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Performance Comparison of DFIG and SCIG based Wind Energy Conversion Systems

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Abstract – **Increasing penetration of wind energy in existing conventional energy systems necessitate better power quality and control. The power electronics is advancing very fast and this facilitates the rapid growth of variable speed wind energy conversion systems (WECS). However, the issue of power quality needs a thorough attention of the people involved in research work. This paper is focusing mainly on the performance comparison of WECSs using doubly fed induction generator (DFIG) and squirrel cage induction generator (SCIG) where both types of WECSs are using similar kind of the control strategies. The aim of this comparison study is to present various aspects of power quality, especially at the point where the WECS is connected to the grid, in a logical manner. This study also aims to find minimum and maximum wind speeds at which these generators can be operated and power generated by these generators at varying wind speed. Both the Energy conversion systems are using vector control technique. In order to harness maximum power at a particular wind speed, maximum power point tracking has been implemented in both the systems.**

Keywords: Doubly Fed Induction Generator (DFIG), Squirrel Cage Induction Generator (SCIG), Wind Energy Conversion Systems (WECS)

I. INTRODUCTION

Due to day to day increment in the demand of electrical energy, increased attention on environmental concerns and decreasing fossil fuels supply, a need has been realized to focus on increased utilization of clean and renewable energy sources. The source of such energy may be wind, solar irradiation, tidal wave, biomass or fuel cell. Out of all the above stated alternatives, wind energy is most popular and widely used renewable energy in India. At the end of 2013, worldwide nameplate capacity of wind-powered generators was 318 GW. Wind power market penetration is expected to reach 8% by 2018. The wind generation has increased more than double in the past three years. Till 2013, several countries have achieved relatively high capacity of wind power generation. China contributes 28.7%, Unites States contributes 19.2%, Germany contributes 10.8%, Spain contributes 7.2% of the World wide wind power capacity. India stands 5th in this list contributing 6.3% [11]. Starting the development of wind power in 1990s, India has achieved a significant share in wind power capacity during last few years. As per the reports of March 2014, installed capacity of wind power in India was 21136.3MW. A capacity of 6,000 MW of additional wind power capacity is expected to be installed in India by the end of 2014 [11].

Wind Energy Conversion Systems (WECS) constitute a main stream power technology which is still under exploited. Wind technology has made major progress from the prototypes of 30 years ago. The main differences in WECS technology are in electrical design and control. At present, typically three types of WECS for large wind turbines exists [5]. The first one is a fixed speed WECS that operates only in a narrow range around the synchronous speed and is directly connected to the grid. Fixed speed WECS are equipped with Squirrel Cage Induction Generator (SCIG), multi stage gear box, soft starter and capacitor bank. This system suffers the problem of high mechanical stress and low aerodynamic efficiency while requiring large gear box with no voltage support to the grid. [3, 6]

The second type known as variable speed WECS allows variable speed operation over quite a large range of wind speeds. Doubly fed induction generator (DFIG) is the chiefly used generator in this type of WECS. Stator winding of the generator is directly connected to the grid. Rotor winding is connected to grid through back to back connected converters of partial rating (25-30% of generator capacity) which offers reactive power compensation and maximum power extraction. This type of WECS necessarily uses a multi stage gear box and offer high controllability with smoother grid connection. [3, 6]

With the reduction in the cost of power electronics during recent past, WECS using fully rated back to back connected power converter is becoming an attractive option which can use squirrel cage induction generator (SCIG) or permanent magnet synchronous generator (PMSG). The concept using SCIG is popular due to improvement in power electronics and lower cost of squirrel cage machines. SCIGs are very easily available and very rugged for any harsh environment.

Variable speed WECS are discussed extensively in literature. In [2], a comparative study of five different generator systems for WECS is given. A DFIG based WECS using three stage gearbox with standard components is most widely used system commercially. The complete modeling and simulation of a grid-interfaced WECS based on DFIG, using dynamic vector approach is presented in [1, 4 and 8]. Two PWM voltage source inverters are used in this configuration with the rotor side converter being for excitation control and grid side converter for power flow control. Vector control or Direct Torque Control of the Induction generator may be used as it allows very efficient and controlled variable speed operation thereby allowing extraction of maximum energy from wind.

