Enhancement of transient stability of distribution system with SCIG and DFIG based wind farms using STATCOM

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Abstract

This paper proposes optimal rating and location of static synchronous compensator (STATCOM) for enhancing transient voltage stability of a real distribution network with wind power generation. The test network consists of fixed and variable speed wind turbines connected to a rural load center. In order to ensure reliable and secure operation of the grid, the wind farm (WF) has to comply with the grid code for its low voltage ride through (LVRT) operation. Loads play significant role in voltage stability analysis. Induction motors and general loads are modeled according to real time data available with the system operator. In this work, dynamic reactive power requirement of wind farms is considered for determination of rating of the STATCOM. Reactive power margin (Q_{margin}) of load bus is used as an index to identify the location of the STATCOM. Extensive simulation has been carried out in DIgSILENT to show the validity of the proposed approach.

1. Introduction

Wind Energy is a rapidly growing technology among renewable energy resources. India has 22,645 MW installed capacity even though its offshore potential is still untapped [1]. The penetration of wind energy in India is 8.5% and 67.5% of total and renewable energy generation respectively. During major disturbances in the grid, the wind farms need to remain connected to the system for stable operation. The dynamic behaviour of power system depends on several factors like level of penetration of wind power, network impedance and type of wind generators, etc., [3].The capability of wind energy conversion

system(WECS) to remain connected to the network during low voltage conditions is called LVRT. Many grid codes demand ancillary services from wind turbines like injection of reactive current during fault and post fault periods[4].Wind farms may be connected to sub transmission or distribution levels of power system depending on wind resource availability nearer to load centres. Fixed speed wind turbines based on squirrel cage induction generators (SCIG-Type A) draw reactive power (Q) for its magnetisation. If voltage dip occurs due to a fault, rotor of SCIG accelerates and causes mechanical stress to the drive train. In addition to that the SCIG consumes large amount of Q during fault conditions. Therefore, the LVRT capability of SCIG was investigated with additional dynamic VAR support such as static VAR compensator (SVC) and STATCOM. [5, 6, 7]. The STATCOM gives better results because of its ability to supply Q at any level of grid voltage. Variable speed wind turbines based on doubly fed induction generator (DFIG -Type B) consists of power electronic converters, hence it is possible to obtain controllable active and reactive power [8]. However, the converter rating is only about 30% of total generator rating which makes DFIG attractive in an economic point of view. Large disturbances in the grid cause excessive currents on rotor side converter (RSC) of DFIG. A protective mechanism called crow bar is activated and rotor terminals are short circuited via resistance.

As a result, the DFIG starts consuming Q whereas the network itself is in need of VAR support. However, Grid side converter (GSC) can be utilized as reactive power source [9, 10]. Various control strategies for improving voltage recovery using GSC were investigated [11]. Nevertheless, the GSC cannot support the grid for voltage recovery as per grid codes. The time taken for reconnection of RSC has an impact on the reactive power consumption of DFIG from the grid, because RSC supplies magnetisation current [12].The STATCOM can be used as supplementary VAR source to strengthen the process of voltage build up after clearance of fault [13].The LVRT operation should only be demanded, if the disconnection of wind farms threatens the stability of power system [14]. VAR planning for a network with distributed generation was carried out using capacitors and STATCOM [15].The best location of Flexible AC Transmission System (FACTS) for the betterment of dynamic stability varies with type and location of faults [16].

The objective of this work is to find out a suitable solution for grid code compliance of wind farms connected to the load centre. The proposed strategy determines the optimal rating and location of the STATCOM based on types of load, generator technology and VAR requirements of test network under steady state and transient conditions.

The paper is organised as follows. Section 2 provides the scenario of mixed generator technologies, need for dynamic Q support and Indian grid code. Section 3 presents the characteristics of the test network and modelling of loads. In section 4, the proposed method for determining optimal rating and location of the dynamic VAR source is described. Section 5 concludes the paper with summary and contributions made by this work.

2. Wind farms connected to distribution system

Fig. 1 shows the simplified grid model of wind farms connected to a distribution system with loads. The infinite grid is modelled as a single source with its equivalent impedance using Thevenin's theorem.

