A Novel Equivalent Capacitance Model of DFIG to Study its Reactive Power Control Capabilities and its Ability to Stabilize SEIG

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Abstract--The penetration of wind generation in modern day energy system is increasing day by day. Wind is a variable parameter in nature which has a significant effect on the generator behavior. Since most of the existing installed generators are self-excited induction generators(SEIG), they have a negative effect on the connected system during varying wind speeds and varying load. The primary parameter found responsible is reactive power requirement for self-excitation. So, instead of replacing these generator sets, an alternative reactive power source connected in coordination to machine can well handle these situations. In this context a new promising method of stabilizing SEIG with doubly fed generator(DFIG) is developed in this paper. A new technique of representing DFIG in terms of its equivalent capacitance is developed, to study its reactive power handling capabilities. The potential of the developed model in stabilizing the SEIG during varying wind speeds and varying load conditions is simulated and analyzed. The developed model is independent of complex d-q axis model and simple to understand the behavior of machine. The result shows that this method of supplying reactive power requirement of SEIG is satisfactory in maintaining voltage build up of SEIG. The results obtained are well validated by power balance.

Key words --Self excited induction generator, Doubly-fed induction generator, Capacitance, Stabilization, Reactive power requirement, Wind turbine generating units (WTGU),Varying wind speed, Varying load.

1. Nomenclature

R_s	Stator Resistance
R_r	Rotor Resistance
R_l	Load Resistance
L_s	Stator Inductance
L_r	Rotor Inductance
L_m	Mutual Inductance
X_m	Magnetizing reactance
X_c	Capacitive reactance
V_s, I_s	Stator voltage, Stator current
V_r, I_r	Rotor voltage, Rotor current
v	Per Unit generator Speed
s	Slip
P_e	3-ϕ Active power output of induction generator
Q_e	3-ϕ Reactive power output of generator
Z_g	Total impendence of inverter and transformer
P_s, Q_s	Active and reactive power corresponding to stator
P_r, Q_r	Active and reactive power corresponding to rotor
f	Frequency
X_l	Load Reactance

2. Introduction

In the present day power scenario electricity produced from wind seems to be a promising alternative among various renewable energy sources due to its abundance availability in the nature. Wind generating schemes are classified as fixed speed and variable speed systems depending on type of prime mover used. The SEIG and DFIG are more dominantly used generator configurations which can be operated both in isolated and grid connected modes[1]. These two generators differ in terms of their characteristics and performance during varying wind speeds and varying loads respectively. SEIG requires a capacitor bank connected across its stator terminals to supply necessary reactive for fruitful voltage build up. The value of capacitance connected depends on generator speed and load [2], because magnetizing reactance value responsible for build up of voltage also depends on capacitance and load mix for a particular generator speed [3]. Since wind is a varying parameter, it influences voltage build-upof SEIG. The reactive power requirements of SEIG vary continuously and it should be supplied by an external source in order to retain the generating characteristics. In [4], some methods are proposed to supply reactive power requirement of SEIG and results obtained are compared. On the other hand, DFIG draws power from utility through rotor to meet the magnetization requirements for voltage build up [5].At any wind turbine rotor speed, magnitude and frequency of generated stator voltages is maintained constant by controlling the magnitude and frequency of currents injected in the rotor side.

Different strategies are summarized for active and reactive power control of DFIG [6]. Satisfying reactive power requirements of SEIG during variable speed operation with the reactive power control mode of DFIG is still of interest if we can model the DFIG accurately in its reactive power control mode.The ability of DFIG to deliver reactive power during variable wind conditions is analyzed [7-8]. They assessed the capacity and limitation of reactive power caused by power rating of converter integrated in rotor side. From above literature it is found that reactive power capability of DFIG can be utilized for stabilization of SEIG, but developed models are d-q theory dependent models[9-12], which makes it complex for distribution load flow studies. Meeghapola [13] made a detailed study on reactive power capabilities of DFIG based on rotor and stator capability curves. Ling [14] consolidated entire low voltage ride through methods of DFIG using its reactive power capabilities and external sources as well. In [15], authors developed a new load flow model for reactive power planning considering DFIG reactive power capabilities. In this paper a new model of DFIG, independent of d-q theory which highlights reactive power handling capabilities is proposed. The ability of DFIG in stabilizing a SEIG during varying wind speed and varying load with proposed model is presented in this paper. In this regard new power flow model of SEIG and DFIG are also derived with limited assumptions and explained in following sections. The developed models are well in agreement with power balance i.e., output active power is equal to sum of input mechanical power P_{mech} and losses. The investigation is done for various wind speeds and varying load conditions.

