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An innovative approach of control and simulation based analysis of doubly fed electrical machines for harnessing wind energy

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Abstract

Background/Objectives: Wind energy systems are need of the hour from electrical energy system point of view. Doubly fed electric machines are best suited for wind systems due to their ability to work under variable speed conditions.

Methods/Statistical analysis: This paper proposes a new configuration of doubly fed induction generator (DFIG) called as single external feeding of DFIG (SEF-DFIG) which has significant merits over the former system.

Findings: The operating mode is presented with detailed analysis of the proposed system. Extensive simulation study is carried out by considering a hybrid energy system which consists of wind as well as other renewable energy sources.

Application/Improvements: The results obtained during the simulation case study demonstrate the usefulness of the proposed system.

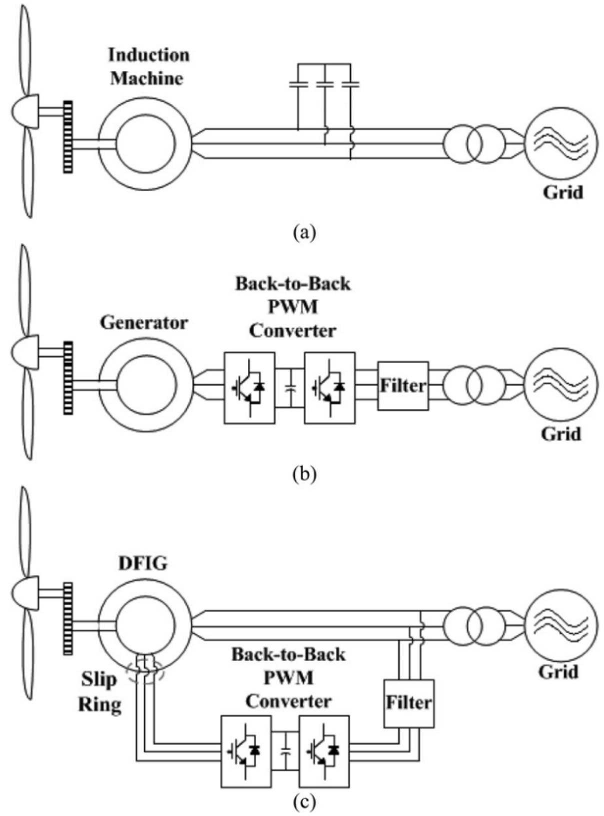
Keywords: Doubly fed induction generator, hybrid energy system, green energy, simulation, variable speed conditions.

1. Introduction

Conventional energy sources like thermal, fossil fuels like petroleum, coal, etc are depleting day by day thereby exploiting these resources to the fullest possible extent. Therefore, this calls for much attention and focus on the harnessing and exploitation of the non-conventional energy resources such as energy from sun, wind, rain, oceans, geothermal, ocean thermal, tides. This move will substantially contribute to the overall decrease in the much alarming greenhouse gas (GHG) emissions which might be a potential threat to the survival of human beings in the near future. This paper focuses on the Wind energy systems which are easy to harness and available everywhere in this world. Wind energy is already in use to maximum possible extent in many developing countries such as Denmark, Italy, etc. India is focusing on wind energy systems seriously and tries to implement a well-defined action plan in this context [1-10]. Wind energy system is well suited for Indian agricultural scenario and can be used to supply power to agricultural pumping systems. Wind systems from the beginning use doubly fed electrical machines for the power production and these are connected to the wind turbines. It is well known fact that the wind energy The principle advantages of these machines is that they perform well in case of variable speeds which is due to the nature of the wind speed. The speed of the wind is stochastic in nature and not constant always to extract power from this natural resource. Doubly fed electric systems are slowly gaining prominence in the recent years and their presence is seen in every daily and household energy needs [11-23].