V_G =Grid voltage

Z_G= Equivalent grid impedance

V_{WT}, Z_{WT}= Voltage and impedance of filter and cable of wind turbine respectively

V_{PCC}= Voltage at PCC

I_{WT} = Current injected by wind turbine

I_L = Load current

$P_{WT} + j Q_{WT}$ =Active and reactive power of wind turbine

$P_L + j Q_L$ =Active and reactive power of local load

Z_{Load}= Equivalent load impedance

$$I = I_{WT} - I_L \quad (1)$$

$$I_{WT} = (S_{WT} / V_{WT})^*$$

$$I_{WT} = (P_{WT} - j Q_{WT}) / V_{WT}$$

I_L can also be written as $I_L = (P_L - j\,Q_L) / V_{PCC}$

The change in voltage between grid and PCC is,

$$\Delta U = V_G - V_{PCC}$$

$$= Z_G * I \qquad (2)$$

From (1)

$$\Delta U = Z_G * (((P_{WT} - P_L) / V_{PCC}) - j ((Q_{WT} - Q_L) / V_{PCC})) \qquad (3)$$

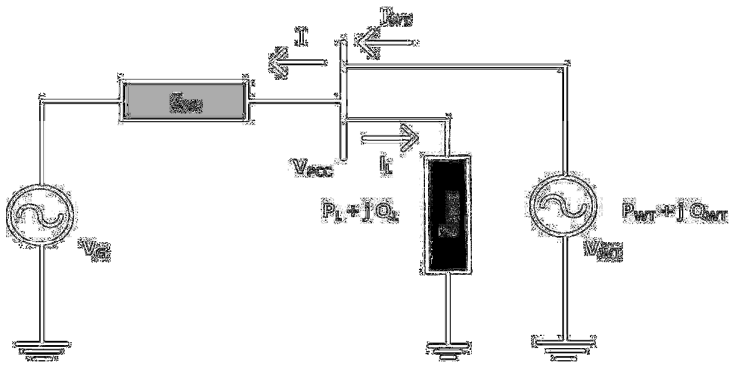


Fig. 1 Equivalent circuit

According to (3), the voltage at PCC is influenced by variations in wind power generation and loads. It can be seen that the voltage stability of the system depends on the characteristics of local load and type of wind generators. Long term reactive power support can be achieved using on load tap changing transformers and shunt capacitors. If the power system cannot maintain its reactive power balance during a fault, then the STATCOM is effective because of its fast response. The impact of Q support provided by dynamic VAR sources depends on short circuit ratio (SCR) and X/R ratio at PCC [16]. These parameters are high for the strong grid. The SCR is defined as

$$SCR = S / S_W \qquad (4)$$

S is the short circuit power in MVA and S_W is the rated power of wind in MVA. The addition of a secondary reactive power source leads to increase in S_W of network which reduces the value of the SCR. For that reason, it is important to decide a suitable rating and location of the STATCOM for LVRT operation of wind farms.

2.1 Scenario of mixed generator technologies

2.1.1 Squirrel cage induction generator

The SCIG injects active power and draws reactive power from the grid. Usually, capacitors provide shunt compensation and its VAR output varies with square of voltage. The reactive power drawn by SCIG is given by (5)

$$Q_{gen} = V^2 / X_m + 3I^2 X_l \quad (5)$$

X_m *and* X_l are the magnetising and leakage reactance respectively. V and I are terminal voltage and current of the SCIG. If the stability of power system is affected by the loss of wind power, then LVRT of wind farm is mandatory.In [6], rating of the STATCOM was increased to enhance the LVRT capability of SCIG. However, increase in rating of the STATCOM gives rise to torque oscillations in the generator. This phenomenon limits the choice of higher rating of STATCOM.