In the present work, WECS have been modeled and simulated for two configurations namely DFIG and SCIG which have partial rated and full rated converters respectively. Vector control strategy has been used to control the converters. This way the maximum power is harnessed from the wind. This paper is organized in five sections where first section reflects the introduction and objective of the work, system configuration and control strategies of both types of WECSs are presented in second section. Third section present the MATLAB simulink models while fourth and fifth sections present explanation/comparison of the results and conclusions respectively.

II. SYSTEM DESCRIPTION

A. Wind dynamics and optimal operation

The power extracted by wind turbine (P_{wt}) in WECS varies with wind speed, this power is given by

$$P_{wt} = \frac{1}{2} \rho \pi R^2 v^3 C_p(\lambda, \beta) \qquad (1)$$

Where ρ is air density which is equal to 1.225 kg/m^3 at 288° K temperature at sea level, R is the length of turbine blade, v is the linear speed of wind, and C_p is the coefficient of wind power. P_{wt} is a function of pitch angle (β) and tip speed ratio (λ). The tip speed ratio (TSR) is given by

$$\lambda = R\, \Omega_l / v \qquad (2)$$

Where, Ω_l represent the turbine shaft speed. For fix pitch angle, the power captured by the wind turbine is depending mainly on Tip Speed Ratio. Specific value of tip speed ratio λ_{opt} corresponds to a well determined maximum value of power conversion efficiency ($C_{p\,max}$).

In this work, the chosen value of λ_{opt} is 8.1 which corresponds the value of $C_{p\,max}$ = 0.48. Knowing these two values, an active power optimal control is applied for which a set point from the shaft rotational speed is used. It could be found from equations (1) and (2) that

$$P_{wt} = \frac{1}{2} \rho \pi R^5 \Omega_l^3 \{C_p(\lambda) / \lambda^3\} \qquad (3)$$

Using the relationship between torque and power, the torque equation can be written as

$$T_{wt} = P_{wt} / \Omega_l = K\, \Omega_l^2 \qquad (4)$$

$$\text{Where, } K = 0.5 \{C_p(\lambda) / \lambda^3\} \rho \pi R^5 \qquad (5)$$

Maximum power at variable speed can be extracted by the wind turbine by maintaining values of $\lambda = \lambda_{opt}$ and $C_p(\lambda) = C_{p\,max}$. The torque control of DFIG is achieved by using vector control in rotor side converter while rotor flux oriented vector control has been used for generator control of SCIG via Machine side converter control.

B. Control Strategy for DFIG

A DFIG based WECS is shown in Figure 1 in which variable voltage and frequency output of rotor is connected to the grid by using two bi-directional, back-to-back connected voltage source converters linked through a DC capacitor. This enhances the flexibility of WECS in controlling the active and reactive powers. Stator output of the DFIG is directly connected to the grid. Power to the grid can be supplied by both stator and rotor. Power flow direction of rotor power depends on generator speed. The converters are rated to handle the slip power only which is very low. The low voltage induced in rotor is stepped up by using a transformer and then connected to the grid. Decoupled control of active and reactive powers is achieved by vector control. The rotor of the machine is capable to supply as well as receive the slip power therefore it can be operated at sub synchronous, synchronous and above synchronous speeds.

