Enhancement of fault ride-through capability of grid-connected wind farm

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Abstract: The distributed power generation (DPG) at low and medium voltage demands that the renewable generation system is always grid connected during fault condition to ensure the stability of wind power system. The DPG consist of wind turbines (WT) along with fixed speed induction generator (FSIG) does not provide accurate reactive power control and hence, there is need for dedicated compensation. Due to fault condition, the negative sequence component is affected and there is direct impact on DPG with reduction in life expectancy. This paper proposes the application of distributed static compensator (DSTATCOM) for fault ride through (FRT) and reactive power compensation. It has been observed that the compensation of negative sequence component improves the performance of FSIG-based WT. Also, the compensation of positive sequence component avoids the collapsing of voltage and improved the stability of WT. The simulation is done in MATLAB and various tests are considered under fault condition in which results are presented. The FRT enhancement of grid connected WT by using DSTATCOM is 30% and hence, 30% additional wind power is penetrated to the grid.

Keywords: distributed power generation; DPG; wind turbines; fixed speed induction generators; FSIGs; fault ride through capability; distributed static compensator; DSTATCOM.

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1 Introduction

Implementation of small power generating sources embedded inside distribution system is referred to as distributed power generation (DPG). It has expanded in the last few years and plays a significant role in future power sector. It improves the system performance, reliability, reduces the technical losses and saves peak demand with other benefits (Dugan and McDermott, 2002). Wind energy is the most prominent renewable power source to be integrated with grid for sustaining the energy supply ecologically (Heier, 2006). There are several challenges in DPG to distribution system operation (Seegers et al., 2004). Due to technological development, there is feasibility to change the generator types used for wind turbines (WT) from fixed speed to variable speed. The amalgamation of squirrel cage induction generator in existing wind farm is 30% in European and Asian countries (EWEA, 2005). The technical standards called as grid codes are implemented by power system operators in wind farm (Ireland National Grid, 2007). The grid codes are classified according to static and dynamic requirements. The steady state behaviour and power flow at point of common coupling (PCC) are involved in static requirements. The WT generator behaviour during fault and disturbances are involved in dynamic requirement. The grid codes carry the power factor regulation, voltage range, frequency range, grid support capability, fault ride through (FRT), low voltage ride through (LVRT), etc. The challenge is to maintain the LVRT capability in grid connected WT. The WT remains connected to grid under voltage sag condition (Yingcheng and Nengling, 2011). The objective of this paper is to investigate the impact of penetrated wind energy on grid system with power quality (PQ) issues. Performance of weak grid system under on grid wind farm has been analysed. The Indian grid codes are strictly implemented for grid connected WT which has been analysed. The reactive power demands under normal and abnormal condition of grid connected WT has been interpreted. The enhancement of LVRT capability has been presented by using custom power device, i.e., distributed static compensator (DSTATCOM). The simulation results are presented in MATLAB.

2 Problem statement

Renewable energy source integrated at distribution level is termed as distributed generation (DG). The utility is concerned due to the high penetration level of wind energy in distribution systems, as it may pose a threat to network in terms of PQ issues and stability. Grid connection of renewable energy sources is essential if they are to be effectively exploited, but grid connection brings problem of voltage fluctuations. Hence, the induction generators are used for direct interfacing with grid. Reactive power consumption increases with increase in number of grid connected induction generators in the power system. The electrical torque of induction generator is given as,

$$T = \frac{3npV_1^2 r_2^1/s}{2pf\left[\left(r_1 + r_2^1/s\right)^2 + \left(x_1 + x_2^1\right)^2\right]} \tag{1}$$

where n_p is number of pole pairs, V_1 is generator terminal voltage, r_2^1 is rotor resistance, s is the slip of turbine, f is voltage frequency, r_1 is stator resistance, x_1 is stator inductance,

x_2^1 is rotor inductance. When fault occur, the electrical output power of the WT is reduced as the electrical torque is proportional to the square of the terminal voltage in (1) (Linyuan et al., 2010).

The speed of WT is constant and hence there is no maximum power point tracking (MPPT) in fixed speed WT. Due to heavy penetration of fixed speed WT the burden of reactive power requirement and its compensation from grid is also increased. In addition to this, during fault condition the reactive power absorption by the induction generator increases. Hence, fixed speed WT has least LVRT capability. Therefore, it would not fulfil the grid code requirement in terms of LVRT. As per the existing nature of Indian grid system and poor infrastructure, the impacts of fault conditions are serious in case of grid connected wind farm.