2.1.2 Doubly fed induction generator

The DFIG shares majority of the market compared to other variable speed wind generators. As shown in Fig. 2, the stator is directly connected to the grid and the rotor via a bidirectional converter. Vector control technique is used for decoupled operation of active and reactive power [8]. The RSC magnetises the DFIG and GSC delivers/absorbs the active power to/from the grid. The reactive power drawn by DFIG is given by (6)

$$Q_m = 3 V_s^2 / 2 X_m \quad (6)$$

$$Q_s = Q_m + Q_r/s \quad (7)$$

Q_m is reactive power for magnetisation of DFIG, V_s is stator terminal voltage and X_m is magnetising reactance. Q_s and Q_r are reactive power of the stator and rotor respectively. s is slip of the generator. Unity power factor operation is required under normal conditions, Q_s=0. If voltage regulation or power factor control is required, i.e. $Q_{s\_required} \neq 0$, then RSC supplies Q without exceeding its rated current carrying capacity. The following set points are given to the control unit of back to back converters.

- The controller of RSC receives two reference signals; torque required for extracting maximum power and reactive power needed for the unity power factor operation of DFIG
- The GSC controller receives the set points for DC link voltage and reactive power

The DFIG can be connected to the weak grid without reducing its stability, thus it is seen as an asset for improving the stability [18].When a fault occurs in the network, the stator current transients produce over current in the rotor which in turn triggers rise in DC link voltage. The problem with the DC link voltage rise can be solved using a chopper. The crowbar is activated, whereas gate pulses to the RSC are blocked till the rotor current decays below a certain value, typical value is 2 p.u. In order to utilize the reactive power capability of GSC, voltage control mode of operation is preferred in weak grids. However, if reactive power is prioritized during post fault recovery of voltage, the GSC current rises abruptly, which is practically not an appropriate solution [19].

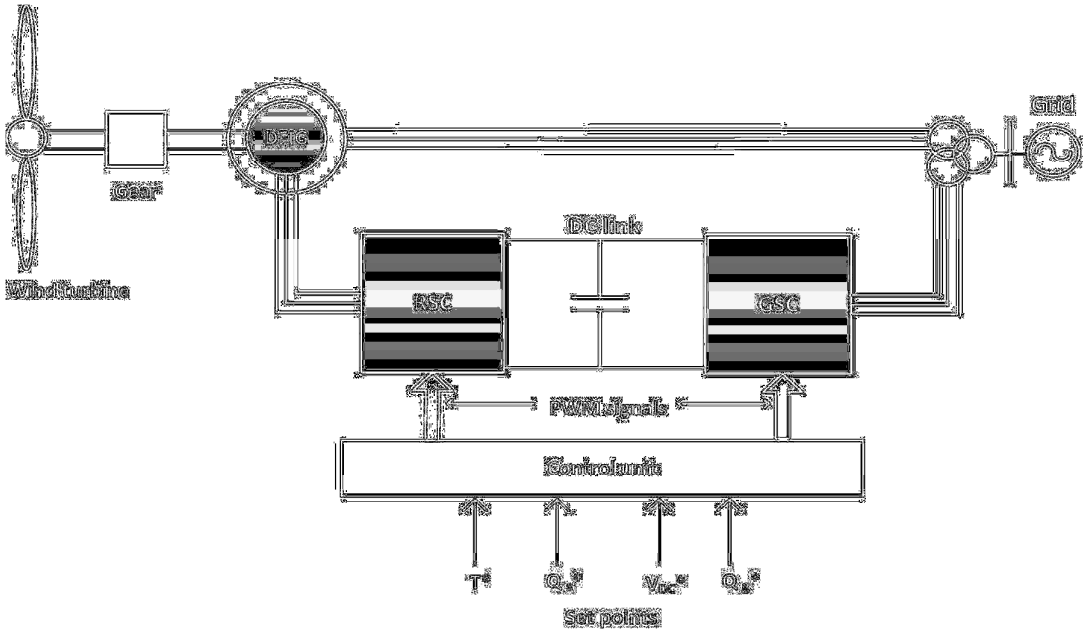


Fig. 2 Doubly fed induction generator

2.1.3 Dynamic VAR source- STATCOM

STATCOM is a voltage source converter connected in parallel to the source. It draws negligible amount of real power to retain its DC link voltage and can deliver reactive power according to the demand. The STATCOM can be made to control voltage, power factor or reactive power by designing a proper control technique. The STATCOM is modelled as a constant current source, hence the VAR output is a linear function of the voltage. It is clear that, the STATCOM is the best choice for providing dynamic VAR support.