The rest of paper is organized as follows: Section 3 describes detailed modeling of wind turbine, power flow modeling of SEIG and DFIG; Section 4 presents proposed method of representing DFIG in terms of equivalent capacitance for reactive power control; Section 5 explains method for voltage control of SEIG with DFIG during varying wind speeds and varying load conditions; Section 6 gives the conclusions.

3. Modelling and Analysis

3.1. Modelling of wind turbine

Wind turbine converts kinetic energy in the wind into mechanical power required for the generator. The wind power is given by

$$P_w = \frac{dW_w}{dt} \tag{1}$$

The energy drawn by the wind turbine is

$$W_w = \frac{1}{2}\rho\left(V_1^2 - V_2^2\right) \tag{2}$$

where ρ=air density, V_1 = velocity of wind, V_2 =wind velocity at the turbine rotor

The wind power is given as

$$P_w = \frac{d\left[V_a \frac{1}{2}\rho\left(V_1^2 - V_2^2\right)\right]}{dt} \tag{3}$$

According to the Betz maximum power output of the turbine

$$P_w = \frac{16}{27}\frac{\rho}{2}V_1^3 A_R \tag{4}$$

where A_R is area swept by rotor

The mechanical power developed by the turbine is

$$P_m = \frac{1}{2}\rho V_w^3 . C_p \tag{5}$$

$$C_p = C_1\left(\frac{1}{\kappa}C_2 C_3 \upsilon - C_4 v^3 - C_5\right)e^{\frac{-C_6}{k}} \tag{6}$$

$$\text{and } \frac{1}{\kappa} = \frac{1}{(\lambda + 0.08v)} - \frac{0.035}{(1+v^3)} \tag{7}$$

The lambda value is obtained from the power co-efficient curve $C_p(\lambda, v)$ and V_w is wind velocity. The theoretical maximum power extractable from wind is 16/27 times power contained in the wind. For most of wind turbines, operating speed is normally between 8 and 16m/s.The algorithm for developed turbine model is

i. The velocity of the wind is taken as input and wind power is calculated from (3)

ii.For the given pitch angle and Lambda obtained calculate value of C_p from (6)

iii. The mechanical output from wind turbine is obtained from (5)

The P_{mech} output of a wind turbine for given wind speed is shown in Table1. From Table, it is seen that as wind speed increases, power generated by turbine increases.

Table 1. Mechanical power output of Turbine at Different wind Speeds

Wind Speed(m/s)	Pmech(MW)	Power(p.u)
8	-0.22	0.153
10	-0.37	0.25
12	-0.66	0.44
14	-1.09	0.73
16	-1.57	1.04

The characteristic of wind turbine model developed in this paper is shown in Fig.1. From the figure, it is seen that for a given wind speed, turbine produces different power outputs for different generator speeds. So, the generator is made to operate at speed where maximum yield of mechanical power can be achieved. It is also observed that owing to Betz constant, maximum power obtained is 73% at rated wind speed of 14m/s and generator speed of 1.2p.uas shown in figure. The negative sign in the Table1 indicates that power is generated by the turbine. This value of power is embedded as mechanical input to the induction generator models.