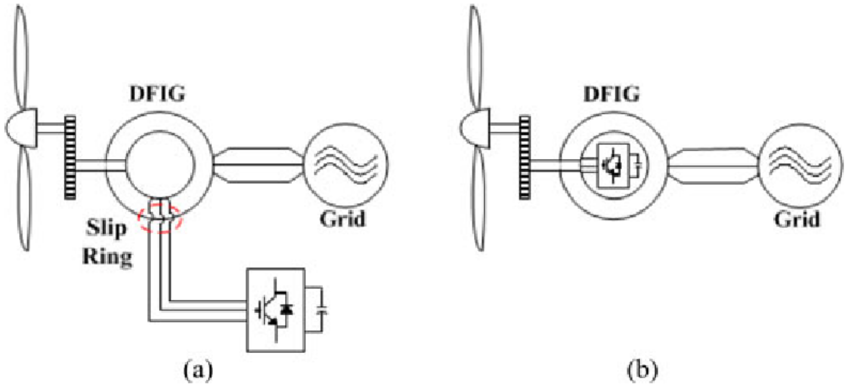
Figure 1(a) represents the direct gird coupled system where the rotor of the electrical machine is shorted or sometimes connected with resistive elements. The PWM converter based variable speed wind system is depicted in Figure 1(b). But, these systems are in much demand due to robust grid code. In this case of energy system, the whole power flow is inherently through the converter enhancing the capacity or rating of the converter but the control of the output power is very well possible and also UPF condition is also a reality from operation point of view.

Figure 1. (a) Grid coupled system (b) System machine in single feeding mode, and (c) System with induction machine in doubly feeding mode



The Doubly fed induction generator (DFIG) coupled to variable speed system is enacted in the Figure 1(c). It is similar to configuration in Figure 1(b) expect for the fact that not the complete output power will flow through the solid state based device and in fact only slip power flows through the solid state based power electronic device(converter).Therefore, the capacity or rating is significantly reduced to typically 25%-30% of the previous configuration. The only disadvantage is that the brushes and slip rings are necessary [15-26].

Figure 2. (a) Wind setup and DFIG with slip rings and (b) Without any slip rings



In this paper a new configuration of DFIG is proposed which is significantly different from the conventional DFIG which is called as Single External feeding of DFIG (SEF-DFIG). In this new configuration, inverter in case of conventional DFIG rotor side is substituted with back to back converter as depicted in Figure 2(a) and 2(b). The inverter present on the rotor side of the electrical machine derives power from the grid connected stator windings. SEF-DFIG facilitate control of power throughput as the parameters like wind generator speed, torque, power are controllable. The rotor side inverter is directly connected to the rotor shaft and completely separated from the gird which in turn cuts down the huge requirement of converter and filter on the gird side. Also the brushes and slip rings are not required for this type of configuration. This calls for sophisticated controlling techniques of DFIG with stator parameters without any rotor side measurements. This paper lays emphasis on the various controlling methods and operating techniques of SEF-DFIG which is shown in Figure 2(a). The power output is controlled by the torque parameter and dc-link voltage is regulated with the help of rotor power. The various operating modes of SEF-DFIG are elaborated clearly in the following sections. During any fault occurrence in the gird is also studied and presented in this paper. The results are detailed in further sections which demonstrate the effectiveness of the proposed technique and new configuration of DFIG.

2. Vector control of d fig

In SEF-DFIG, the stator is connected to the gird which is the sole source of power and the rotor side is connected o dc-link capacitor coupled with PWM inverter which is electrically isolated. The traditional methods of torque and power of stator control as same for DFIG and SEF-DFIG as the control of rotor power balance is undertaken grid-side inverter in both the configurations. The reference frame considered is stator flux. In this section, vector control of DFIG is presented along with dc-link capacitor and rotor side inverter. The conventional DFIG equations in arbitrary reference frame with ω are given as follows:

$$V_a = i_a r_s + P\,[L_{aa} i_a + L_{ab} i_b + L_{ac} i_c + L_{aA} i_A + L_{aB} i_B + L_{ac} i_C] \tag{1}$$

$$V_b = i_b r_s + P\,[L_{ba} i_a + L_{bb} i_b + L_{bc} i_c + L_{bA} i_A + L_{bB} i_B + L_{bc} i_G] \tag{2}$$

$$V_c = i_c r_s + P\,[L_{ca} i_a + L_{cb} i_b + L_{cc} i_c + L_{cA} i_A + L_{cB} i_B + L_{cc} i_C] \tag{3}$$