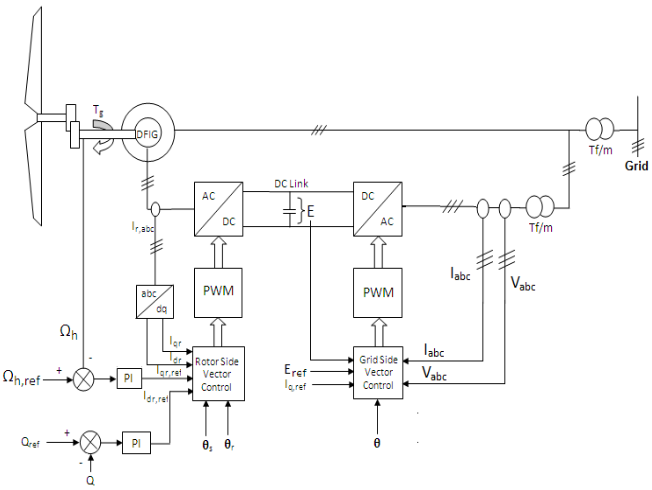

Figure 1: Block diagram of DFIG based WECS

The voltage source converters connected in rotor circuit are named Rotor side converter (RSC) and Grid side converter (GSC). Constant DC link voltage is maintained by grid side converter in both directions of rotor power flow. A vector control technique is used in which the reference frame is oriented along with grid voltage vector. The DC link voltage is regulated by direct axis component of current (I_d) while the transfer of reactive power is controlled by quadrature axis component of current (I_q).

Transaction of stator active and reactive powers is controlled by RSC. Direct axis component of stator flux (Φ_{sd}) is oriented with stator flux vector thus setting quaderature axis stator flux (Φ_{sq}) to zero. With this the Torque T is expressed as

$$T = -(3/2)\, P\, (L_m/L_s)\, \Phi_{sd}\, I_{qr} \qquad (6)$$

In the above equation, P is pairs of poles, L_m and L_s are magnetizing and stator inductances respectively and I_{qr} is quaderature axis rotor current. It could be seen from above that electromagnetic torque is controlled by I_{qr}. This is how the active power is controlled. [4&8]. Reference I_{qr} is computed by using relations given above (equations 2,3,4,5 and 6).

C. Control Strategy for SCIG

The system consists of a WT coupled to a SCIG through a gearbox. The stator terminals of the SCIG are connected to the grid through back to back connected voltage source converters and coupling inductors as given in figure 2.

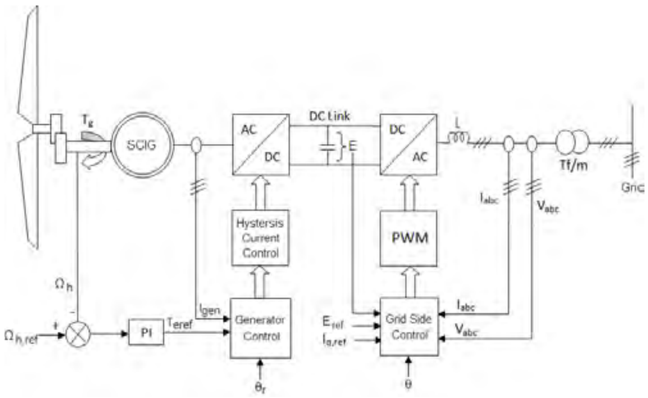

Figure 2: Block diagram of SCIG based WECS

The transformer connected at the grid side also helps in filtering high frequency ripples which are produced due to switching of the converter devices. The voltage source converter at machine side controls the generator and feeds the grid side inverter. It is also capable of providing the magnetizing current for induction generator at an increased converter rating and hence eliminates the requirement of the excitation capacitors. A vector control strategy having reference frame oriented with the supply voltage vector is used to independently control the active and reactive power flow between grid side converter and the grid. The power extracted by the turbine is maintained maximum at variable wind velocities by maintaining the tip speed ratio at its optimal value i.e. λ_{opt}. This is achieved by adjusting the generator torque according to optimal regimes characteristic (ORC).

Grid side converter (GSC) works same as the one used for DFIG, implementing control using PWM where the output of dc-link voltage controller sets the d-axis reference current, $I_{d,ref}$ and reactive power controller creates the q-axis reference current, $I_{q,ref}$. These reference currents are compared to the actual currents through a PI controller and the error signals are further processed to create the voltage references for the PWM converter. Phase locked loop (PLL) is used for extracting the phase angle of the grid voltages.

