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Fault Ride Through Analysis Of Wind Farm In Low Voltage Distribution System

Manju Aggarwal, S. K. Gupta, Madhusudan Singh
Apeejay Stya University, Sohna, Haryana, India, DCRUST, Murthal, Haryana, India
Delhi Technological University, Delhi, India

Abstract

In this paper, a wind farm comprising of squirrel cage induction generators (SCIG) is described and impact of different types of faults, balanced and unbalanced, at different locations in low voltage distribution system has been analyzed. A distribution Static Compensator (DSTATCOM) is being used for Fault Ride through (FRT) analysis of wind farm in low voltage distribution system. The role of a DSTATCOM is to enhance the capability of wind farm as required by grid code for grid below100kV.

1. Introduction

Today, modern energy industry faces a growing awareness regarding the impact of conventional power generation on the environment. Issues such as limited fossil fuel reserves, climate change due to CO2 emissions, brings to attention alternative technologies [1-2] to generate electricity in a more sustainable manner. Wind power is the world's rapid growing source of energy. The penetration of wind power in the electrical grids increases steadily in many European countries, with highest percentage found in Denmark (28%). Increasing penetration of wind turbines into grid system has led system operator to develop new grid codes. Grid code describes the connection condition of wind turbines to grid. The grid codes are mainly related to fault ride through (FRT) capability, power quality issues, grid stability, and reactive power control of wind turbines. Connection requirements of wind power generating units have been explained in [3-7]. Six Grid Codes are selected for the analysis of a generic Grid Code. Among the chosen Grid Codes is Denmark due to the high penetration of wind power. Ireland, EON [8] (a German transmission system Operator (TSO)), Scotland and the UK. The Grid Code of Germany is chosen due to the important wind power market and due to detailed technical descriptions in the Grid Code of EON. The squirrel cage induction generators (SCIG) which typically employ a conventional induction machine, is simpler in design and do not incorporate power electronics and thus do not have issues related to harmonic injection into the system. However, the wind turbines drain large amount of reactive power from the grid which causes low voltage. Reactive power capacity of SCIG [9-14] can be controlled by using shunt capacitors during steady state operation. However, reactive power injection capability decreases during fault conditions therefore, these devices require some additional power electronic compensation devices to fulfil FRT capability. Among other devices DSTATCOM is best suited for such applications as DSTATCOMs are faster, smaller and have better performances at reduced voltages.

This paper explains the analysis of different types of faults i.e. unbalanced and balanced, at different location in low voltage distribution system. The role of DSTATCOM [15-20] is to enhance the FRT capability of wind farm as required by grid code. The fault ride through (FRT) capability, which is one of the most demanding requirement that have been included in the grid codes and shown in Fig.1.The wind turbine should remain stable and connected during the fault while voltage at the PCC drop to 15% of the nominal value i.e. drops of 85% for the part of 150 msec. Only when the grid voltage falls below the curve, the turbine is allowed to disconnect from the grid.

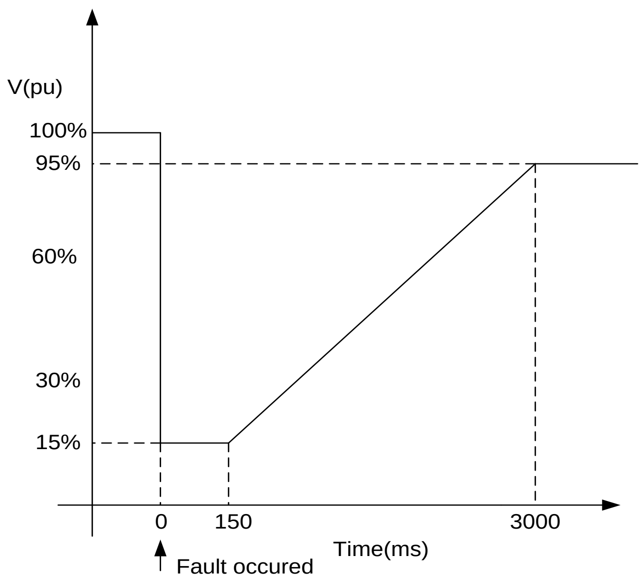

Fig. 1. Fault Ride Through (FRT) capability

2. System Configuration

The proposed system consists of 11kV, 450kVA, 50Hz low voltage distribution system along with a wind energy conversion system (WECS) connected directly to the grid and DSTATCOM as shown in Fig.2. The distribution system consists of a11kV/415V transformer and a feeder. Voltage at the point of common coupling (PCC) is 415V. Wind farm comprising of three 7.5kW Squirrel Cage Induction Generators (SCIG) driven by fixed speed wind turbines. A DSTATCOM supplies the lagging or leading current to manage the constant terminal voltage at PCC during fault conditions.

