modulation indices for the control of the RSC are determined.

B. Vector Control of GSC

The main objectives of the grid side converter vector control strategey are to regulate DC bus voltage and to control the reactive power exchanged bidirectionally between the rotor of the machine and the grid. This is achieved by, aligning the grid voltage vector with direct axis in synchronous frame of reference, and its indirect axis component becomes null. Hence, the GSC

$$v_{fd} = -(R_f i_{dg} + L_f \frac{di_{dg}}{dt}) + v_{sd} + \omega_s L_f i_{qg} \qquad (9)$$

$$v_{fq} = -(R_f i_{qg} + L_f \frac{di_{qg}}{dt}) - \omega_s L_f i_{dg} \qquad (10)$$

$$P_g = \frac{3}{2} v_{sd} i_{dg} \qquad (11)$$

$$Q_g = -\frac{3}{2} v_{sd} i_{qg} \qquad (12)$$

Where v_{fd} and v_{fq} are GSC output voltage vector components i_{dg} , i_{qg} and v_{sd} are grid current and voltage respectively, as $v_{sq} = 0$. *From e*quations (11) & (12) it is clear that, active power and consequently DC busvoltage can be controlled via i_{dg} , whereas reactive power flow in the grid can be controlled by i_{qg} .The outer voltage PI controller helps in maintaining the DC bus voltage constant, which processes the error between reference and measured DC bus voltage and yields i^*_{dg} . While i^*_{qg} is set to zero to balance for reactive power at the grid side. Finally the measured grid currents (i_{dg} , i_{qg}) and reference currents (i^*_{dg} , i^*_{qg}) are compared then processed by inner current PI controllers, in order to generate appropriate signals for the GSC.

3. CONTROL OF PMSG BASED WECS

The configuration of the PMSG WECS with back-to-back converters is shown in figure 2. The PMSG converts the mechanical power from the wind turbine into ac electrical power, which is then converted to dc power through a converter with dc link supplying either the stand-alone load or the inverter to a grid connection. By using an additional inverter, the PMSG can supply the ac electrical power with constant voltage and frequency to the power grid. Modelling of PMSG, the generator side converter control and the grid side converter control schemes are explained in [11].

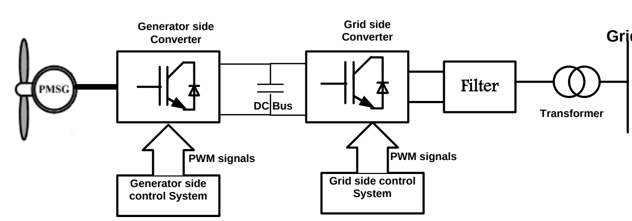

Figure 2. Block diagram of PMSG based Wind Energy Conversion System

The generator is normally modelled in the rotor field synchronous reference frame. The generator voltage equations of the generator are given by

$$v_{ds} = -R_s i_{ds} - \omega_r \lambda_{qs} + p\lambda_{ds} \qquad (13)$$

$$v_{qs} = -R_s i_{qs} + \omega_r \lambda_{ds} + p\lambda_{qs} \qquad (14)$$

Where λ_{ds} and λ_{qs} are the d-axis and q- axis stator flux linkages, given by

$$\lambda_{ds} = -L_d i_{ds} + \lambda_r \qquad (15)$$

$$\lambda_{qs} = -L_q i_{qs} \qquad (16)$$

Where λ_r is the rotor flux, L_d and L_q are stator dq- axis self inductances. Substituting (15), (16) in (13), (14) and for constant field current I_f , We have

$$v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d p i_{ds} \qquad (17)$$

$$v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q p i_{qs} \qquad (18)$$

The electromagnetic torque can be calculated by

$$T_e = \frac{3P}{2}\left[i_{qs}\lambda_r - \left(L_d - L_q\right) i_{qs} i_{ds} \right] \qquad (19)$$

Below the rated wind speed, the generator is controlled by controlling variable speed wind turbine. The major objective is to make best use of the power arrest at variable wind speeds, by adjusting turbine speed. The path of maximum power points represents a power curve which can be described by

$$P_m \propto \omega_m^3 \qquad (20)$$

Power captured by the turbine can be expressed as,

$$P_m = T_m \omega_m \qquad (21)$$

Where T_M is the turbine mechanical torque. From (20) & (21)

$$T_m \propto \omega_m^2 \qquad (22)$$

MPPT scheme, with optimal torque control is realized by computing the desired torque reference T_e^* . The generator side converter is controlled by zero d-axis current control along with MPPT and the grid side converter is controlled by voltage oriented control [10].