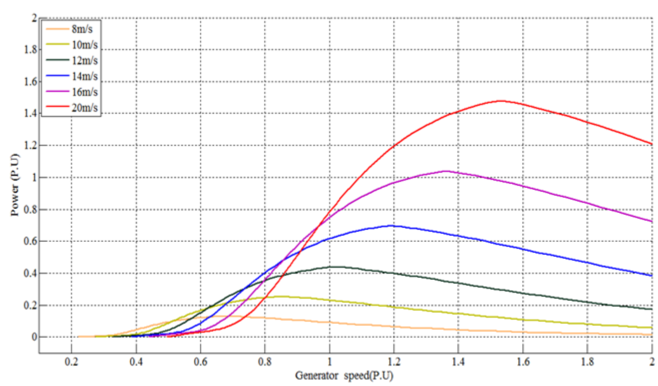

Fig. 1. Wind turbine characteristics

3.2. Modeling and analysis of SEIG

From literature it is seen that magnetizing reactance (X_m) responsible for voltage build up of SEIG depends on capacitance and load combination for given generator speed [3]. The minimum capacitance value required for excitation of SEIG at different wind speeds is calculated for full load condition (1 p.u) .The load is kept at 1p.u or say full load because the generator is made operate at full load in most of the conditions. From Fig. 2, it is observed that minimum capacitance requirement at rated speed of 1500rpm is 68μF. The analysis of SEIG is done by keeping both capacitance and load fixed but varying the wind speed i.e., generator speed. The nodal admittance method of solving the per-phase equivalent model [16] of SEIG is adopted in this paper. The value of X_m is obtained by solving the fifth order polynomial equation in [16].

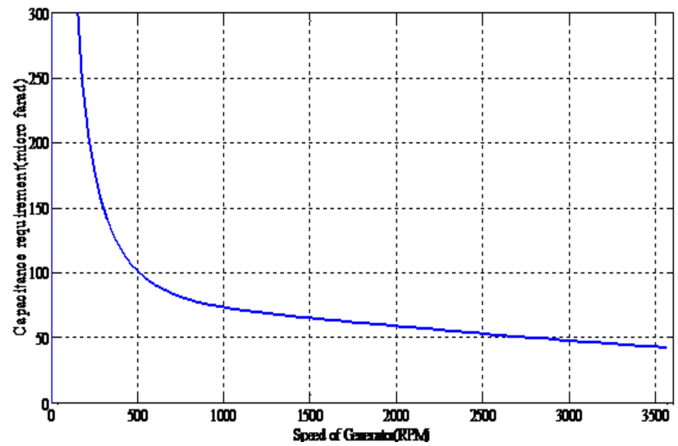

Fig. 2. Minimum capacitance(per-phase) requirement for different generator speeds

The real and positive values of X_m are considered in the analysis of SEIG. Wind speed and excitation capacitance are given as input for (8)-(12), the terminal voltage and active power at different wind speeds is calculated. The value of reactive power is calculated as function of active power and terminal voltage.

$$I_s = \frac{\frac{E_s}{f}}{\frac{R_s}{f} + jX_s - \frac{jX_c R_L}{f^2 R_L - fX_c}} \quad (8)$$

$$I_R = \frac{-\frac{E_s}{f}}{\frac{R_R}{f-v} + X_R} \quad (9)$$

$$I_L = \frac{-jX_c I_s}{R_L f - jX_c} \quad (10)$$

$$V_T = I_L R_L \quad (11)$$

$$P_{out} = 3|I_L|^2 R_L \quad (12)$$

Substituting the value of voltage and active power [17] the reactive power can be estimated

$$Q_{out} = \frac{A}{B} \quad (13)$$

where

$$A = [X_m X_r s^2 (X_m + X_r) + X_s s^2 (X_m + X_r)^2 + R_s^2 (X_m + X_s)]V^2$$

$$B = [R_s R_r + s(X_m^2 - (X_m + X_r)(X_m + X_s))]^2 + [R_r (X_m + X_s) + sR_s (X_m + X_r)]^2$$

Considering above equations, SEIG is modeled and performance of machine for varying wind speeds is observed.From the results in Table 2 it is seen that, as wind speed varies terminal voltage also varies. If speed is less than minimum value suitable for capacitance value, there is no excitation which results in voltage collapse. During such a case in normal practice, generator is cut off from load or utility. The generator maintains the rated voltage of 1.36kV(per-phase) at a wind speed of 12m/s. When the speed reaches 10m/s voltage value reduces and further reduction in speed below 10m/s the terminal voltage collapses as shown in Table 2. This is because the fixed capacitance of 68μF is not sufficient for the machine to retain its excitation at this low wind speed.