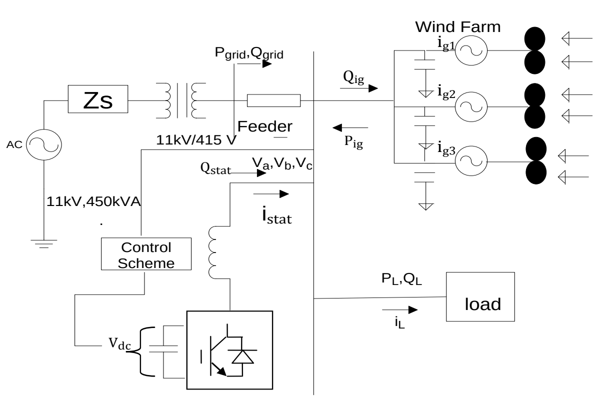

Fig. 2. Basic Structure of Test System

3. System modelling

3.1. Model equations of wind turbine

A wind farm consists of several wind generators connected to the grid system through a single bus. Equivalent model of wind farm [21-22] can be built by combining all wind turbines into single equivalent turbine. By Betz theory, power extracted from air through wind turbine is given by

$$P_{wind} = \rho \frac{\pi R^2}{2} v_{wind}^3 \quad (2)$$

$$P_m = C_p(\lambda , \beta)\, P_{wind} \quad (3)$$

Where P_{wind} is the power absorbed, P_m is the mechanical output power of the turbine and C_p is the performance coefficient of the turbine, λ is the ratio of the rotor blade tip speed to wind speed, ρ is the air density (Kg/ m3) and β is the blade pitch angle in radian, R is turbine radius in meters, v_{wind} is the wind speed in m/s. The equation for $C_p(\lambda , \beta)$ is given by

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right) exp\left(\frac{-C_5}{\lambda_i}\right) + C_6\lambda \quad (4)$$

With $$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (5)$$

Power coefficient C_P is the function of tip speed ratio and blade pitch angle. In order to achieve high C_P, (C_{Pmax}) optimal value of tip speed ratio and blade pitch angle is required and therefore giving the maximum power output at all available wind speed. Optimal value of C_P can be achieved at one optimal value of tip speed ratio i.e. λ_{nom}. So it is required to control tip speed ratio according to wind speed which is known as maximum power point tracking. Active pitch control is used mainly for high wind speed. In the present analysis pitch angle is zero which is a valid assumption for low to medium wind speed. In this analysis the system maximum value of power coefficient ($C_{Pmax})$ is 0.48 when $\beta = 0$.

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3.2. DSTATCOM Control algorithm

Basic working principle of DSTATCOM is described by the following equations. The instantaneous value of current are written using Kirchoff's current law's as

$$i_{grid}(t) = i_L(t) - i_{stat}(t) - i_g(t) \tag{6}$$

$$i_g(t) = i_{g1}(t) + i_{g2} + i_{g3}(t) \tag{7}$$

Where $i_{grid}, i_L i_{stat}, i_g$ are the grid current, load current, compensator current and wind farm current respectively. $i_{g1}(t), i_{g2}(t), i_{g3}(t)$ current supplied by each wind generator

Compensating currents provided by DSTATCOM to make utility voltage purely sinusoidal are given as

$$i_{stat}(t) = i_L(t) - i_{grid}(t) - i_g(t) \tag{8}$$

The main current needs to be sinusoidal for ideal compensation; irrespective of the nature of the load based on the generation of source currents components.