2.1.4 Indian grid code

As stated by Indian grid code, the wind farm should be capable of supplying reactive power so as to maintain the power factor within the limits of 0.95 lagging to 0.95 leading. The above performance shall be achieved with voltage variation of ± 5%**.** During the voltage dip the generating station

- shall generate active power in proportion to the retained voltage
- shall maximise the supply of reactive current till the voltage starts recovering or for 300 ms which ever time is lower (Fig. 3).

The latter term insists on the need for additional reactive power support for wind farms.

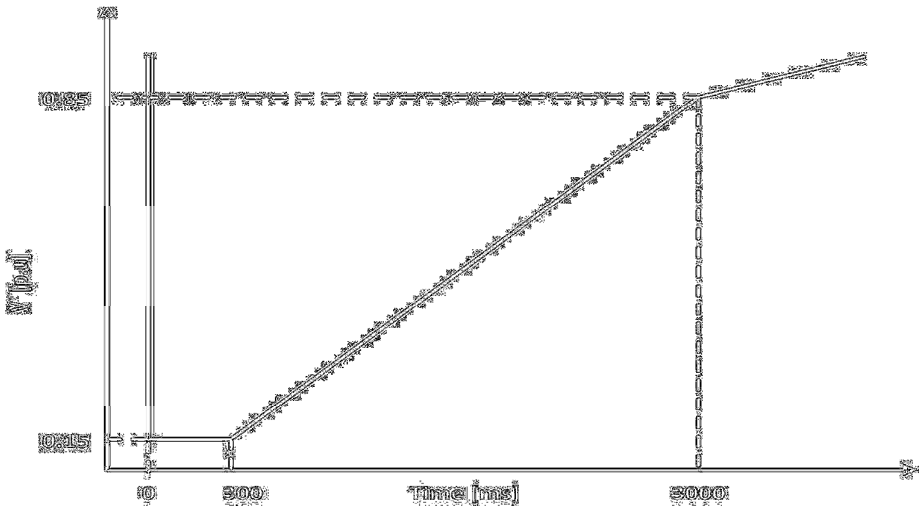
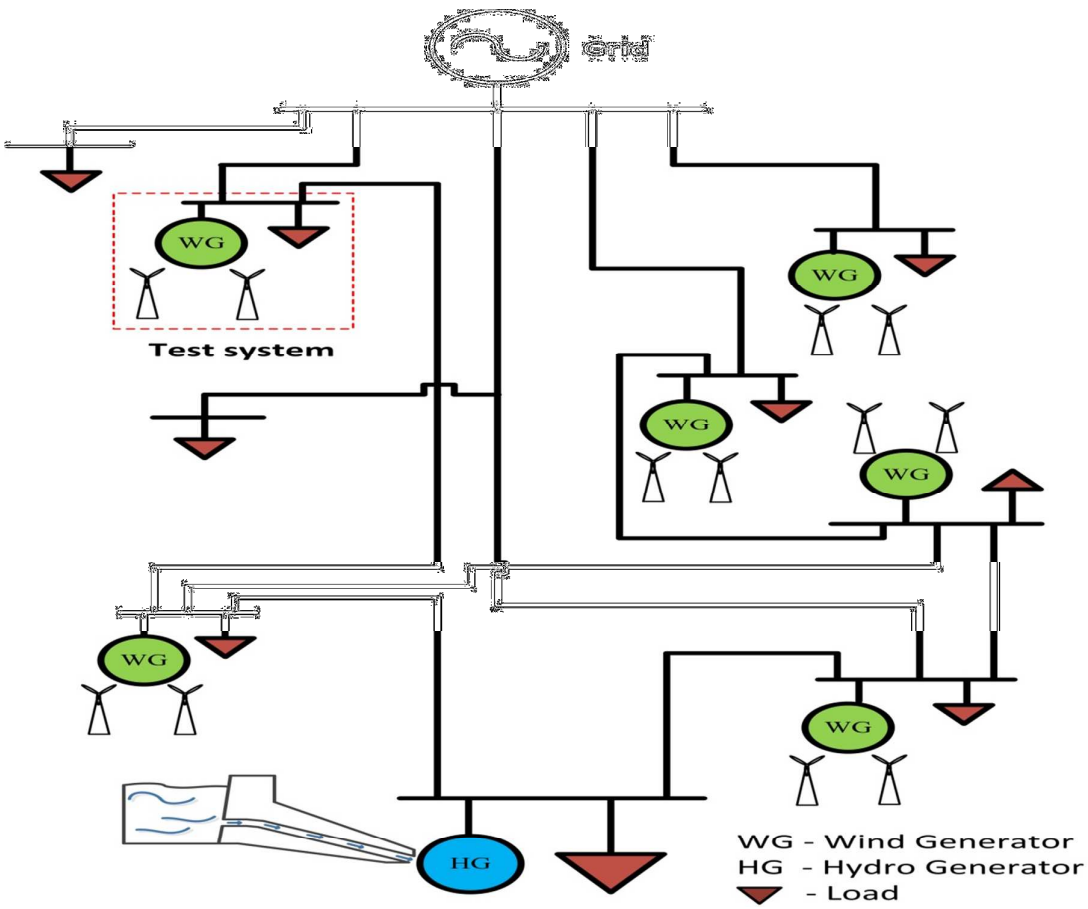