Apply Parks transformation to equ (1) and equ (3), we get

$$Vqds = rs * iqds + jWe\psi qds + d/dt(\psi qds) \tag{4}$$

$$Vqdr = rs * iqdr + jsWe\psi qdr + d/dt(\psi qdr) \tag{5}$$

$$\lambda_{ds} = V_{ds} - (i_{ds} * r_s) + (\omega_1 * \lambda_{qs}) \tag{6}$$

$$\lambda_{ds} = V_{qs} - \left(i_{qs} * r_s\right) + (\omega_1 * \lambda_{ds}) \tag{7}$$

$$i_{ds} = \frac{\lambda_{ds} - (L_m * i_{dr})}{L_s} \tag{8}$$

$$i_{qs} = \frac{\lambda_{qs} - (L_m * i_{qr})}{L_s} \tag{9}$$

Where the variables and symbols have their usual meanings [1-5]. When ω=0 and stator resistance is neglected, we have. In steady state frequency of stator flux is not changing which is similar to the grid frequency. The value of $d - q$ fluxes of the stator along with their respective differentiations is given by [16], where the symbols have their usual meaning. The torque equation in equation (5) can be written as

$$\mathrm{T_e} = -\frac{3}{2}\frac{P_n}{2}\frac{L_m}{L_s}\left(I_{qr}^{we}\ \lambda_{ds}^{we}\right) \tag{10}$$

$$= -\frac{3}{2}\,\mathrm{K_T}\, I_{qr}^{we}$$

Where K_T is the torque constant.

If the stator resistance is considered as negligible, the reactive and active powers are given in terms of stator flux along d-axis and currents in the rotor ,

$$\mathrm{P_s} = -\frac{3}{2}\frac{L_m}{L_s}\,\mathrm{W_e}\,\lambda_{ds}^{we}\lambda_{ds}^{we} \tag{11}$$

$$\mathrm{Q_s} = \frac{3}{2}\frac{w_e\lambda_{ds}^{we}}{L_s}\left(\lambda_{ds}^{we} - L_m\, I_{dr}^{we}\right) \tag{12}$$

From equation (12) it is clear that q-axis current of rotor controls the active power of the stator. The stator Q is controlled by the d-axis current of the rotor which is clearly implicated from equation (13). The stator PF is regulated using d-axis rotor current as it is well known fact that the PF has relation with wattles power(reactive power) at constant watt power(active power).

3. Control strategies of SEF-D FIG

In case of SEF-DFIG, the rotor is electrically isolated from the gird and the power does not flow through the rotor side inverter except for the windings of the rotor. The power fed to the rotor from the inverter on rotor side is denoted byP_r. The dc link voltage depends onP_r. If this value is positive, power is transferred from dc-link to rotor, else the value is negative, and the power transfer takes place from the rotor to the dc-link. Indirectly, rotor power is used to regulate the voltage of the dc-link. If there exists some instant where the rotor power is equal to inverter power, the dc-link energy is balanced. Neglecting the power consumed by the inverter, the following hypothesis can be made: the constant dc-link voltage can be achieved when$P_r = 0$. In general,P_r is given by

$$\mathrm{P_r} = \frac{3}{2}\,\mathrm{R_r}\left(I_{dr}^{we^2} + I_{qr}^{we^2}\right) + \frac{3}{2}\,\mathrm{s}\,\mathrm{w_e}\frac{L_m}{L_s}\lambda_{ds}^{we} I_{qr}^{we} \qquad (14)$$

For a specific slip, the condition $P_r = 0$ is satisfied by the following equation.In case of SEF-DFIG, we have

$$\mathrm{P_r} = -\mathrm{P_{dc}} = -\mathrm{V_{dc}}\,\mathrm{I_{dc}} = -\mathrm{V_{dc}}\,\mathrm{C_{dc}}\frac{d\,V_{dc}}{dt} \qquad (15)$$

The control of the voltage of dc-link is illustrated in Figure 3. The control technique to generate the reference current is scripted in Figure 4.