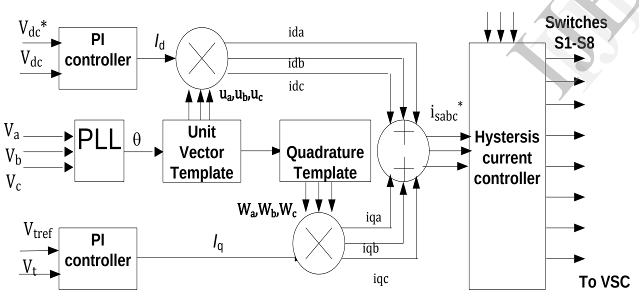

Fig. 3. Control scheme of DSTATCOM

Control scheme of DSTATCOM is shown in Fig.3. Reference source currents are the sum of direct and quadrature axis currents. Direct axis currents (idabc) are derived by first calculating unit vector template from a phase locked loop (PLL) by generating angle θ as

$$u_a = sin(\theta) \tag{9}$$

$$u_b = sin\left(\theta - \frac{2\pi}{3}\right) \tag{10}$$

$$u_c = sin\left(\theta + \frac{2\pi}{3}\right) \tag{11}$$

The in phase component of reference currents are derived using in phase unit vector template as

$$i_{da} = I_d * u_a \tag{12}$$

$$i_{db} = I_d * u_b \tag{13}$$

$$i_{dc} = I_d * u_c \tag{14}$$

Where I_d is the output of PI controller regulating dc bus voltage of DSTATCOM. Quadrature components of reference current are obtained as follows

$$w_a = -u_b/\sqrt{3} + u_c/\sqrt{3} \tag{15}$$

$$w_b = \sqrt{3}u_a/2 + (u_b - u_c)/2\sqrt{3} \tag{16}$$

$$w_c = -\sqrt{3}u_a/2 + (u_b - u_c)/2\sqrt{3} \tag{17}$$

Quadrature component of reference source current (i_{qabc}) is calculated by

$$i_{qa} = I_q * w_a \tag{18}$$

$$i_{qb} = I_q * w_b \tag{19}$$

$$i_{qc} = I_q * w_c \tag{20}$$

Where (I_q) is obtained by by comparing it with the reference voltage i.e. maximum value of desired A.C voltage (Vtref) at PCC. PI controller processes the voltage error. The amplitude of reactive current to be produced by the STATCOM is decided by the output of the PI controller in AC voltage control loop. In inner current loop hysteresis current controller is used, where source currents are compared with reference current derived from outer loop. This enables the source current controlling to be sinusoidal. This method is simple, robust and favorable as compared with other methods.

4. Simulation results and discussion

Fault ride through analysis of wind farm with and without static compensator is analyzed for various types of faults, at different location in low voltage distribution system. The proposed scheme is modeled and simulated in MATLAB/simulink. The r.m.s value of voltage at point of common coupling (Vpcc), rms voltages of each phase (Vabc), rotor speed (w), and reactive power of wind generators (Qig) are presented with and without controller. Positive values of active / reactive power of wind generator and DSTATCOM imply that these powers flow towards PCC.

4.1. Analysis of low voltage distribution system with Line to line fault near grid without/with controller

In order to analyze the behavior of the 11kV, 450kVA, and 50Hz low voltage distribution system following unbalanced fault, a line to line fault has been simulated near grid. Line to line fault is applied at t = 1.0s and clearance time is 150ms. Fig.4 presents the voltage at the point of common coupling (Vpcc), rms voltages of each phase (Vabc), speed of rotor (w), reactive powers absorbed by the generators (Qig) and Fig.5 presents reactive power injected by DSTATCOM and dc link voltage (Vdc) in addition to waveforms of Fig.3.

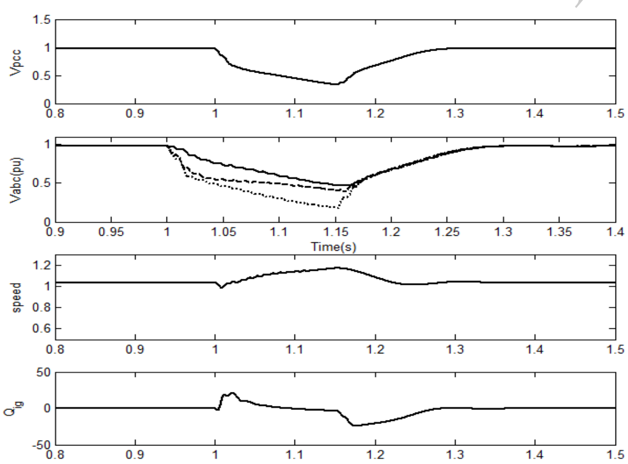

Fig. 4. R.m.s.voltage at the point of common coupling(Vpcc), rms oltages of each phase at pcc(Vabc), speed (w), reactive power absorbed by wind farm(Qig), without DSTATCOM

It has been observed from that DSTATCOM helps in reducing the voltage dip and time to clear fault by supplying reactive power during fault. Frequency increases to 1.2pu without controller but with DSTATCOM it is within range i.e. 1.05pu. The values of voltage at point of common coupling and time to clear the fault for different types of fault at different location has been given in Table1.