Fig. 3 LVRT requirement for wind farms as per Indian grid code

3. Network model

3.1 External grid

A grid in Tamilnadu-Otthakalmandapam region has been taken for case study. It consists of 354 MW of wind and 110 MW of hydro generation connected to load centres through 110 kV lines. Fig. 4a, shows the single line diagram of the regional grid. In this network, substantial amount of wind power is connected without LVRT capability. The impact of a fault event in the regional grid was passed on to the inter-regional links and caused loss of wind generation due to absence of LVRT operation. The stability of the system was threatened as a result of cascade tripping [20]. Therefore, the WF should not be disconnected from the grid. All wind power installations are composed of Type A and Type B generators that do not have the capacity to control their reactive power in fault conditions.



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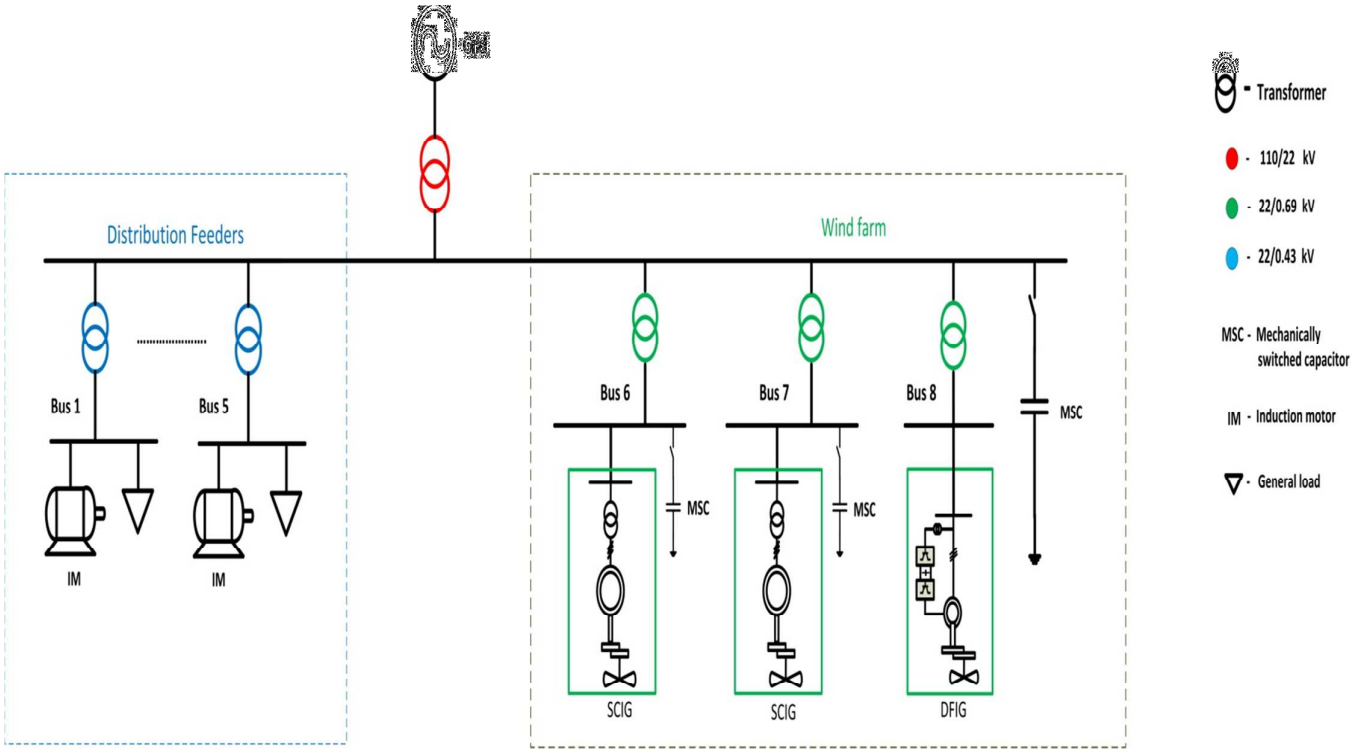