A. Generator Side Converter Control

The generator side control scheme is shown in figure 3.The generator torque reference T_e^* is generated by the MPPT method in accordance with the measured generator speed ω_m . The ZDC control is realized by resolving the three phase stator current in the stationary reference frame to d and q axis components in the synchronous frame. The d- axis component i_{ds} is kept to be zero [6]. With direct axis current zero, the stator current becomes equal to q- axis current i_{qs} .

$$i_s = i_{qs} \qquad (23)$$

Where i_s , is the stator current space vector. With zero d-axis current the torque equation (19) becomes

$$T_e = \frac{3P}{2}\left[i_s \lambda_r \right] \qquad (24)$$

From the above equation , the generated torque is directly proportional to stator current i_s .The reference torque T_e^* is generated from MPPT controller and torque producing component i_{qs}^* is calculated from (24)

$$i_{qs}^* = \frac{2T_e^*}{3P\lambda_r} \qquad (25)$$

The rotor flux position angle θ_r is to be detected for rotor fluxfield orientation. Three phase currents are measured and are then transformed into i_{ds} and i_{qs} using abc/dq transformation. These currents are compared with i_{ds}^* and i_{qs}^* and the corresponding errors are processed by the controllers to generate v_{ds}^* and v_{qs}^* for the rectifier. These voltages are transformed to three phase reference voltages using dq/abc transformation. Active power of the generator is controlled by controlling the rectifier using PWM technique.

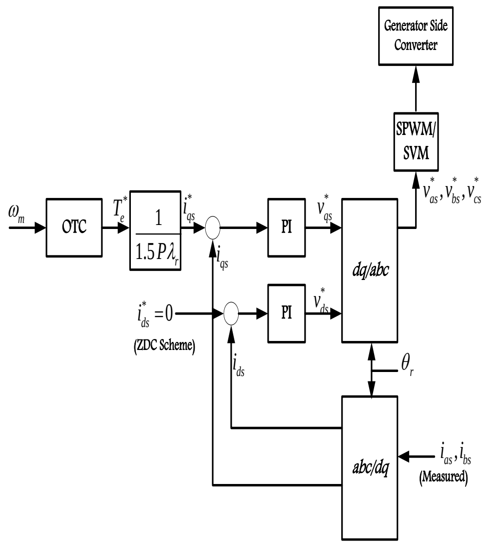

Figure 3.Generator side converter control scheme

B. Control of the Grid Side Converter (inverter)

The main function of grid side converter is to control the reactive power and the DC link voltage v_{dc} . Grid voltage vector is tracked and the angle θ_g is generated by phase locked loop. This angle and grid voltage is used for the VOC of the grid side inverter. The block diagram of grid side converter control scheme is shown in figure 4.