Figure 3. Control of dc-link voltage

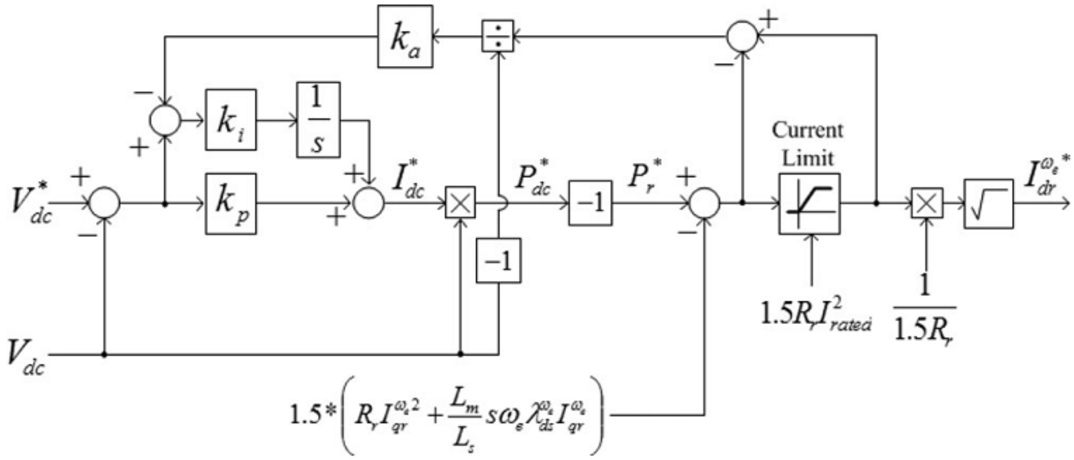
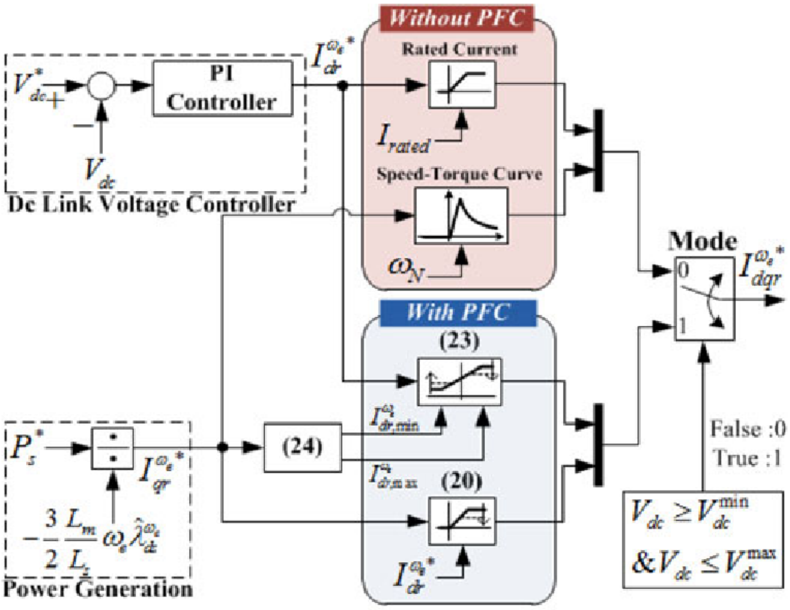


Figure 4. Current reference generator block



The output of power generation block is the reference value of q-axis rotor current [12]. The dc-link voltage is embodied with high PF (HPFC)[25]. The proposed configuration of DFIG does need P and Q power control. In case of Q control, the voltage regulation of dc-link is also taken up simultaneously by interchanging d-q axis rotor currents. It is well known fact that the Q is controlled by d-axis rotor current. The necessary perquisite for making P_r=0 is q-axis rotor current. For control of dc-link voltage, we typically employ a PI controller, whose output is fed current reference block. In general, the reactive power requirement has to be typically met from the grid. In reactive power control of SEF-DFIG , the q-axis rotor current is to made zero which is also required for making P_r=0. Therefore, the constraints imposed on this mode of control are the speed which is variable in nature. When the rotating speed is near to nominal speed, then the reactive power requirement will be automatically low. If the dc-link voltage is not well within the prescribed limits, then conventional techniques of reactive power control can be employed.