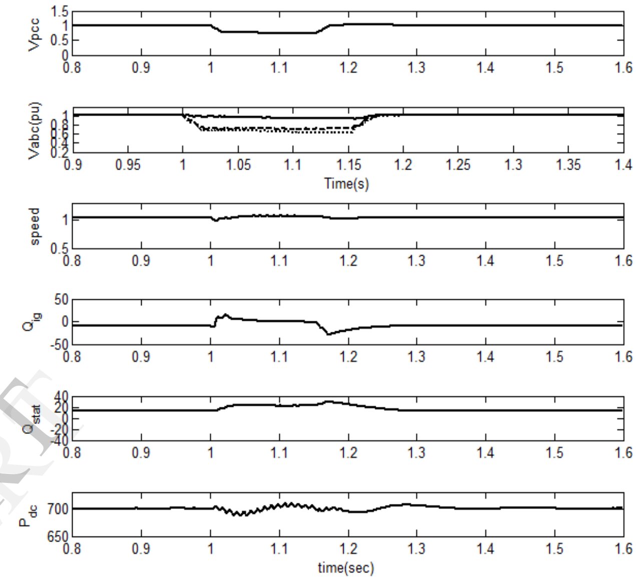

Fig. 5. R.m.s.voltage at the point of common coupling(Vpcc), rms voltage aof each phase at pcc, speed (w), reactive power absorbed by wind farm(Qig), reactive power injected by DSTATCOM(Qstat),dc link voltage(Vdc)

4.2. Analysis of low voltage distribution system with three phase fault near grid without/with controller

To analyze the behavior of the system with balanced fault, three phase fault has been simulated near grid. Fig.6 shows that the voltage at the point of common coupling drops below 0.15pu during fault occurrence which leads to disconnection of wind turbine from the grid as depicted in Fig1. DSTATCOM helps to avoid such situation by supplying reactive power as observed from Fig.7 hence, contributing to FRT enhancement

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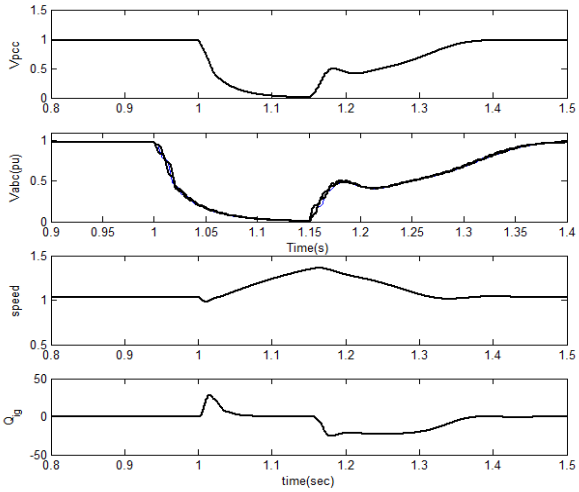

Fig. 6. R.m.s.voltage at the point of common coupling(Vpcc), rms voltage aof each phase at pcc, speed (w), reactive power absorbed by wind farm(Qig), without DSTATCOM

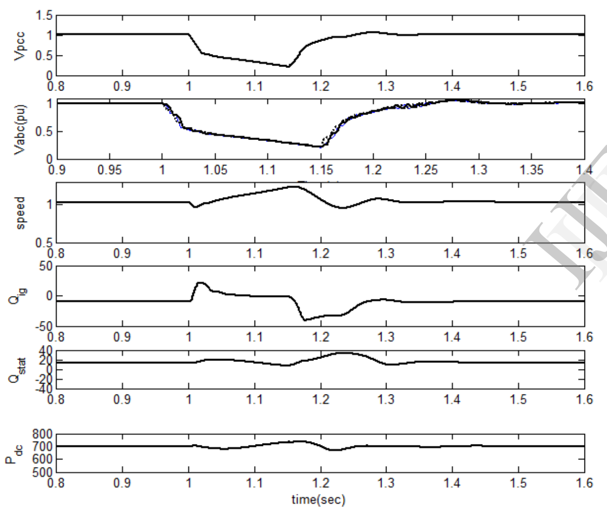

Fig. 7. R.m.s.voltage at the point of common coupling(Vpcc), rms voltage aof each phase at pcc, speed (w), reactive power absorbed by wind farm(Qig), reactive power injected by DSTATCOM(Qstat),dc link voltage(Vdc)