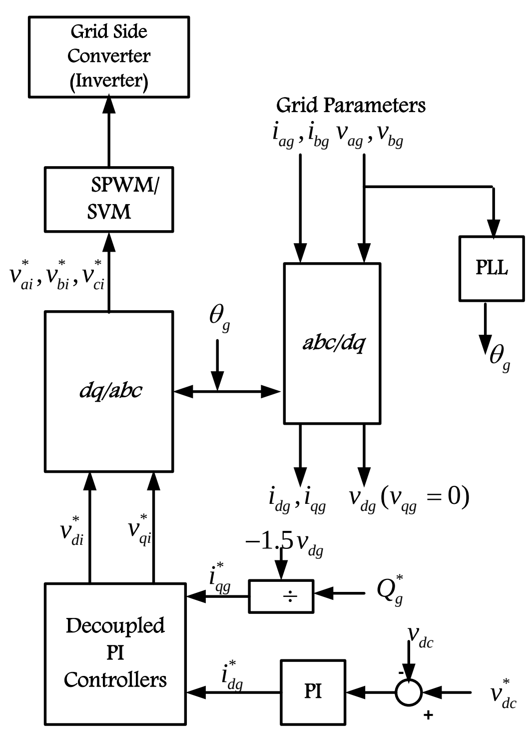

Figure 4. Grid side converter control scheme

In VOC scheme, three feedback control loops are present: two inner current loops for the accurate control of the dq-axis currents i_{dg} and i_{qg} , and one outer DC voltage feedback loop for the control of DC voltage v_{dc} . The independent control of i_{dg} and i_{qg} provides accurate control of active and reactive power control. To obtain the VOC scheme, the d-axis of the synchronous frame is aligned with the grid voltage vector, therefore ($v_{dg} = v_g$), and *q-axis* voltage v_g is then equal to zero, from which the active and reactive power of the system can be obtained by

$$P_g = \frac{3}{2} v_{dg} i_{dg} \tag{26}$$

$$Q_g = -\frac{3}{2} v_{dg} i_{qg} \tag{27}$$

The q- axis reference current will be obtained from

$$i_{qg}^* = -\frac{2}{3} \frac{Q_g^*}{v_{dg}} \tag{28}$$

With negligible losses in the inverter, the real power on the AC side of the inverter is

$$P_g = \frac{3}{2} v_{dg} i_{dg} = v_{dc} i_{dc} \tag{29}$$

4. Results and Analysis

The simulation of PMSG and DFIG based WECS have been performed using Matlab/Simulink. Both the systems are simulated for a variable wind speeds to check the system performance. Figure 5 shows variation of wind speed in per unit. Figures 6 and 7 show the variation of DFIG and PMSG speeds with respect to wind speed. It is clear that, both the generators speed is adjusted according to wind speed variation to arrest the power at different wind speeds.

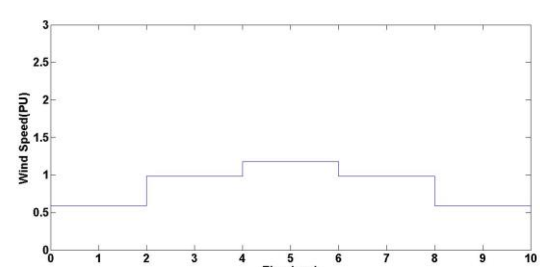

Figure 5. Variation of Wind speed

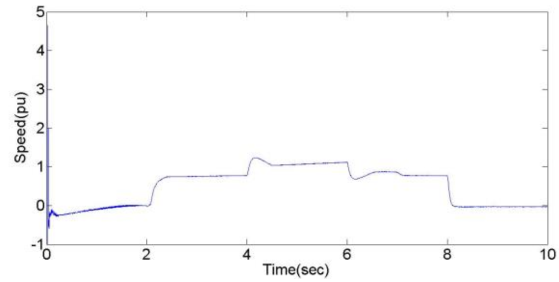

Figure 6. Variation of DFIG speed

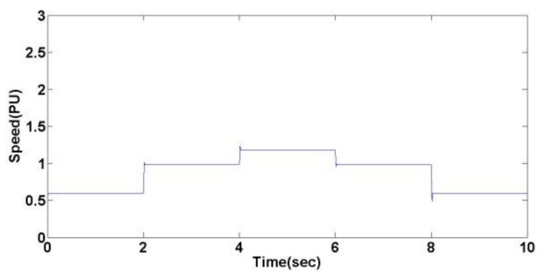

Figure 7. Variation of PMSG speed

Variation of active power delivered by DFIG and PMSG generators is shown in figures 8 and 9 respectively. It can be observed from the results that, with reference to the variation of wind velocity, the power delivered by both DFIG and PMSG is also variable.