Table 2. Voltage Build Up at Different Wind Speeds

Wind Speed (m/s)	Generator speed (rad/sec)	Speed (p.u)	V_t kV (per phase)	Excitation capacitance (p.u)	P_e MW	Q_e MVAr
12	157.5	0.9	1.36	1.0	0.65	0.023
10	133	0.85	1.00	1.0	0.27	0.003
9.5	125	0.8	Voltage collapse	1.0	--	--
9	117	0.75	Voltage collapse	1.0	--	--
8	102	0.7	Voltage collapse	1.0	--	--

In the literature many methods were proposed and explained to control the terminal voltage of SEIG. In this paper voltage control of SEIG is done by varying the excitation capacitance virtually, utilizing the reactive power handling capabilities of DFIG. DFIG in terms of its equivalent capacitance is modelled and the interaction of DFIG during this mode with SEIG is analysed in the following sections.

4. Modelling and Analysis of DFIG

4.1 Steady state model of DFIG

The model developed in this paper is steady state model independent of d-q reference frame. This model is derived from [18-19], reducing complexity in drawing the exact characteristics of DFIG. The two inputs required for this model are the stator voltage and wind speed. The rotor voltage, rotor and stator active reactive powers are given in (14)-(16). The change in wind speed forces the rotor side converter to inject currents necessary for generating rated stator voltage, hence rotor voltage changes with respect to change in wind speed. If the generator speed is in sub-synchronous region generator absorbs power from rotor side in order to maintain the necessary magnetizing reactance for stator to produce power. If the machine is running in super-synchronous mode, power absorbed by rotor decreases and power flow takes place from both stator and rotor side. Substituting (16) in (15), we can obtain two equations having two unknown variables. There are two equations having two unknowns which are solved using Newton-Raphson iterative method. Solving these equations gives the value of I_s and I_r i.e. the stator and rotor currents. The performance characteristics of DFIG at different wind speeds are given by (17) to (21).

$$V_s \angle \psi_s = R_s + j(X_s + X_m)) I_s \angle \phi_s + jX_m I_r \angle \phi_r \tag{14}$$

$$V_r \angle \psi_r = R_r + j(X_r + X_m)) I_r \angle \phi_r - jX_m I_s \angle \phi_s \tag{15}$$

The relation between stator and rotor voltages is given as

$$V_r = jX_r I_r + \frac{X_m}{X_s} sV_s \tag{16}$$

The real and reactive power output of the grid side VSC reaching a point of common coupling (PCC) when DC link is considered lossless [20]is given by

$$P_r = real\left\{ V_s \left[\frac{V_s - V_r}{Z_g} \right]^* \right\} \tag{17}$$

$$Q_r = imag\left\{ V_s \left[\frac{V_s - V_r}{Z_g} \right]^* \right\} \tag{18}$$

The real and reactive powers of the wound rotor induction machine are given from the following equations

$$P_s = real[V_s I_s^{\,*}] \tag{19}$$

$$Q_s = imag[V_s I_s^{\,*}] \tag{20}$$

The total active and reactive power output of DFIG is

$$P_e = P_s + P_r \tag{21}$$

$$Q_e = Q_s + Q_r \tag{22}$$

$$P_{mech} = P_s + P_r + P_{loss} \tag{23}$$

where $P_{loss} = I_s^2 R_s + I_r^2 R_r$

From the above equations the power output and rotor voltage of DFIG is obtained for different wind speeds.

Table 3. Performance of DFIG at different Wind Speeds

Wind Speed (m/s)	Generator Speed (rad/sec)	P_e (MW)	Q_e (kVAr)	V_r (V)	P_{mech} (p.u)	P_e (p.u)
8	102	-0.22	-9.03	142.94	0.16	0.146
10	133	-0.34	-19.3	136.3	0.25	0.236
12	157.5	-0.64	-23.9	64.2	0.44	0.42
14	188	-1.07	-18.4	-153	0.73	0.72
16	212	-1.5	-69.53	-396	1.04	1.026

In the above Table 3 negative sign indicates power flow out of generator and positive sign indicates that power is observed by generator. During sub synchronous mode rotor voltage is positive which means power is absorbed from rotor side, which is from wind speed of 8m/s to 12m/s. During super synchronous mode rotor voltage is negative which means power is injected from both rotor and stator side, which is from 14m/s to 16m/s. The power factor obtained at different wind speeds is constant and hence model developed is constant power factor model that can be easily injected into power flow studies. The validation of model can be justified as given in (23),generated power is almost equal to its input mechanical power and difference is the losses in the generator.