There is a scope for prettifying the LVRT capability of grid connected fixed speed WT as per Indian scenario. When the Indian grid code is concerned the operator is only focused on constant voltage and frequency. Hence, maximisation of power is also one challenge in existing condition of wind power system. Because of the shortage of power, people suffer due to load shedding problems and hence, to create the encouragement for more utilisation of renewable energy this attempt is need to be considered. The PQ is also affects due to heavy penetration of grid connected WT. During fault, one or more of the phase voltages at PCC may suddenly drop to close to zero. Hence, huge stator transient currents flow (Ling and Cai, 2013). The disconnection of WT during fault condition is also a major issue. The solution against the above mention problem is obtained by using custom power device, i.e., DSTATCOM.

3 Grid codes requirements

There are some technical rules for the connections of electric generators to the grid, so as to ensure the continuous, reliable and economical operation of power system. These technical rules are called as grid codes [Australian Energy Market Operator (AEMO), 2011]. The grid codes are generally applicable to large wind farms rather than smaller WTs. These grid codes impose that wind farms should contributes to frequency and voltage control and emphasise wind farm behaviour in case of fault condition of the network. The most common requirements includes FRT capability, voltage and frequency variations limit, active power control, frequency control, reactive power (power factor) and voltage regulation capabilities (Tsili and Papathanassiou, 2009; Singh and Singh, 2012; Mohseni and Islam, 2012). In this case, it is mainly focused on FRT or LVRT capability. In case of voltage collapse, WT is required to remain connected for particular time duration prior to being allowed to get disconnected. There is no loss of power generation for normally cleared faults. Sudden disconnection of WT would have negative impact on the grid of heavy penetrated wind farm. Grid codes requires large wind farms enduring voltage sags down to particular rated level at a particular time. Such condition is called as FRT or LVRT requirement (Iov et al., 2007). The FRT capability requirement suggests that voltage of WTs should not be less than 15 to 25% of the rated voltage during the fault and it must be restored to 75–90% within 0.75 to 0.5 sec (Chia-Tse et al., 2011; Shih-Feng et al., 2011; Giddani et al., 2010; Energinet, 2010). The grid codes requirements depend upon particular compensators. Figure 1 shows the LVRT characteristics in details.

Figure 1 The LVRT characteristics (see online version for colours)

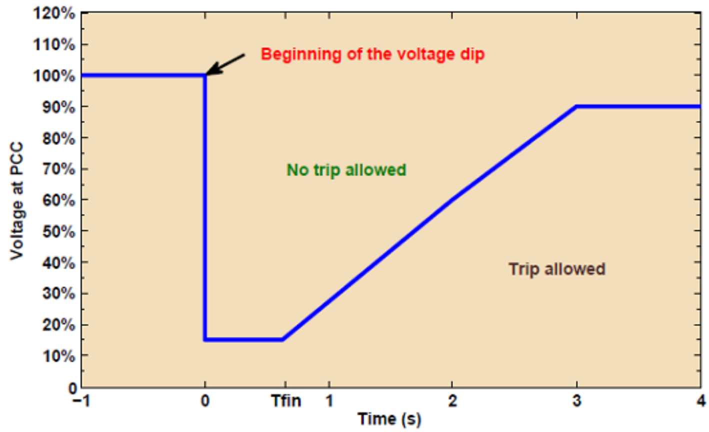
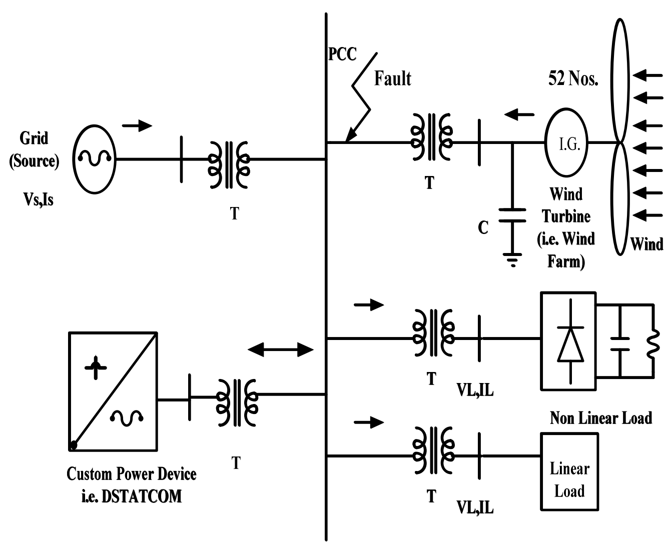


Figure 2 Study case of wind farm-propose problem



4 Role of DSTATCOM

A wind farm consists of 52 individual WT generators connected to grid system. The capacity of each WT is 1.25 MW and the wind power is generates at 690 V which is further stepped up to 33 KV and 132/220 KV by using step up transformer. The electric power is further given to electric grid system and different linear and nonlinear loading system. Figure 2 shows the study case of proposed wind farm.