4.3. Analysis of low voltage distribution system with Line to line fault at pcc without controller

Now, the system is analyzed with same type of faults i.e. balanced and unbalanced. However, the location is weakest point i.e. point of common coupling because at this point where the wind turbine is connected to low voltage distribution system and from this point the wind turbine takes its reactive power and sends its generated power to the grid.

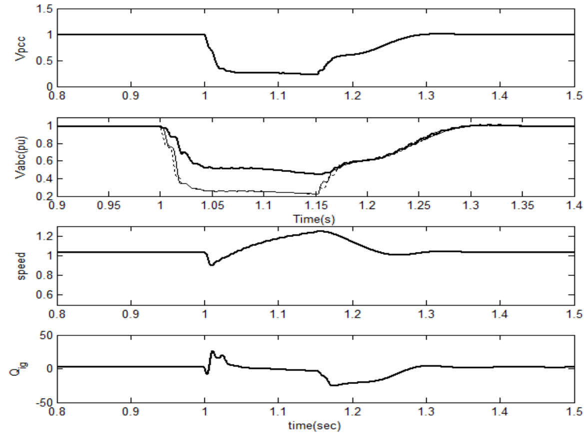

Fig. 8. R.m.s.voltage at the point of common coupling(Vpcc), rms voltage aof each phase at pcc, speed (w), reactive power absorbed by wind farm(Qig), without DSTATCOM

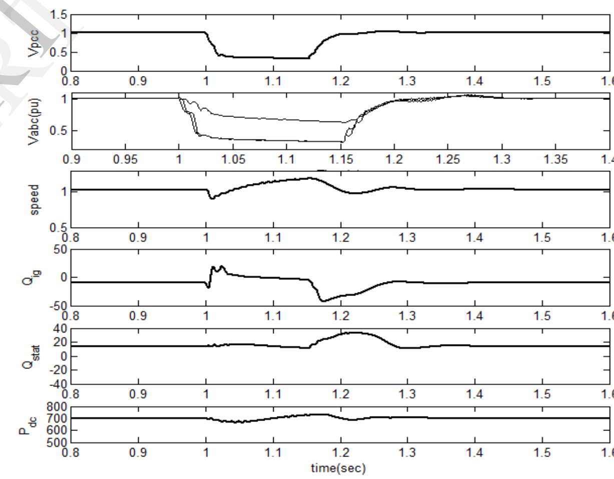

Fig. 9. R.m.s.voltage at the point of common coupling(Vpcc), rms voltage aof each phase at pcc, speed (w), reactive power absorbed by wind farm(Qig), reactive power injected by DSTATCOM(Qstat),dc link voltage(Vdc)

Line to line fault is applied between phase a and phase b. The contribution of DSTATCOM is very little in case of a fault as the voltage drop in fault condition is major, hence reactive power injection is limited. Instead, DSTATCOM plays a vital role in post fault clearance scenario when it injects reactive power as per its rated capacity to help recover the voltage faster and hence improving the system stability

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4.4. Analysis of low voltage distribution system with three phase fault at pcc without controller

For the three phase balanced fault at pcc, the DSTATCOM do not have the ability to let the wind turbine ride through this type of fault because voltage on its terminal will be zero. After the fault clearance DSTATCOM helps in reducing the time to clear the fault.