III. MODELLING AND SIMULATION

A. Modelling and Simulation of DFIG

The system reflected in Figure 1 is modelled by using Sim Power Systems toolbox of MATLAB. The stator of the generator is connected to 11kV, 50Hz grid by using a step up transformer. Rating of 4 pole, wound rotor induction generator is 1.5MW at 3-phase, 0.690 kV, 50 Hz. The Stator winding resistance (R_s) and inductance (L_s) are 0.0022 ohm and 0.12 mH respectively. Rotor winding resistance (R_r) and rotor winding inductance (L_r) of the machine are 0.0018 ohm and 0.05 mH respectively while magnetizing inductance (L_m) of the machine is 3.1mH. The system is exposed to varying speed wind (from 5 m/s to 13 m/s). The variation is done in step of 1 m/s at a gap of 2 seconds. This way the system reaches to steady state of the speed and remains in steady state before next change in wind speed is affected. This variation facilitates the sub-synchronous, near-synchronous/synchronous and super-synchronous operations of the system. Generator speed is set according to wind turbine characteristics to get optimal power generated for each wind velocity. The difference of actual and reference speeds is used as input to PI controller for getting ($I_{q,ref}$) for rotor side converter control

The reactive power actually absorbed at point of grid and DFIG connection is compared to a suitable reference value (Q_{ref}). The error is fed to a PI controller which provides reference current ($I_{dr,ref}$) as output. This reference current is compared with actual value of I_d; the error is fed to another PI controller which provides direct axis reference voltage ($V_{d\ ref}$). Same way the difference between the values of I_{qr} and $I_{qr,ref}$ is fed to a PI controller which provides the value of quadrature axis reference voltage ($V_{q\ ref}$). After dqo to abc transformation, these voltages are used as modulating wave by the sinusoidal PWM converter. A transformer connected between GSC and grid acts as smoothening reactor also.

Difference between the value of actual DC link voltage and reference value is fed to PI controller which provides direct axis reference current ($I_{d,ref}$). This reference current is compared with actual direct axis current and the error is fed to second PI controller which provides direct axis voltage reference (V_{dref}). RSC regulates the power factor hence there is no need to control reactive power by GSC. According to the power factor requirement, q-axis reference current is fixed this value is compared with actual q-axis current (I_q) the difference is fed to a PI controller which provides V_{qref} in its output. After transformation from dqo to abc, the voltage wave is used for modulation in conventional sinusoidal PWM converter.

B. Modelling and Simulation of SCIG

The stator of 4 pole SCIG is connected to 11kV, 50Hz grid trough two back to back connected PWM converters and a transformer. The induction machine rated for three phase, 690V, 50 Hz. The stator winding resistance (R_s) and self inductance (L_s) are 0.007 pu and 0.18 pu respectively while cage resistance (R_c) and rotor self inductance (L_r) are 0.0072 pu and 0.16 pu respectively. The mutual inductance (L_m) between rotor and stator is 3.2pu.

The output of SCIG stator is converted into DC by machine side converter which charges a capacitor. The capacitor voltage (DC link voltage) is maintained at 1200V. This system is also operated at wind speed varying from 5-13 m/s. This machine is operated in two modes namely sub synchronous and synchronous modes only.

The optimal power control ensures that the rotor rotates at the reference value as per the wind speed. A PI controller with the input of the difference of reference and actual speeds of generator yields the reference torque or indirectly $I_{sq,ref}$ for the machine side converter. A wind speed of 10 m/s causes the speed of generator to reach its synchronous speed.

At wind speeds greater than 10 m/s, a speed constraint is activated which limits the generator speed to its rated value (1 pu). Here, the wind turbine enters the power limiting mode and the pitch control is activated. Pitch control mechanism, reduces the power captured by the wind turbine to its rated value, following another constraint which is applied to limit the power at rated (i.e. 1 pu).

The Grid side converter is controlled to keep the DC voltage on the capacitor constant at 1200V; hence the grid side control meets the real power demands of machine side. The difference of actual DC link voltage and its reference is used as input to a PI controller which provides d-axis reference current ($I_{d\ ref}$) for grid side controller. The q-axis reference current (Iq ref) is achieved on the basis of the difference of reactive power reference and the actual reactive power required by the WECS. The q-axis reference current is controlled such that unity power factor operation is achieved i.e. the power taken through the grid only takes care of the reactive power requirements of the generator.