The modelling of wind farm is performed in MATLAB. To study the effect of wind velocity on the performance of dynamics of power system and to develop the effective wind farm model of individual WT. The asynchronous induction generator (ASIG) with WT is considered with fault condition.

5 LVRT capability

To maintain the stable operation of the grid system, the operators define the requirements for integration of the wind farm to the grid. The LVRT capability of WT means its ability to remain connected during fault, disturbance, and dip condition at rated values. The Indian grid code suggests that the wind farm should maintain a power factor of 0.95 lagging to 0.95 leading.

Ability of the WT is to remain connected to the grid without tripping from the grid during a voltage drop at the point of connection. Period of FRT depends upon magnitude of voltage drop at the PCC. During the fault condition the time is taken by the grid system to recover to the normal state. During system disturbances, if generators of large generating capacity is connected to the grid continue their operation, then it aids the system in returning to normal operation. During a fault that causes a voltage drop at the wind turbine terminals, the reactive power demand of induction generators increases. Unless a reactive power support is available at the generator terminals, the reactive power will be drawn from the grid and further will become vulnerable (Katyal, 2012).

6 Operation of proposed model

The operation of proposed model is classified as the following.

6.1 Normal operation

The modelling of wind farm under normal operation is considered here. Normally, the system works satisfactorily. Due to use of ASIG in wind farm the requirement of reactive power is increased. Hence, the reactive power demand is fulfilled by fixed capacitors. But there is a lack of accurate reactive power management and more burden of reactive power on grid. Due to heavy penetration of wind farm to grid, the PQ issues are also exploited along with above said problems. Hence, there is a scope for accurate reactive power control and PQ issues in the normal operation.

6.2 Abnormal operation

ASIG is prevailing because of their advantages such as simple and robust construction, low cost, less maintenance, but it has disadvantage of uncontrollable reactive power absorption. There is a need of capacitor bank for mitigation of reactive power at no-load. In low voltage condition, the ASIG becomes unstable and low terminal voltage increases the reactive power absorption and rotor slip. Hence, further lowering of the voltage leads to disconnection of WT (Noureldeen, 2011; Anaya-Lara et al., 2009; Jelani and Molinas et al., 2015; Kim and Song, 2015). The torque of ASIG depends on the positive sequence stator voltage, which can be given in equation (2) (Anaya-Lara et al., 2009) as,

$$T_p(S) = 3.\frac{P}{2}.\frac{Rr}{Sws}.\frac{Vs_p^2}{(Rs + Rr / s)^2 + j(Xs + Xr)^2} \tag{2}$$

where *Rs*, *Xs*, *Rr*, and *Xr* are the stator and rotor resistance and impedance parameters of the ASIG respectively. *P*, *S*, *ω* are the number of poles, slip and frequency of grid. As per equation (2), it is clear that for smaller voltage dip/sag due to a small fault, ASIG may regain a stable operation but for a deep voltage dip/sag due to big fault (symmetrical and unsymmetrical fault) the ASIG loses its torque and get disconnected from the grid due to over speed or a voltage collapse may happen in the network due to high reactive power consumptions (Anaya-Lara et al., 2009; Jolani and Molinas et al., 2015). Due to the fault, an unbalance voltage condition is created and hence, stator currents are also unbalanced. A small amount of negative sequence voltage V_{SN} results in very high negative sequence current I_{SN} which is given in equation (3) (Anaya-Lara et al., 2009; Jolani and Molinas et al., 2015).