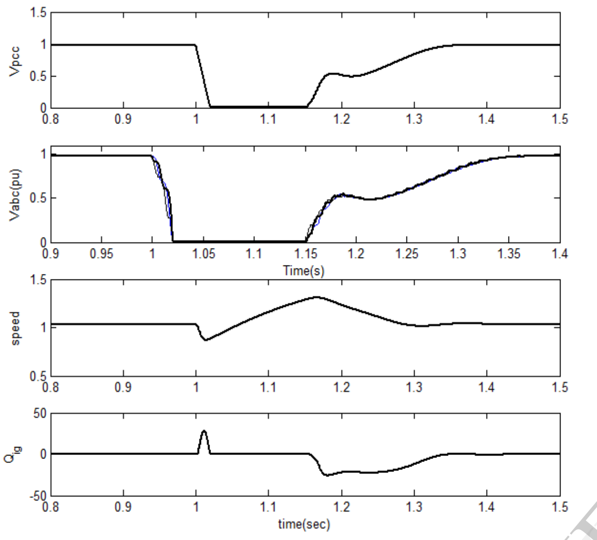

Fig. 10. R.m.s.voltage at the point of common coupling(Vpcc), rms voltage aof each phase at pcc, speed (w), reactive power absorbed by wind farm(Qig), without DSTATCOM

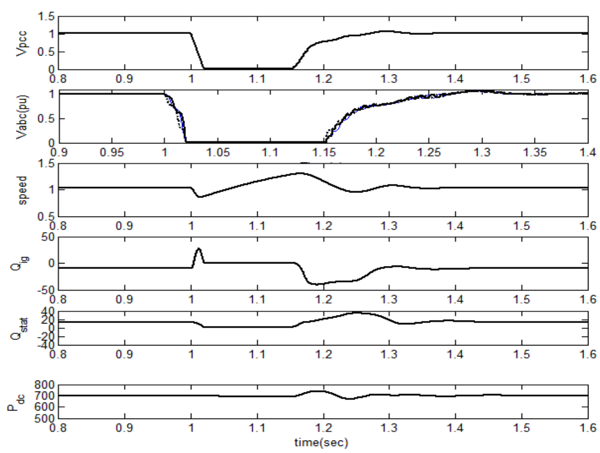

Fig. 11. R.m.s.voltage at the point of common coupling(Vpcc), rms voltage aof each phase at pcc, speed (w), reactive power absorbed by wind farm(Qig),a active power injected by DSTATCOM(Qstat),dc link voltage(Vdc)

TABLE 1. rms voltages at pcc and time to clear fault for different types of fault at different location

Location of fault	Type of fault		Vpcc t=1s t=1.15	Time to clear fault
Near Grid	Three phase fault	Without controller	0	0.24s
		With controller	0.2pu	0.1s
Near Grid	L-L Fault	Without controller	0.22pu	0.15s
		With controller	0.54pu	0.02s
At point of common coupling	Three phase fault	Without controller	0	0.25s
		With controller	0	0.11s
At point of common coupling	L-L Fault	Without controller	0.22pu 0.32pu	0.15s 0.05s
		With controller	0.32pu	0.05s

TABLE 2. rm voltages at pcc and time to clear fault for different types of fault at different location

Location of fault	Rms voltage of each phase	Without controller	With controller
Near grid	Va	0.19pu	0.62pu
	Vb	0.44pu	0.74pu
	Vc	0.45pu	0.93pu
At pcc	Va	0.22pu	0.32pu
	Vb	0.22pu	0.33pu
	Vc	0.45pu	0.63pu

5. Conclusion

This paper analyzes the impact of different types of faults at different location, in low voltage distribution system with and without DSTATCOM. Results shows that DSTATCOM helps in providing voltage support following voltage dips that arise from external short-circuits occurrence. DSTATCOM is considered as an effective means of enhancing the FRT capability of wind farm.

6. Appendix

The parameters of 11kV, 450kVA, and 50 Hz low voltage distribution system are given below:

SCC=450kVA, X/R =7

Feeder parameters:

R= 0.2 Ω, L=4.4mH

Following are the parameters of 7.5kW, 415V, 50Hz, 4-pole Y - connected induction machine:

Rr =0.03pu, Rs = 0.035pu, Xlr = Xls= 0.062pu, J = 0.1384 kg-m2

DSTATCOM Parameters:

Lf = 5mH, Rf = 0.01Ω, Vdc=700volts and Cdc = 8000uF

Parameters of AC voltage regulator

Kiq = 0.008, Kpq = 0.5

Parameters of DC voltage regulator

Kid = 10, Kpd = 0.6

Wind turbine Characteristics:

Three turbines of rating 7.5kW

Cp=0.48, μ = 8.1

$c1 = 0.5176$, $c2 = 116$, $c3 = 0.4$, $c4 = 5$, $c5 = 21$ and $c6 = 0.006$

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