4. Wind power generation using SEF-DFIG

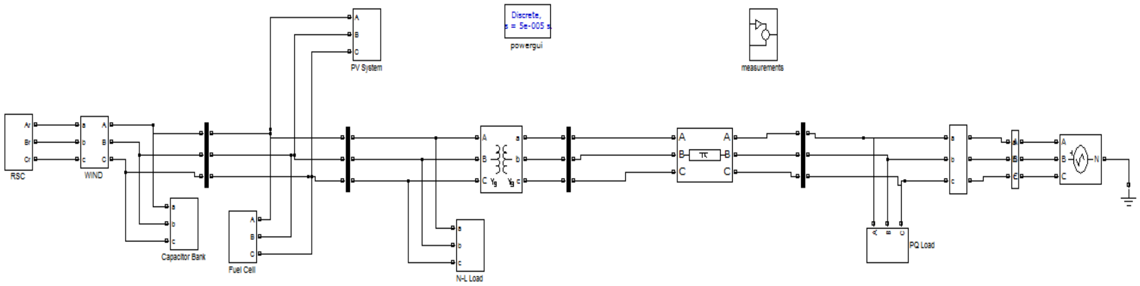
The wind speed is ever fluctuating, which demands for the need of devices like DFIG in the wind energy systems. The wind turbine generator system is operating under non uniform speed mode, which is dependent on wind speed. In case of extraction of maximum power from the wind energy system [3-7], output power is proportional to the third degree of speed of the wind while the torque is proportional to second degree and speed of the turbine to the first degree of wind speed respectively. This mode of operation tends to enhance the power throughput by 10% [13]. For a constant value of speed of the turbine, the torque increases to the rated value after which, the torque along with the speed of the turbine are maintained constant and pitch mode of control is employed for controlling the output power. Sometimes, the value of torque reduces for increase in speed of rotation which is not desirable for maximum power extraction and might lead reduction in power output of the wind energy system. The solution for this problem is installing capacitor bank on the stator side of DFIG. The following is the ideal value of capacitance to be chosen for this purpose.

$$C_{comp} = \frac{1}{L_s w \frac{2}{g}}$$

During any fault occurring in the gird, DFIG quickly reacts to these fluctuations in case the DFIG is connected to the grid directly. Therefore, this calls for sophisticated protection schemes to prevent any unforeseen damage to the DFIG [21-25] which is also mentioned in the grid code regulations. In case of traditional DFIG system, low voltage ride through (LVRT) protection scheme is employed. In addition to this, many other schemes have been proposed for DFIG system which can be very well applied to the SEIF-DFIG system in case of system disturbances like voltage fluctuations, short circuit condition which results in excessive flow of current in the system. The dc-link voltage indirectly controls the rotor winding losses. In general, the speed is close of the nominal speed in order to minimize the slip power. The induced voltage in the rotor windings is in direct proportion to the slip. In order to enable current control on the grid side, the dc-link voltage should be always higher than grid voltage even though voltage necessary for rotor windings is low. The losses due to switching occupy lion's share in the losses of the converter, can be minimized by minimizing the dc-link voltage.

5. Results and discussions

Figure 5. Simulation model of the proposed system



The complete grid connected hybrid system is given in Figure 5. The PV system consists of two PV arrays with two PV modules in series mode and boost converter. The ratings of wind energy and fuel energy system are 16KW and 17KW respectively for 11 kV, 50MW power grid connection with load connected to the system. The real and reactive of the system are given in Figure 6. The speed of the wind turbine waveform with respect to time is depicted in Figure 7. The voltage rating and frequency of electrical machine are 460 V and 60 Hz respectively. Figure 8 shows the voltage and current of the DFIG. The reactive power is supplemented according to the requirement of the system for changes in load. Figure 9 shows the rotor speed and direct and quadrature axis currents of DFIG. Figure 10shows the variation of P&Q vs time at grid. Figure 11 shows the variation of P&Q vs time at load.