$$I_{SN} = \frac{V_{SN}}{w_{s.S} L_{s.} I_{s.N}} \tag{3}$$

where L_S, $I_{S.N}$, σ are the stator inductance, stator current, and leakage factor. Average torque is not affected much by the negative sequence current; however, it causes the torque ripples of double grid frequency (Anaya-Lara et al., 2009; Jolani and Molinas et al., 2015). The ripples in magnitude of positive and negative sequence torque T_P, T_N can be given in equation (4) as,

$$T_p = 3.\frac{P}{2ws}.V_{SP}.I_{SP} \tag{4}$$

$$T_N = 3.\frac{P}{2ws}.V_{SP}.I_{SN} \tag{5}$$

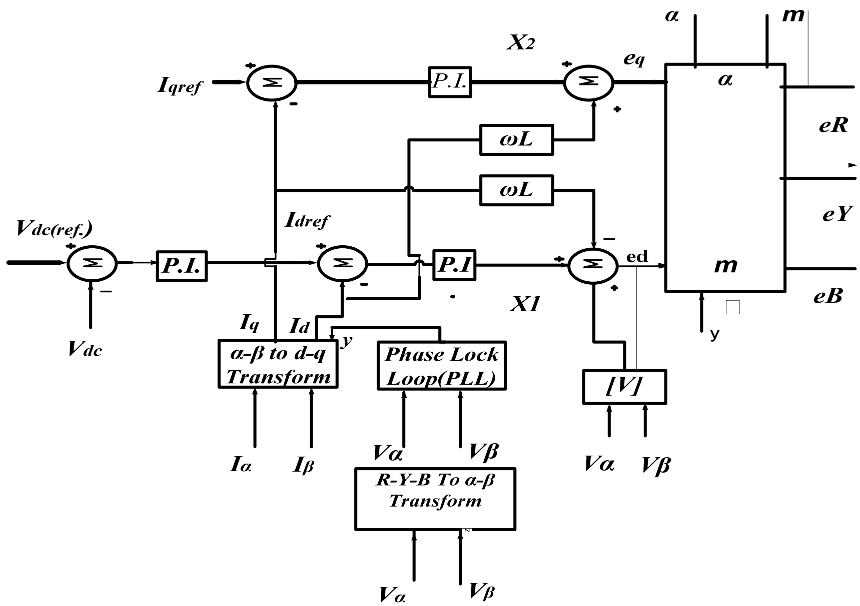
The average torque is reduced due to decrease of positive sequence voltage which leads to the acceleration of generator. The torque oscillations of double grid frequency result in the heating of the stator windings and decreases the lifetime of WT drive train. The average torque and torque ripples can be controlled independently if DSTATCOM is able to control positive and negative sequence voltages (Anaya-Lara et al., 2009).

6.3 Role of DSTATCOM in normal and abnormal operation

The work presented analyses the performance of DSTATCOM connected at the PCC of wind energy generating system and the existing power system to mitigate the PQ issues like reactive power under normal and abnormal operation, voltage dip, fault, etc. (Ballal et al., 2016). DSTATCOM capacity is 415 KVAR. DSTATCOM is interfaced with transmission line PCC for exchanging the power. The active power flows from higher δ (power angle $\delta 1$) to lower δ (phase angle $\delta 2$). The reactive power flows from higher voltage magnitude to lower. But during this process, the voltage of capacitor gets reduced and voltage across the capacitor must be constant (Bhadane et al., 2012, 2014, 2016a, 2016b, 2017). The storage capacitor link voltage V_{dc} actual and V_{dc} reference are compared and error obtained is given to *PI* controller. It indicates the I_d^*. Similarly, the

Vq actual and *Vq* reference are compared and error obtained is given to *PI* controller. It indicates the I_d^*.

Figure 3 Indirect current control scheme of DSTATCOM



Similarly, I_q^* reference and *Iqactual* is compared and error is obtained in PI controller. It will indicate the modulating index *M*. Similarly, I_d^* reference and Id actual are compared and error is obtained in *PI* controller. It will indicate the angle *δ*. Id is active current component and *Iq* is reactive current component. RYB to $\alpha\beta$.