4.2 Equivalent Capacitance model of DFIG

The method of supplying reactive power requirements of SEIG from DFIG during varying wind speeds and varying load conditions is explained in this section. In the equivalent capacitance model, machine is considered as a rotating transformer. The reactive power enhancement in DFIG depends up on reference value of rotor side convertor controller. Since power electronics converters are designed to withstand 150 % of rated current, hence the rotor side converter current limit is increased beyond the normal value for reactive power control. For this analysis analytically, a new term 'K' is introduced into steady state equations (14) and (15), this term resembles the current limit of rotor side converter as given in (27) and it is varied between 1 and 1.5. The value of rotor side and stator side currents is obtained by solving (24) and (25).For rotor power absorbed, corresponding stator current is calculated by solving these equations. Once imaginary component of stator side current is known, reactive power can be calculated using (22). The obtained reactive power can be converted in to equivalent capacitance using (26).

$$V_s\angle\psi_s = R_s + j(X_s + X_m))I_s\angle\phi_s + jX_m * K * I_r\angle\phi_r \qquad (24)$$

$$V_r\angle\psi_r = R_r + j(X_r + X_m))*K*I_r\angle\phi_r - jX_m I_s\angle\phi_s \qquad (25)$$

$$X_c = \frac{Q_e}{imag[I_s^2 \sin(\tan^{-1}\frac{Q_e}{P_e})]} \qquad (26)$$

$$I_{r\,new} = K * I_r \qquad (27)$$

$$Q_{\max} = \sqrt{S^2 - P_r^2} \qquad (28)$$

The value of X_c gives equivalent capacitive reactance value of DFIG. The value of 'K' is varied until equivalent capacitance value obtained matches with required capacitance of SEIG to self excite. By applying this method it is observed that reactive power output changes with high difference with small change in the rotor current limit. The algorithm for operation of DFIG in reactive power mode is explained with the help of the flow chart shown in Fig. 3. The program converges when equivalent capacitance value reaches desired capacitance value for SEIG to self-excite, provided the value of 'K' is less than 1.5 and X_c is equal to the value obtained from Fig.2. In the flow chart mode 1 indicates normal operation of DFIG and mode 2 indicates reactive power control mode. The maximum reactive power output at different slips is always limited by the rating of the machine, which is given by (28).The value of current limit of the rotor side converter can be increased until the reactive power output value reaches Q_{max}.During the conventional operation of DFIG there is no increase in the reactive power, for rated active power output of DFIG reactive power output is not more than 30% of active power. From (16) it is observed that reactive power output depends on difference of stator and rotor voltage. When the rotor voltage increases naturally DFIG will have the capability of producing more reactive currents owing to machine power rating given by (28).

Table 4. Equivalent capacitance of DFIG at different wind speeds

Wind Speed (m/s)	Generator Speed (rad/sec)	Rotor side Converter current	Equivalent Capacitance per phase (µF)	Capacitance (p.u)
12	157.5	$I_{rnew}=I_r$	10.2	0.15
10	133	$I_{rnew}=I_r$	15.5	0.23
9.5	125	I_{rnew} =1.24 I_r	22.56	0.32
9	117	I_{rnew} =1.45 I_r	30.3	0.43
8	102	I_{rnew} =1.48 I_r	37.4	0.55

5. The result from Table 4 shows that by increasing the current limit of rotor side converter, reactive power produced by DFIG increases and hence enhances its capabilities. As wind speed reduces rotor side converter is made to draw current from utility and injects more reactive currents on the stator side and thus equivalent capacitance value increases. The developed model demonstrates the reactive power handling capabilities of DFIG very well.Voltage Control of SEIG with DFIG

The voltage build up of SEIG depends on both generator speed and value of the load connected. The reactive power requirement of the machine changes with wind and load variations. So, the reactive power requirement of SEIG is supplied in order to maintain the generating characteristics. In this section, the ability of DFIG in stabilizing SEIG during wind and load variations is demonstrated using proposed equivalent capacitance model.