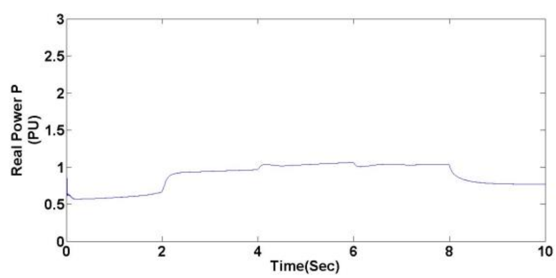

Figure 8. Variation of Active power supplied by DFIG

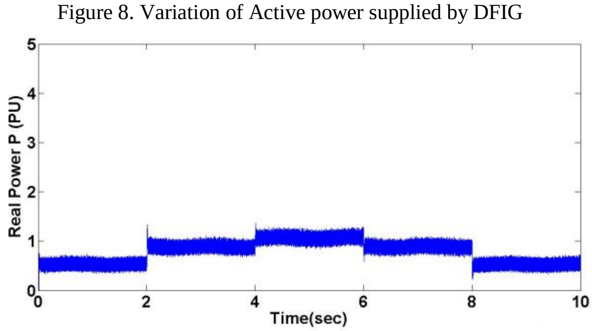

Figure 9. Variation of Active power supplied by PMSG

The power quality is compared with the help of total harmonic distortion (THD) in current supplied to grid.THD of current supplied to grid by DFIG is shown in figure 10 and that of PMSG is shown in figure 11. It is clear from the results that, THD value is lower in case of DFIG when compared to PMSG based WECS.