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Fig. 4 Single line diagram
a Regional grid
b Test system

3.1.1 Test system

The motivation behind the choice of the test system is that the WF is connected to substation with radial feeders in a rural area. The entire wind farm is modelled as a single aggregated system from buses 6 to 8 as shown in Fig. 4b. The substation consists of type –A machines on two feeders and Type –B machines on one feeder as shown in Table 1. The DFIG offer indirect voltage support by meeting up its Q demand with the help of RSC when the fault is cleared. The total level of wind penetration is 92 %. The faults on radial distribution systems are considered less severe than that of transmission lines because they cause only disconnection of loads. In spite of that, the consequences of a fault cannot be ignored in the regional due to the integration of WF on distribution substation. The short circuit capacity of 110kV grid is 2974 MVA. A bank of mechanically switched capacitors (2.4MVAR) has been installed at 22kV collector bus in the substation.

Table 1 Details of wind generators in the test system

Generator	LVRT	Voltage support	Penetration*
SCIG - 19.5 MW (11 * 250 kW, 11 * 1.25 MW, and 2 * 1.5 MW)	Yes	No	69%
DFIG - 8.85 MW (4 * 2 MW and 1 * 850 kW)	Yes	Partial	31%

* Generator wise penetration

3.2 Modelling of loads

Realistic representation of loads has a noteworthy impact on dynamic analysis of power system. Load shedding models are required for dynamic simulations, hence daily load pattern was analysed using the available data in the substation. The industry and general loads are energized for the whole day and agricultural pumps would get only six hour supply. A detailed study has been done to model the seasonal variations of load and their composition in the simulation. The implementation of load shedding is by simply assuming that each part of the load is tripped according to its proportion of the total load [21, 22].

Loads are categorized as general loads and induction motor (IM) loads. The General load comprises of lighting, air conditioners and fans. The IM load can be divided into two groups, industry loads and agriculture pumps. If the voltage falls below 65% of its rated value, the under voltage relay disconnects the motor from the supply.

4. Proposed methodology

4.1 Load flow studies

The purpose of the analysis is to investigate the short term voltage stability of the power system. Thus, the emphasis is given to reactive power requirements of the network for different loading conditions. It is known that, the maximum power transfer brings the worst case scenario needed for transient stability studies. Fig. 5 gives the methodology followed for obtaining optimal rating of the STATCOM.

Q-V curves are obtained, when the network is critically loaded with maximum wind power generation. Table 2 shows the composition of loads considered for load flow studies. More details are given in Appendix.