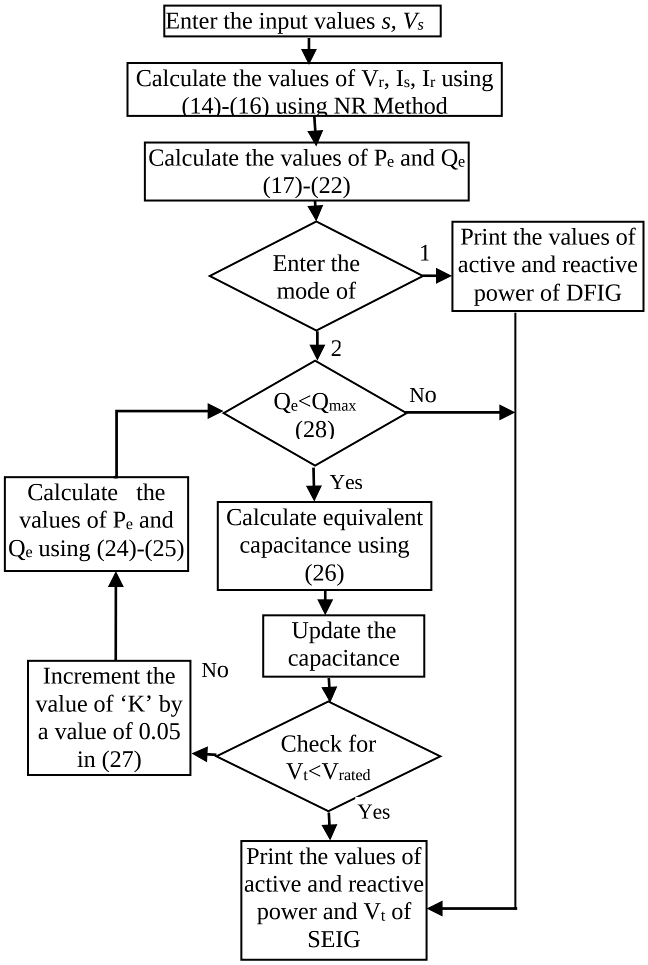

Fig. 3. Flow chart for proposed Model

The condition of wind variation is taken from 12 to 8m/s, load variation is considered for critical condition of low wind speed (8m/s) and high load of 1.0 p.u for effective demonstration of the model.

5.1 Voltage control during different wind speeds

The reactive power flow during normal wind speeds takes place from SEIG to load .When the wind speed reduces, SEIG acts as reactive load which is a additional burden to utility, so in the proposed method DFIG changes its mode of operation and supplies the necessary reactive power of SEIG to maintain its generating characteristics, the flow of the reactive power in different cases is shown in Fig.4

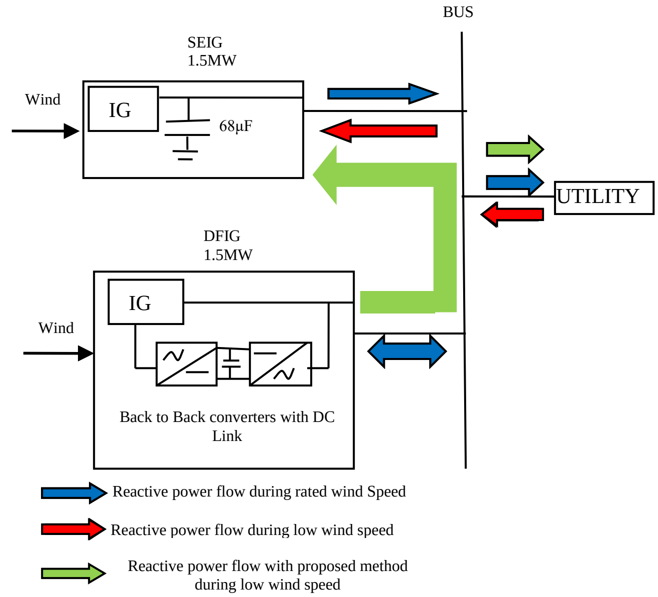

Fig. 4. Reactive power flow during normal mode and proposed mode of operation

The reactive power required by SEIG for its voltage build up requirement during low wind speed is converted into equivalent capacitance, which can be obtained from Fig.2.The DFIG is made to produce this required reactive power with the help of (24) and (25) and this reactive power is converted into equivalent capacitance using (26).The capacitance value obtained is added to parallel capacitance connected across SEIG which is a constant value (1 p.u) as shown in Table5. If terminal voltage reaches rated value of 1.36kV,program converges or else, value of 'K' is incremented by a value of 0.05 until it reaches the maximum limit of 1.5and also $Q_e<Q_{max}$(28).