Figure 6. P,Q vs Time

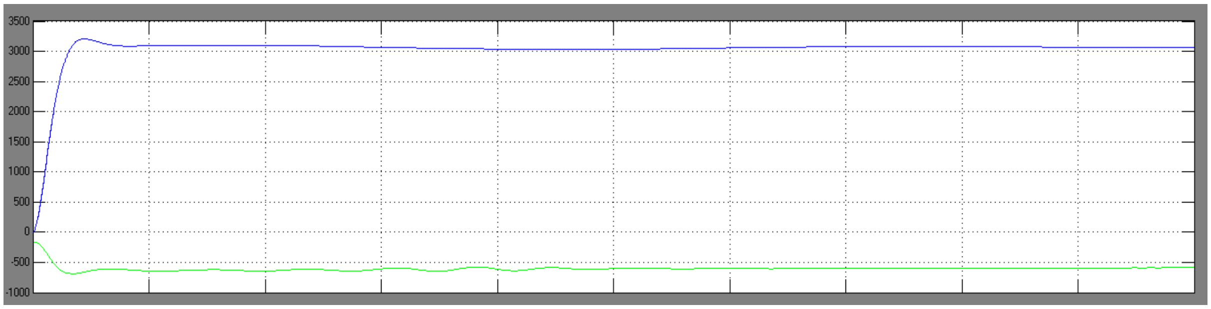


Figure 7. Speed vs time

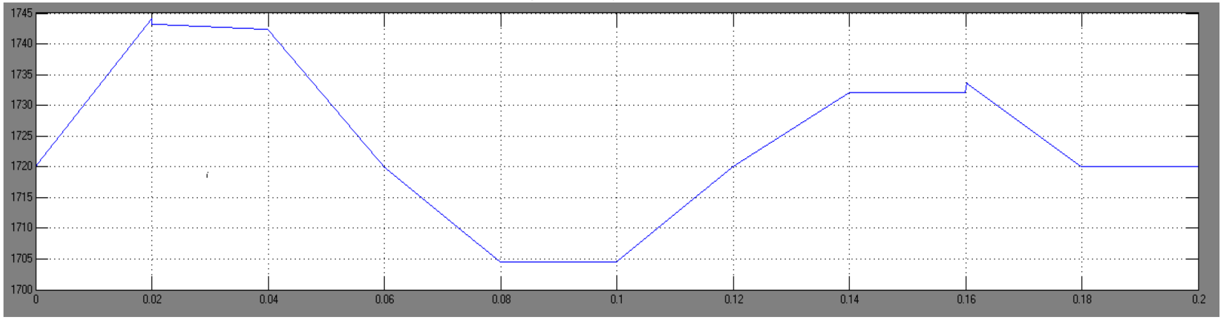


Figure 8. V&I vs Time

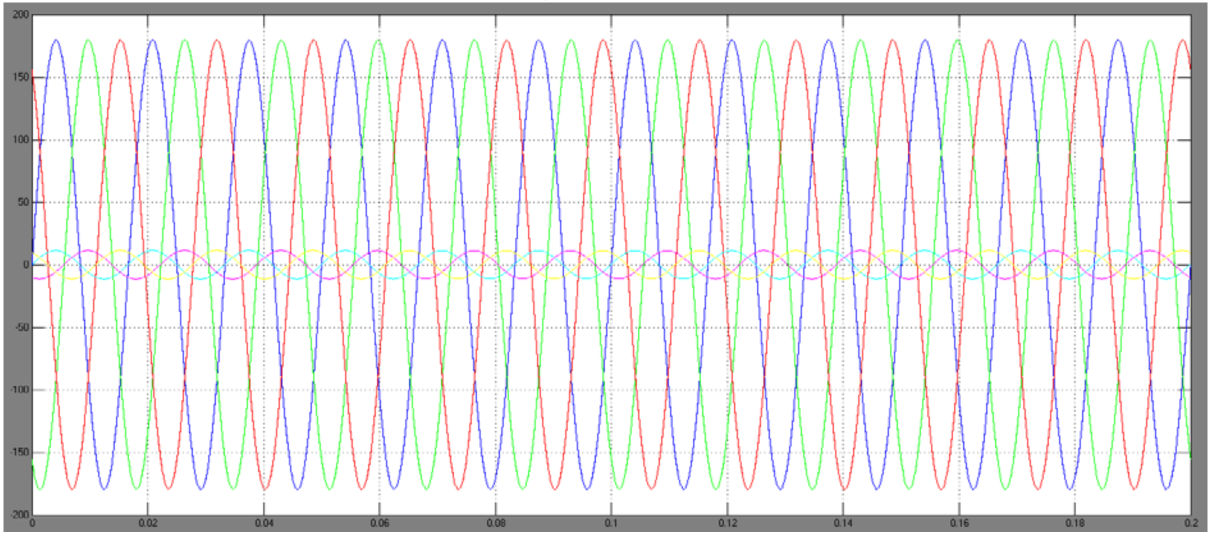


Figure 9. D&Q axes rotor currents vs time

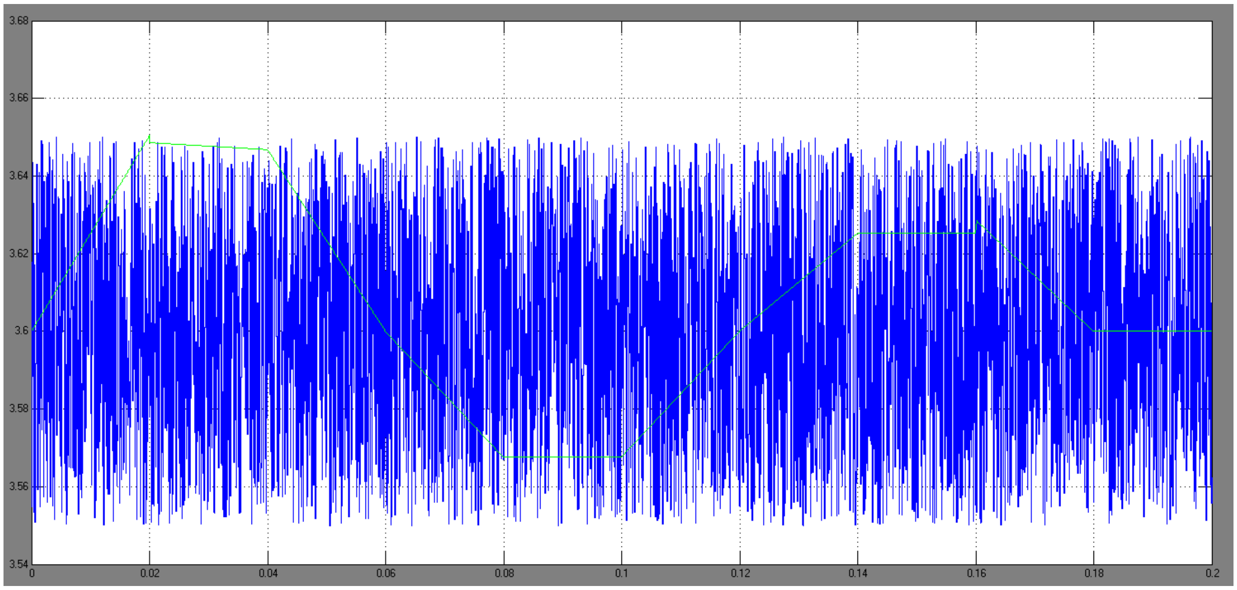


Figure 10. P&Q vs time at grid

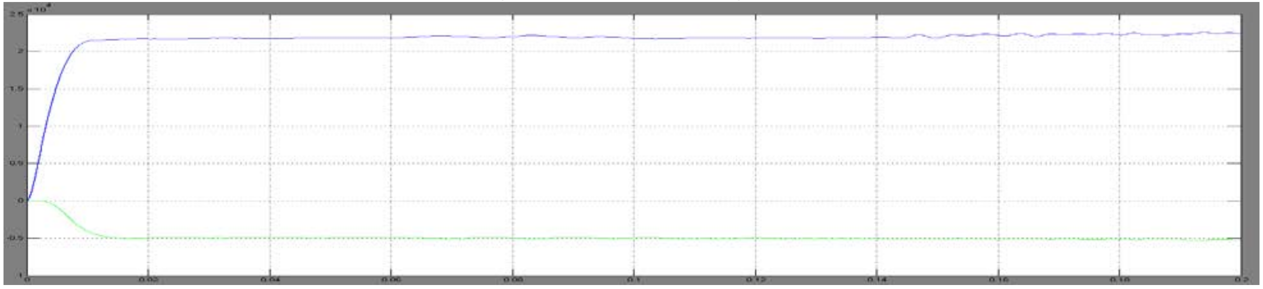
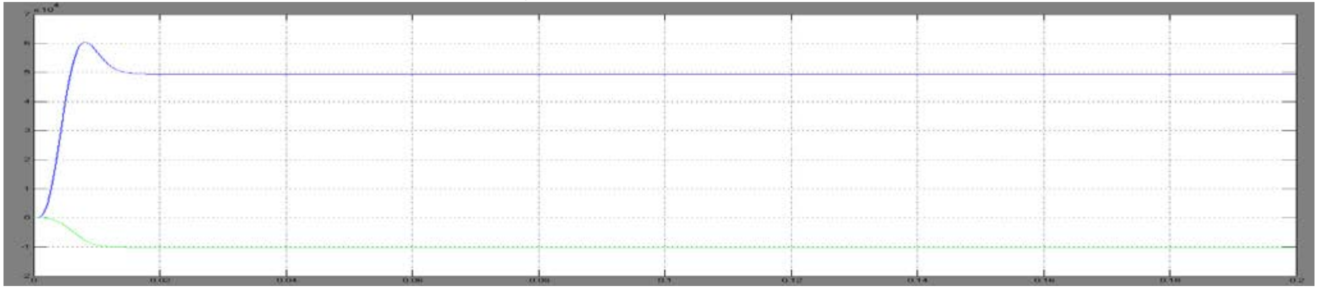


Figure 11. P&Q vs time at load



The real and reactive power consumption in the proposed system is given in Table 1. The load to be met from the hybrid system is 55.2KW and 13 KVAR. In the first case, the combination of wind energy system with SEF-DFIG along with PV and fuel cell system is considered where 27.8 KW and 8.5 KVAR is met by the hybrid system while the difference is supplied by the gird. Hence, the load demand is satisfied using the combination of hybrid energy system and gird connection. In case 2, only wind energy and fuel cell is considered where 