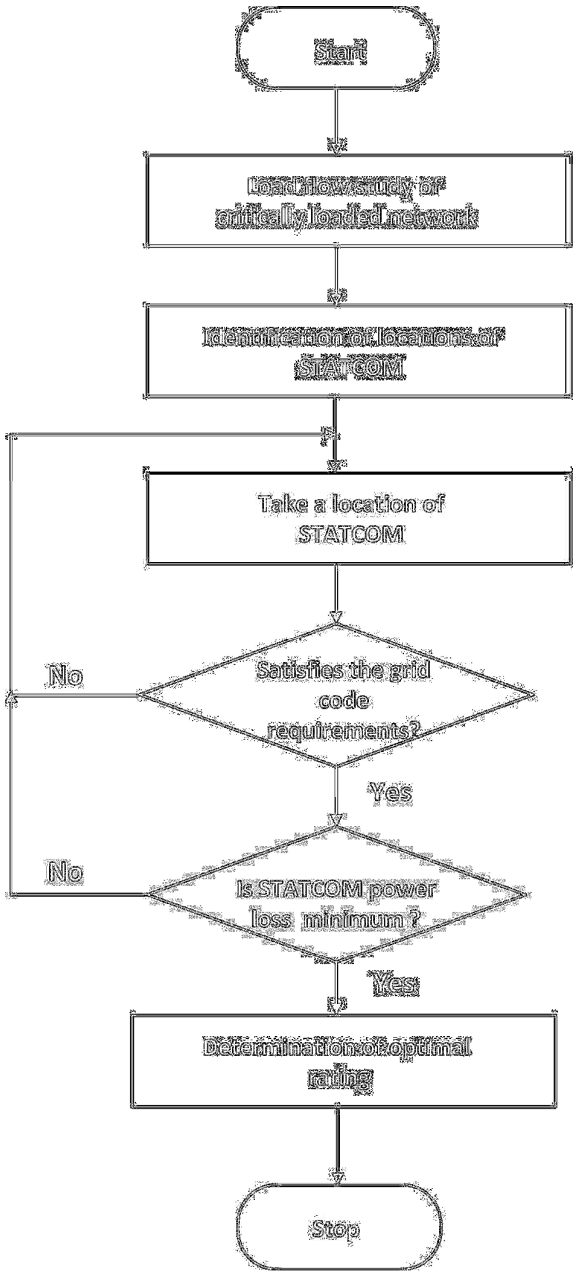


Fig.5 Flow chart

Table 2 Composition of loads

Industry load		Agricultural pump (HP)	Domestic load (MW)
Induction motor(HP)	General load(MW)		
4826	0.450	4666	10.446

4.2 Optimal location of STATCOM

In conventional distribution networks, permissible variation of voltage level is defined by technical regulations, for example ± 5% of nominal voltage. Shunt capacitors, on load tap changers and FACTS devices maintain the desired voltage. VAR planning with a combination of mechanically switched shunt capacitors and FACTS offers beneficial solution with reasonable cost. However, the capacitors can provide voltage support only during steady state conditions, whereas FACTS give steady state voltage support and improve transient voltage stability as well.

The context of transient stability of the chosen network is different altogether, as the LVRT operation of the wind farm has to be ensured, along with the attainment of steady state voltage regulation. Therefore, placement of additional capacitors is ruled out in this work, because of its inadequate support during low voltage conditions. During normal conditions, the capacitor banks in the distribution substation, industry and SCIG wind farms meet the reactive power demand of the network.