Table 5. Stabilization of SEIG with DFIG at different wind speeds

Wind speed (m/s)	Speed (rad/s)	$X_c$added from DFIG (p.u)	Total Excitation Capacitance (p.u)	V_t kV	P_e MW	Q_e MVAr
12	157.5	Nil	1.0	1.36	0.65	0.026
10	133	0.19	1.0+0.23	1.36	0.39	0.025
9.5	125	0.34	1.0+0.32	1.36	0.31	0.024
9	117	0.43	1.0+0.43	1.36	0.263	0.024
8	102	0.55	1.0+0.55	1.36	0.22	0.023

From above Table 5 it is observed that reactive power supplied by DFIG is well sufficient for SEIG to escape from voltage collapse, and maintain its generating characteristics during low wind speeds. The terminal voltage at different wind speeds is constant and equal to rated value of 1.36 kV per phase as shown in Fig.5.

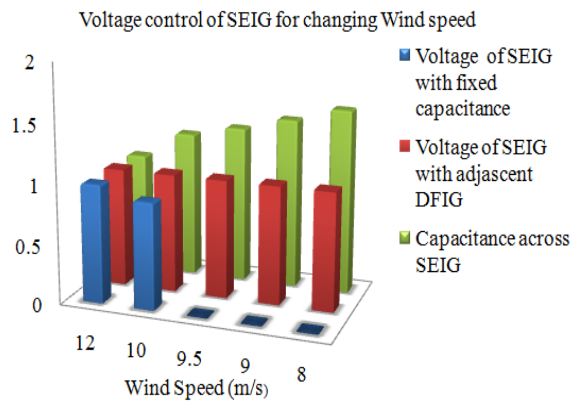

Fig.5. Voltage build up of SEIG during normal mode and proposed mode for different wind speeds.

FromTable2, it is observed that machine voltage collapses when wind speed is less than 10m/s. When DFIG is supplying necessary reactive power during its reactive power control mode, SEIG escapes from state of under excitation and voltage collapse. More over due to increase in value of terminal voltage, value of active power output of SEIG is also increased which can be observed by comparing Table3 and Table 4. This method of voltage control increases the generating capacity of SEIG for wide range of wind speeds. The power generating capability of SEIG is increased from 12m/s to 8m/s without using any additional equipment or investment. The DFIG in normal operation supplies active power in addition to SEIG which aids to health of power system. This method of control can assist DFIG to supply reactive power for utility even at wind speed close to zero.

5.2 Voltage control during different loads

Variation of load also shows effect on the SEIG voltage build up characteristics [1-3]. The SEIG's reactive power requirement changes with variation in load. The condition at low wind speed of 8m/s is considered and load is assumed to be varying in steps of 0.1 p.u from 0.5 to 1.0 for the analysis. In this section robustness of developed model is tested during low wind speeds (8m/s) and varying load conditions (0.5 to 0.9 p.u). From Table 6, it is observed that ,at a load of 0.5 and 0.6 p.u, capacitance connected across SEIG is sufficient to supply the voltage build up requirements and hence DFIG is operating in normal mode. A method of adding virtual load is used control the voltage of SEIG [1], when the capacitance value is more than the required value. If the load increases further, SEIG fails to self excite because of increase in reactive power requirement. In this case DFIG changes its characteristics and is made to operate in proposed reactive power control mode. The current controller of DFIG rotor side converter estimates rotor current limit to be set for generating required reactive power and supplies the required VAR's of SEIG. The capacitance requirement for different load conditions at constant wind speed of 8m/s is given Table 6.