IV. Results and Discussions

The simulation of WECS based on DFIG and SCIG has been performed for similar ratings of both the generators. Both WECS are operated for different wind velocities to check if the system can successfully function in both sub-synchronous as well as super-synchronous speeds.

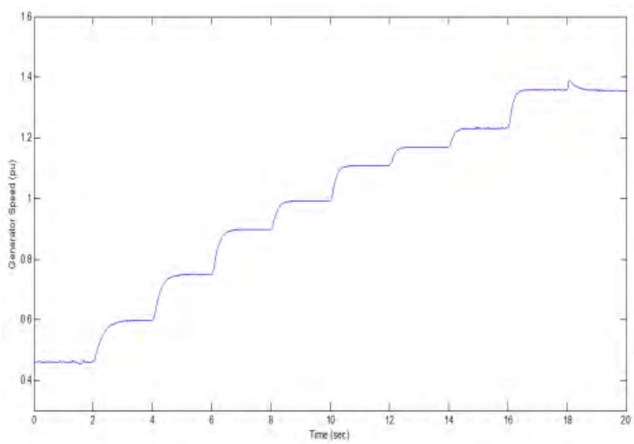

Figure 3 (a): Variation in generator speed with respect to change in wind speed for DFIG.

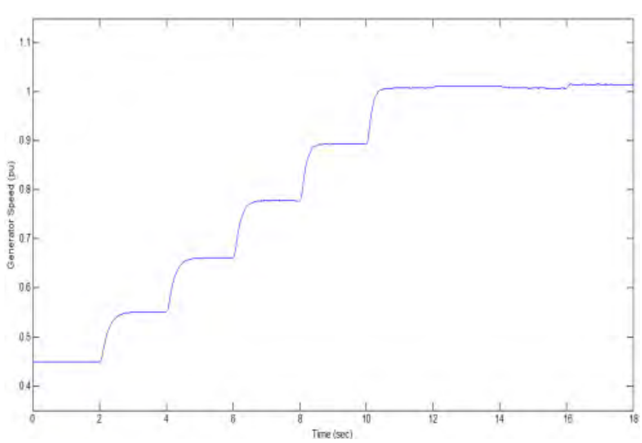

Figure 3 (b): Variation in generator speed with respect to change in wind speed for SCIG.

Figure 3 (a) and 3 (b) shows the variation in generator speed with the change in wind speed, for both WECS. It can be seen that the generator speed is adjusted according to the reference speed to capture maximum power at different wind velocities.

The values of active power output observed from Figure 4 (a) and 4 (b) for DFIG and SCIG respectively are summarized in Table 1. It can be seen that DFIG is capable of delivering more power at lower wind speeds (5-6 m/s) and higher range of wind speeds (10.5 to 13 m/s) This may be attributed to the power delivering capability of the DFIG from both stator and rotor sides. It is observed from these simulations that DFIG is capable of generating even for wind speeds as low as 5 m/s.