Transformation (stationary) is obtained by using Clarkes transformation.

$$\begin{aligned} V_R &= V_m sin\omega t \\ V_Y &= V_m sin(\omega t - 120)^\circ \\ V_B &= V_m sin(\omega t - 240)^\circ \end{aligned} \tag{6}$$

$$V_a = \frac{3}{2} V_R V_\beta \tag{7}$$

$$V_b = \sqrt{3/2}\left(V_B - V_Y\right) \tag{8}$$

$$V_S = V_R + V_{Ye^{i4P/3}} + V_{Be^{i2P/3}} \tag{9}$$

$\alpha\beta$ to *dq* (rotating) Transformation is obtained by using Parks transformation.

$$V_a = V_S cos\omega t; V_b = V_S sin\omega t \tag{10}$$

$$V_d = V_S cos\left(\omega - \omega_1\right)t; V_q = V_S sin\left(\omega - \omega_1\right)t \tag{11}$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{pmatrix} cos\omega_1 t & sin\omega_1 t \\ -sin\omega_1 t & cos\omega_1 t \end{pmatrix} \begin{bmatrix} V_a \\ V_b \end{bmatrix} \tag{12}$$

By using DSTATCOM, switching techniques simplifications are as follows,

$$\begin{aligned} e_R &= \frac{\left(2S_R - (S_Y + S_C)\right)}{3} \\ e_Y &= \frac{\left(2S_Y - (S_B + S_A)\right)}{3} \\ e_B &= \frac{\left(2S_B - (S_R + S_Y)\right)}{3} \end{aligned} \tag{13}$$

Figure 3 indicates the indirect current control scheme of DSTATCOM. The implementation of mathematical equations of DSTATCOM using Figure 3 is obtained. The exchanging of active and reactive power under normal and abnormal condition with help of controller of Figure 3 is obtained.

Figure 4 Nature of fault current with and without DSTATCOM (see online version for colours)

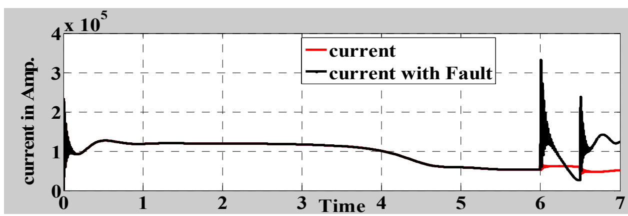
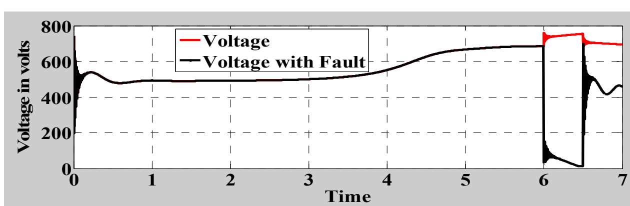
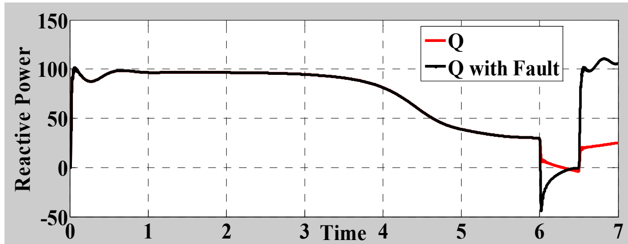


Figure 5 Nature of faulty voltage with and without DSTATCOM (see online version for colours)



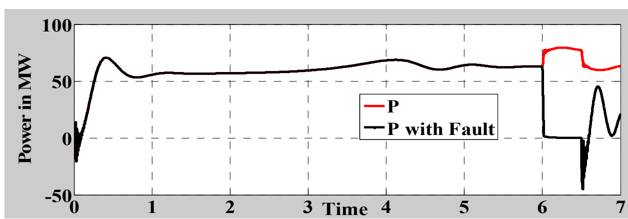
The normal operation of wind farm gives satisfactory performance. But under faulty (3Φ fault) condition the performance of wind farm is affected and hence, the wind turbine is disconnected from the grid. In this case, due to faulty condition at 6 to 6.5 sec the fault current is reached 3.5 to 2.5 × 105 A. WT cannot sustain the heavy current and hence, gets disconnected the WT. Due to the use of DSTATCOM, the fault current is reduced from 3.5 × 105 A to 1 × 105 A and during this faulty period the WT is not disconnected. DSTATCOM hold this faulty period and requirement of voltage due to the fault is supplied by it. Also, it fulfils other technical parameter requirements. Figure 4 indicates the nature of current under fault with and without DSTATCOM. The black colour waveform indicates the faulty current without DSTATCOM and red colour waveform indicates the faulty current with DSTATCOM.