Table 6. Stabilization of SEIG with DFIG at different Loads

Speed (rad/s)	Load on SEIG (p.u)	Voltage build Up without DFIG (kV)	Capacitance added from DFIG (p.u)	Capacitance required by SEIG (p.u)	Rotor Side Converter current of DFIG	Equivalent Capacitance added per phase (μF)	V_t (kV)
102	0.5	1.36	Nil	0.64	I_{rnew}=I_r	Nil	1.36
	0.6	1.36	Nil	0.86	I_{rnew}=I_r	Nil	1.36
	0.7	--	0.10	1.0+0.10	I_{rnew}=1.12I_r	7	1.36
	0.8	--	0.32	1.0+0.38	I_{rnew}=1.32I_r	26	1.36
	0.9	--	0.51	1.0+0.51	I_{rnew}=1.40Ir	34.5	1.36
	1.0	--	0.55	1.0+0.55	I_{rnew}=1.48I_r	37.4	1.36

From Fig. 6 it is observed that, as the load demand at constant wind speed (8m/s) increases, the reactive power requirement of SEIG increases. The DFIG connected adjacent to SEIG should be able to supply this VAR requirement with varying load as shown in figure. The reference current of rotor side converter is varied from 1 to 1.5 such that maximum limit is less than 1.5. The mode of DFIG is shifted to reactive power control mode and generates necessary reactive power for voltage control of SEIG. The results show that terminal voltage of SEIG is maintained constant and generating capabilities are retained at low speed of 8m/s under varying load conditions.

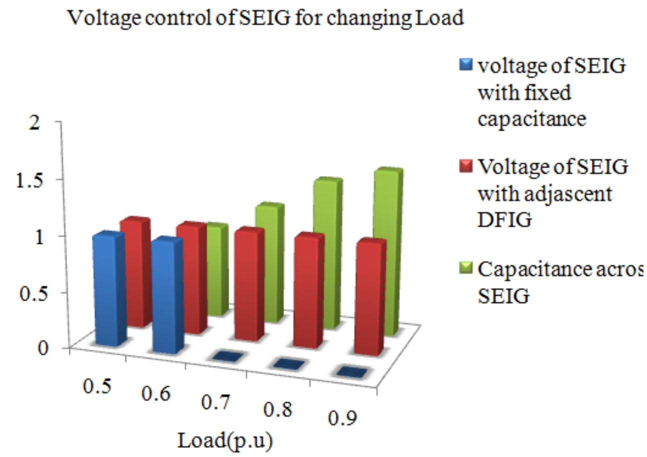

Fig. 6. Voltage build up of SEIG during normal mode and proposed mode for different loads.

6. Conclusion

The results show that DFIG has additional capability of handling reactive power requirements of SEIG. The approach of equivalent capacitance model is simple and independent of complex d-q models and effectively demonstrates the reactive power control mode of DFIG. During low wind speeds instead of disconnecting the SEIG it is made to generate power by supplying the required reactive power for self-excitation from the DFIG. In the case of varying load also at low wind speed of 8 m/s, SEIG is able to retain is generating characteristics with the coordination of DFIG.In this paper power generating capability of SEIG is enhanced from 12m/s to 8 m/s of wind speed in both conditions of varying wind speeds and varying load. Since the assumptions made are very less, accurate results can be obtained by this method. These developed models are well validated by power balance equations. Since these models are derived in steady state platform, they can be easily incorporated into load flow analysis, which is the main objective of this work .These models are suitable for predicting the behavior of the machines during varying wind speed, time varying loads and their effect on the power system. This model can also be extended for load flow analysis of multi machine system during time varying loads very effectively.

7. Appendix

The parameters of the induction machine considered are given below are taken from [17].

Induction machine parameters

Wound Rotor Induction Machine Stator/grid Voltage V_S (r.m.s. L-L)	2400 V
Nominal power : 2250 hp *746 VA	1.6MVA
Nominal phase Voltage V (Per Phase)	1368 V
Nominal frequency (f)	50 Hz
Stator resistance (R_s)	0.029 Ω
Stator inductance (L_{sl})	0.226/377 H
Rotor resistance (R_r)	0.022 Ω
Rotor inductance (L_{rl})	0.226/377 H
Mutual inductance (L_{ml})	13.04/377 H

Inertia coefficient (J)	63.87
Pole pairs (P)	2
Pitch angle(β)	0 degree
Data Nominal mechanical output power (P_{nom})	1.5 MW
Base power of the electrical generator (S_b)	2250 hp
Base wind speed (ω_{base})	14 m/s
Max. power at base wind speed (p.u. of nominal mech. power)	0.73
Base speed (p.u. of base generator speed)	1.2
Excitation capacitance (each phase) (C)	68μF
Inverter and transformer impedance (Zg)	0.37mH

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