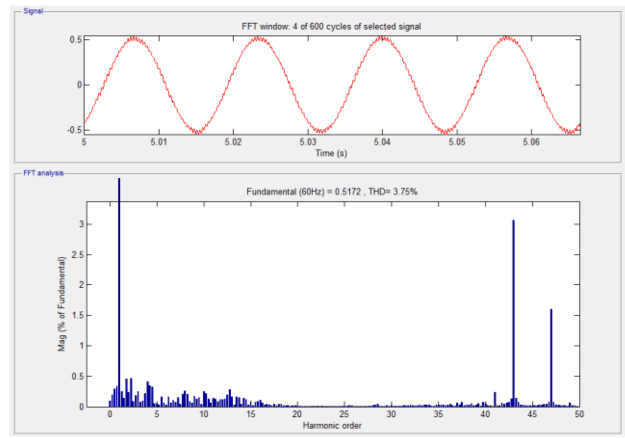

Figure 10. THD of Grid Current in DFIG based WECS

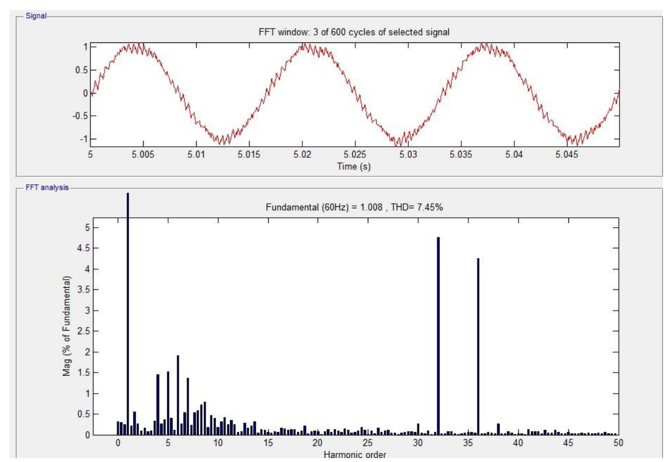

Figure 11. THD of Grid Current in PMSG based WECS

5. Conclusions

In this paper, an effort has been made to evaluate the performance of the DFIG and PMSG based wind energy conversion systems. The system models are implemented in the MATLAB/SIMULINK software. In case of DFIG based WECS, bi-directional power flow control is possible with the help of BTB connected converters of 25-30 % rating of generator. Where as in case of PMSG based WECS, the rating converters of BTB connection are around 100% rating of the generator. DFIG is better alternative when compared to PMSG at low and variable wind speeds for on shore applications.For off shore applications PMSG is advantageous compared to DFIG because of its less maintenance and constant wind speed. As Losses in PMSG are less when compared to DFIG, power supplied by PMSG is slightly higher than that of DFIG.As stator of the DFIG is connected directly to grid, THD of grid current is less in case of DFIG when compared to PMSG.DFIG and PMSG comparison is of more economical issue than technical. DFIG is good until 5 MW; PMSG is good from 1 MW to 10 MW.

NOMENCLATURE

v_{sd}, v_{sq}, v_{rd}, v_{rq}	Stator and rotor voltages in dq frame.
i_{sd},i_{sq},i_{rd}, i_{rq}	Stator and rotor currents in dq frame.
R_s,R_r	Stator and rotor resistances
L_s,L_m,L_r	Stator, magnetizing, rotor inductances.
T_m,ω_m	Electromagnetic torque, mechanical speed
R_f, L_f	Grid filter resistance and inductance
P_g,Q_g, P_s,Q_s	Grid and stator, active and reactive powers
θ_s,θ_m,θ_r	Stator voltage, rotor electrical, slip angles
v_{fd},v_{fq}	GSC output voltage vector components
i_{dg}, i_{qg},v_{sd}	Grid current and voltage respectively

REFERENCES

[1] Vijay chandGanti, Bhim Singh, Shiv Kumar Agarwal and Tara Chandra Kandpal, "DFIG based wind power conversion with grid power levelling for reduced gusts", IEEE Transactions on Sustainable Energy, Vol:3,No.1, pp:12-20 (2012).

[2] Li H, Chen Z, "Overview of different wind generator systems and their comparisons", IET Renewable Power Generation, Vol. 2, No. 2, pp. 123-138, (2008).

[3] Datta Rajib, Ranganathan VT, "Variable speed wind power generation using doubly fed wound rotor induction machine - a comparison with alternative schemes," IEEE transactions on Energy conversion,Vol. 17, No. 3, pp. 414-421, (2002).

[4] Some Important Issues Related to Wind Energy Conversion System (WECS)", International Journal of Environmental Science and Development, Vol. 1, No. 4, (2010).

[5] Munteanu lulian, BratcuLulianaAntoneta, Cutululis Antonio Nicolaos, Ceanga Emil, "Optimal control of wind energy systems," 1st ed., Springer-Verlag London Limited, pp. 71-108, (2008).

[6] Polinder Henk, Pijl Van der F.A Frank, Gert-Jan de Vilder, Tanver Peter, "Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines", in proceedings of IEEE conference on Electric Machines and Drives, pp. 543-550, (2005)

[7] Fernandez LM, Garcia CA, Jurado F, "Comparative Study on the Performance of Control Systems for DFIG Wind Turbines Operating with Power Regulation", Energy 33, pp. 1438-1452, (2008).

[8] Pena R, Clare JC and Asher GM, "Doubly fed induction generator using back to back PWM converters and its application to variable-speed wind-energy generation," IEE Proc. - Electrical Power Applications, Vol. 143, No. 3, pp. 231-241, (1996).

[9] Chinchilla Monica, Arnaltes Santiago and Burgos Carlos Juan, "Control of Permanent-Magnet Generators Applied to Variable-Speed Wind-Energy Systems Connected to the Grid", IEEE Transactions on Energy Conversion, Vol. 21, No. 1, pp. 130-135, (2006).

[10] H.Abouobaida, M.Cherkaoui, " Modeling and Control of DFIG wind Energy Conversion System" Journal of Electrical Engineering,15(1), pp. 1-12.

[11] Tripura Pidikiti,G.Tulai ram Das, "Power Maximization and Control of PMSG Wind Energy System without Wind Speed Sensors" International Journal of Control Theory and Applications, vol.25,No.10,pp.253-260,(2017).

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