22.2. KW and 6.5 KVAR are met and the remaining energy demand is met by the gird achieving generator-load respectively. In case 3, wind energy with PV system is considered meeting 19.2 KW and 6.1 KVAR of load demand with the rest being supplied by the load. In case 4, PV and fuel cell is considered sharing 17.2 KW and 5.8 KVAR of the load remaining being met the gird. In cases 5, 6 and 7 only wind energy, PV and fuel cell are considered individually where 13 KW and 3.5 KVAR, 7.4 KW and 2.5 KVAR, 10.7 KW and 3 KVAR are met by the hybrid system considered in each case and rest being met by the gird.

Table 1. Real and reactive power consumption in the proposed system

Mode of operation	**Wind**		**Pv**		**Fuel**		**Grid**		**load**	
	P	**Q**	**P**	**Q**	**P**	**Q**	**P**	**Q**	**P**	**Q**
W+P+F	11.6k	2.9k	6.4k	2.2k	9.5k	2.3k	27.4k	4.5k	55.2k	13k
W+F	11.6k	2.9k	-	-	9.5k	2.3k	33k	6.5k	55.2k	13k
W+P	11.6k	2.9k	6.4k	2.2k	-	-	36k	6.9k	55.2k	13k
P+F	-	-	6.4k	2.2k	9.5k	2.3k	38k	7.2k	55.2k	13k
W	11.6k	2.9k	-	-	-	-	42.2k	9.5k	55.2k	13k
P	-	-	6.4k	2.2k	-	-	47.8k	10.5k	55.2k	13k
F	-	-	-	-	9.5k	2.3k	44.5k	10k	55.2k	13k

6. Conclusion

The effectiveness of isolated power systems are evaluated in MATLAB PC environment. The system considered is wind along with PV and fuel cells to meet the load which is highly advantageous for remote and inaccessible loads. The proposed DFIG configuration is better compared to the conventional configuration with more power output and improved system characteristics. It is observed that the proposed configuration is low cost and having less complexity. The gird is utilized to supply to the unmet power demand by the isolated power systems if they are connected to the grid. On the whole, the performance of isolated system is better and economically beneficial to the customers at large and is very effective for rural areas to met remote loads.

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