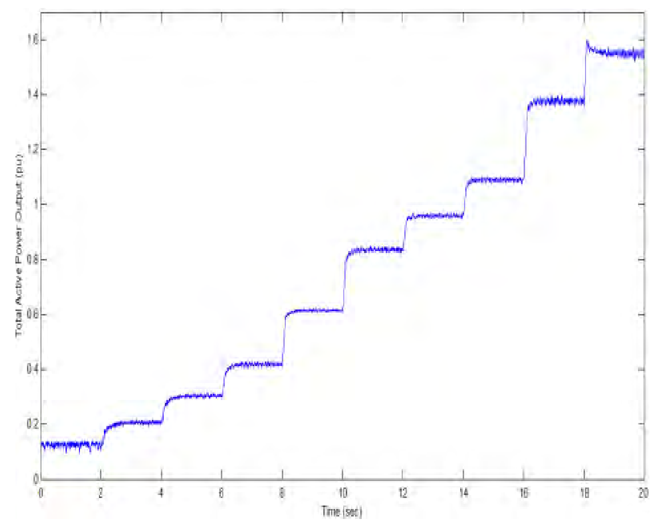

Figure 4 (a) : Active Power Harnessed at various wind speeds for DFIG

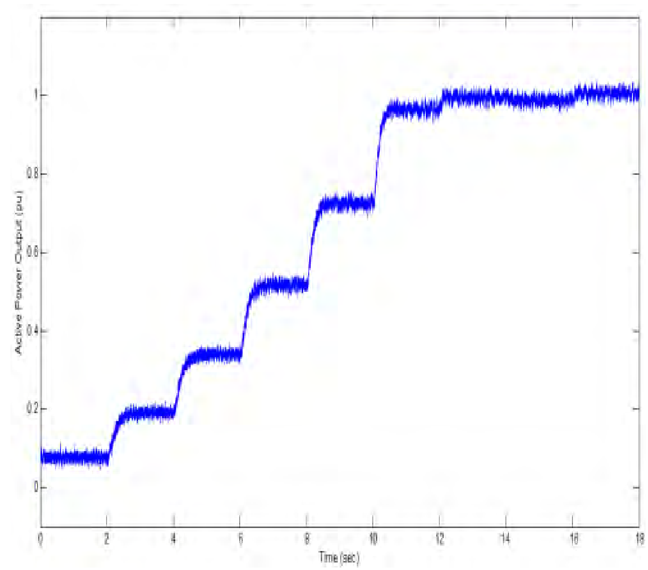

Figure 4 (b) : Active Power Harnessed at various wind speeds for SCIG

Table 1: Comparison of active power delivered by both WECS at various wind speeds.

Active Power Output (pu)				
Wind Speed (m/s)	*DFIG*			*SCIG*
	Stator Output	*Rotor Output*	*Total Power Output*	*Total Power Output*
5	0.28	-0.15	0.13	0.08
6	0.35	-0.14	0.21	0.19
7	0.41	-0.10	0.31	0.34
8	0.47	-0.05	0.42	0.52
9	0.62	-0.01	0.61	0.73
10	0.76	0.08	0.84	0.97
10.5	0.82	0.14	0.96	1.00
11	0.89	0.20	1.09	0.99
12	1.02	0.35	1.37	1.00
13	1.15	0.40	1.55	1.01

At wind speeds between 7 to 10 m/s the power delivered by SCIG is more than DFIG which can be attributed to its higher efficiency. It was also observed that DFIG can handle larger range of wind speeds. At sites with lower wind speeds, WECS using DFIG may be considered as a better option.

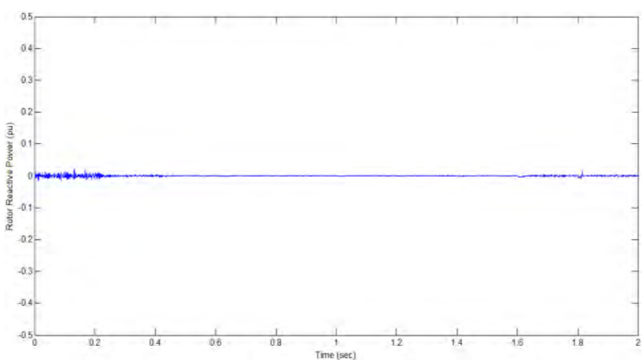

Figure 5 (a): Reactive Power flow (through power converters) at various wind speeds for DFIG.

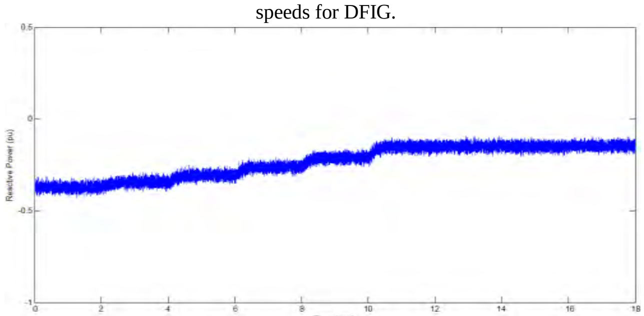

Figure 5 (a): Reactive Power flow (through power converters) at various wind speeds for SCIG.