Figure 6 Nature of fault condition reactive power with and without DSTATCOM (see online version for colours)



In this case, due to faulty condition at 6 to 6.5 sec the faulty voltage is reduced from 695 V to 50V. As per Indian grid code, the WT sustain the lowest reduced voltage and therefore disconnects the WT. due to the use of DSTATCOM the faulty voltage is enhanced from 50 V to 710 V and during this faulty period the WT remains connected. DSTATCOM holds this faulty period. Requirement of voltage, active and reactive power due to fault is supplied by it. Figure 5 indicates the nature of voltage under fault without and with DSTATCOM.

Figure 7 Nature of fault condition active power with and without DSTATCOM

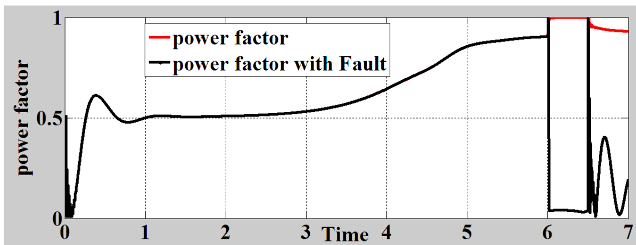


In this case, due to faulty condition at 6 to 6.5 sec the reactive power is reduced from 10 MVAR to –50 MVAR and later on increases the reactive power demand up to 120 MVAR during fault condition. The accurate reactive power compensation is a very salient aspect of PQ issues. As per Indian grid code, the WT cannot sustain this case which loses the FRT capability and disconnects the WT. due to the use of DSTATCOM the reactive power is reduced from 120 MVAR to 25 MVAR and during this faulty period the WT remains connected. DSTATCOM holds this faulty period and requirement of reactive power due to fault is supplied by it. FRT/LVRT capability is increased by using DSTATCOM. Figure 6 indicates the nature of reactive power under fault without and with DSTATCOM.

In this case, due to faulty condition at time period of 6 to 6.5 the active power is reduced from 62 MW to –38 MW. Hence, it loses the FRT capability and disconnects the WT. due to the use of DSTATCOM the active power is enhanced from earlier said value to 78 MW and during this faulty period the WT is not disconnected. DSTATCOM holds this faulty period and requirement of active power due to fault is supplied by it. FRT/LVRT capability is increased by using DSTATCOM. Figure 7 indicates the nature of active power under fault without and with DSTATCOM. In this case, due to faulty condition at 6 to 6.5 sec the power factor is reduced from 0.96 to 0.2. Hence, it loses the FRT capability and disconnects the WT. Due to the use of DSTATCOM, the active power is enhanced and also reactive power compensation by DSTATCOM is enhanced.

Hence the power factor is increased from 0.2 to unity during the faulty condition. During this faulty period, the WT is remains grid connected. DSTATCOM holds this faulty period and requirement of active power along with voltage profile is also increased. FRT/LVRT capability is increased by using DSTATCOM. Figure 8 indicates the nature of power factor under fault without and with DSTATCOM.

Figure 8 Nature of fault condition power factor with and without DSTATCOM (see online version for colours)



The overall active and reactive power of wind farm without and with DSTATCOM is given in Figure 9. The overall active power is increased from 40 MW to 90 MW. The overall reactive power is decreased from 50 MVAR to 38 MVAR. The active power enhancement and reactive power compensation is obtained by using MATLAB-based simulations of DSTATCOM. The important findings are as follows:

1 By injecting the positive sequence reactive current component I_q^+ at PCC with the help of DSTATCOM, the positive sequence voltage compensation is obtained. Hence, during the fault condition, increased positive sequence active current is controlled. The stable operating condition is obtained because of controlling the positive sequence voltage.

2 By using DSTATCOM control strategy the mitigation of negative sequence component of PCC is done. This is done by injecting the active and reactive current I_{dq}^- negative sequence component with the help of DSTATCOM. Hence, during the fault condition the repulsive nature of torque is reduced significantly. A decrease in the positive sequence voltage component because of ASIG consumes more reactive power from the grid, resulting in voltage collapse. Due to this, the system becomes unstable mechanically and after the fault the system does not return to normal operating condition. During the fault conditions, the interaction between both the positive and negative sequence voltage and current components exhibits the active, reactive power which generates the harmonics. There is oscillation to the input side of active power at balanced load condition. During the fault condition the oscillations are more.

3 Under the fault condition, the positive and negative sequence voltage components are controlled by using DSTATCOM and it perform the said function by maintaining the nominal current and injecting both the positive and negative sequence of the current. It mitigates both the positive and negative sequence components during the fault condition. Hence, the voltage is controlled during the fault which reduces the repulsive nature of torque and rotor acceleration. ASIG regains the normal operating condition after and during the fault.

4 The enhancement of torque capability of ASIG is obtained by mitigation of positive sequence components and also reduces the acceleration of its rotor.

5 Due to reduction of repulsive nature of torque, the negative sequence voltage mitigation support to improve the life expectancy of ASIG.

6 In this case, the LVRT/FRT capability of grid connected wind farm under faulty condition is obtained by using DSTATCOM.

Figure 9 Active and reactive power, with or without DSTATCOM in wind turbine (see online version for colours)

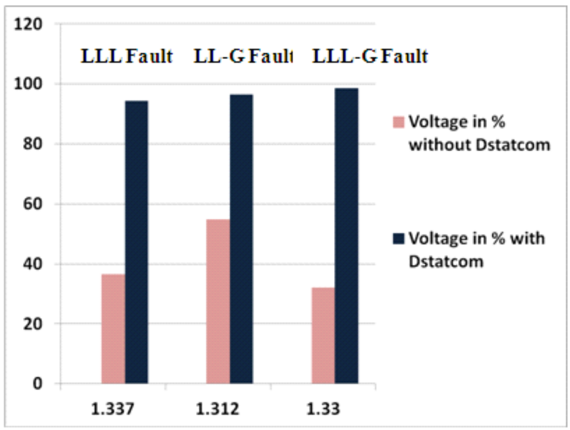


Table 1 The requirement of LVRT/FRT capability

Types of fault	*Voltage at fault condition*	*Time in sec.*	*Pre fault voltage*	*Requirement of LVRT/FRT in %*	*Voltage in %*
LLL	48.19 KV	1.337	131.69 KV	48	36.61
LL-G	72.17 KV	1.312	131.68 KV	46	54.80
LLL-G	42.39 KV	1.33	131.93 KV	47.51	32.13

Table 1 indicates the requirement of LVRT/FRT capability of wind farm under various fault conditions. Table 2 indicates the enhancement of LVRT/FRT capability of wind farm under various fault conditions by using DSTATCOM.

Table 2 The enhancement of LVRT/FRT capability by using DSTATCOM

Types of fault	*Voltage at fault condition*	*Time in sec.*	*Pre fault voltage*	*Requirement of LVRT/FRT*	*Voltage in %*
LLL	124.1 KV	1.337	131.69 KV	48	94.26
LL-G	126.9 KV	1.3125	131.68 KV	46	96.37
LLL-G	130.3 KV	1.33	131.93 KV	47.51	98.80

The comparative analysis of grid connected induction generators under fault condition are given in Figure 9. The enhancement FRT capability of wind farm in terms of percentage voltage is shown in Figure 9. In LLL fault condition, the percentage voltage is 36.61 without DSTATCOM and the percentage voltage is increased to 94.26 with

DSTATCOM. In LL-G fault condition, the percentage voltage is 54.8 without DSTATCOM and the percentage voltage is increased to 96.37 with DSTATCOM. In LLL-G fault condition, the percentage voltage is 32.13 without DSTATCOM and the percentage voltage is increased to 98.80 with DSTATCOM.

7 Conclusions

It is gratified that the LVRT/FRT capability of grid connected wind farm under faulty condition is enhanced up to 30% and hence, the additional 30% power is penetrated to the grid by using DSTATCOM. The enhancement of torque capability of ASIG is obtained by mitigation of positive sequence components which also reduces the acceleration of its rotor. Due to reduction of repulsive nature of torque, the negative sequence voltage mitigation supports to improve the life of ASIG.

During the LLL fault condition, voltage availability is 36.61% without DSTATCOM and the percentage voltage is increased to 94.26 with DSTATCOM. In LL-G fault condition, voltage availability is 54.80% without DSTATCOM and the percentage voltage is increased to 96.37 with DSTATCOM. During the LLLG fault condition, voltage availability is 32.13% without DSTATCOM and the percentage voltage is increased to 98.80 with DSTATCOM.

It has been found that the DSTATCOM injects less amount of current for LVRT/FRT capability enhancement. This case presents the possibility of using DSTATCOM to mitigate the grid faults in grid connected to large wind farm. The proposed method shows an alternative to the conventional methods and wind farm by utilising its resources in an effective manner. A detailed MATLAB-based modelling and simulation analysis is done to know the renewable generation system which is always grid connected during fault condition to ensure the stability of wind power system.

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