The output voltage and current supplied to the grid through both types of WECS are shown in Figures 6 and 7 (the x-axis scale at the top and bottom of the waveforms are respectively for the expanded and normal waveforms). The observations derived from these waveforms are detailed in Table 2. The power quality is compared by measuring the total harmonic distortion THD in waveforms of voltage and current delivered to grid. It is analysed that the power quality provided by the DFIG based WECS is better compared to WECS using SCIG near synchronous speed while the power quality of WECS using SCIG is better at very low and very high wind speeds.

Table 2: Comparison of THD for both types of WECS at various wind speeds

Total Harmonic Distortion, THD (%)				
Wind Speed (m/s)	*DFIG*		*SCIG*	
	THD for V	*THD for I*	*THD for V*	*THD for I*
5	2.51	38.28	0.70	19.02
6	2.03	26.46	0.63	13.73
7	1.46	15.76	0.69	13.14
8	0.77	5.65	0.55	8.86
9	0.36	1.12	0.70	6.32
10	0.65	2.2	0.51	4.76
10.5	0.88	3.26	0.52	5.44
11	1.20	3.96	0.69	5.3
12	1.82	4.73	0.47	4.39
13	1.79	4.35	-	-

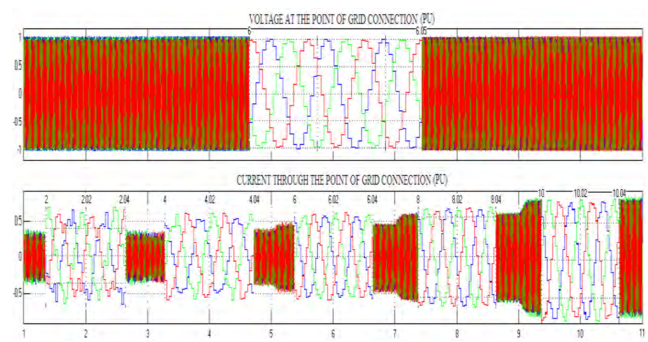

Figure 6: Voltage and current waveforms at the point of interconnection between grid and DFIG based WECS.

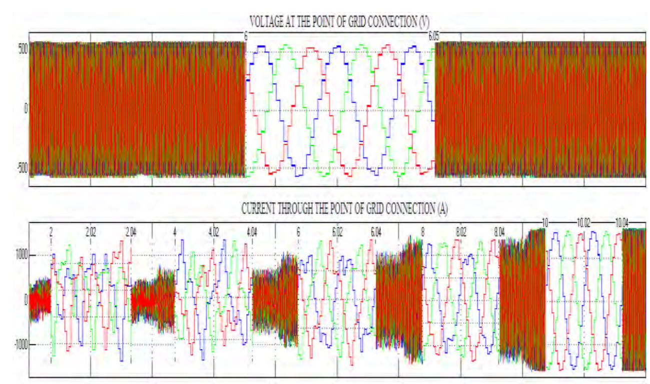

Figure 7: Voltage and current waveforms at the point of interconnection between grid and SCIG based WECS.

V. Conclusion

An attempt has been made in this paper to compare the performances of the WECS based on DFIG and SCIG, pertaining to power quality, range of wind speed that each of the generators can handle and power harnessed from both WECS at various wind velocities. The system models are developed in the MATLAB Sim Power Systems toolbox. Wind turbine characteristics are embedded in both of the models to harness maximum possible power from the wind. Both of the models have been developed based on dynamic vector control approach. DFIG seems to be a better option compared to SCIG especially at the sites with low wind speeds. However, SCIG is able to generate marginally higher amount of power as compared to DFIG at wind speeds corresponding to synchronous speed of machine. The THDs of voltage and current are lower in the case of DFIG. This may be attributed to the fact that the stator of the DFIG is directly tied up to the grid whereas the power converters (that distort the voltage and current) at the rotor side handle only a small portion of the total power generation. In all, this paper presents a complete performance comparison of WECS based on DFIG and SCIG for large power ratings.

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