The Q-V curve analysis has been done for load buses in order to assess its stability. Q_{margin} reflects a minimum reactive power required for stable operation of the system [17]. In the test system, it is found that the bus 1 is the critical bus prone to instability because it has the lowest $Q_{margin.}$ Section 2.1.3 highlights the suitability of STATCOM for improving transient stability of wind farms. In literature, location of reactive power sources is determined by assessing a variety of indices such as change in voltage with change in reactive current injection, deviation of rotor angle and voltage sag in network buses

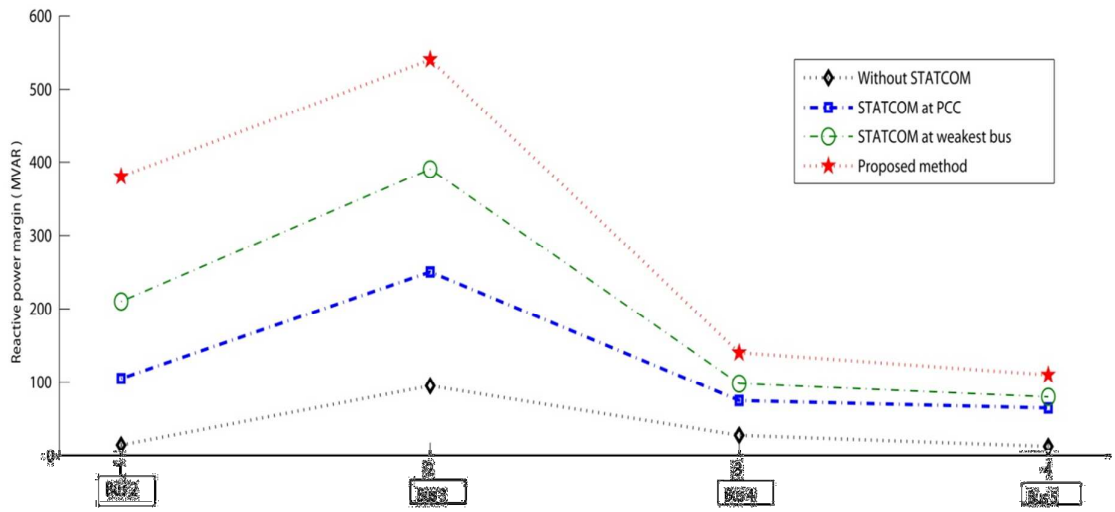
etc., [15, 16, 23]. In this work, two control strategies for placement of STATCOM are considered; aggregated and dispersed placement strategies. As seen earlier, maximum reactive current should be injected from the WF for fast recovery of voltage after a fault. Hence, initially 100% rating of the wind farm has been assumed for STATCOM.

The aggregated placement strategy indicates the location of STATCOM at one bus. Instead of delivering reactive power at one location, it can be split between two or more locations. This is termed as dispersed placement strategy. The suitable locations for the aggregated placement of STATCOM are PCC of the wind farm and the weakest bus [24].Great deal of voltage fluctuations are observed in load buses due to the operation of agricultural pumps without p.f correction facility. The Q-V curve of bus 1 reveals that, ± 5.74 MVAR is needed for maintaining ±10% voltage regulation.

In this work, dispersed placement of STATCOM at the weakest bus and PCC is proposed. Amount of Q support needed for ±10% voltage regulation has been determined from Q-V curve analysis. It has been taken as rating of the STATCOM at bus 1 and the rest is allotted for PCC (5.74 + 22.61 MVAR). Fig. 6a, shows the Q_{margin} of load buses except bus 1. It can be seen that, the proposed strategy of dispersed placement increases Q_{margin} of buses which indicates the enhancement of the loadability. If the STATCOM is placed at PCC, Q_{margin} of bus 1, increases by 24% as compared to the system without STATCOM. It is well known that the active power loss is a major concern, while searching for best location of STATCOM.

Fig. 6b, shows the power losses in the STATCOM for three strategies. The aggregated placement of STATCOM at weakest bus gives the lowest power loss. However, the proposed method enhances the loadability with lower amount of losses compared to STATCOM at PCC strategy. Therefore, reliability of the power system is strengthened by the dispersed placement of STATCOM at weakest bus and PCC. Before determining the location of STATCOM, its economic feasibility should be analysed. Usually, small units of STATCOM in the level of kVAR rating are combined to meet the requirement of

larger rating. A central controller is provided for integration of all control units. The aggregated placement strategy needs only one transformer, whereas the proposed solution makes it necessary for one more transformer.



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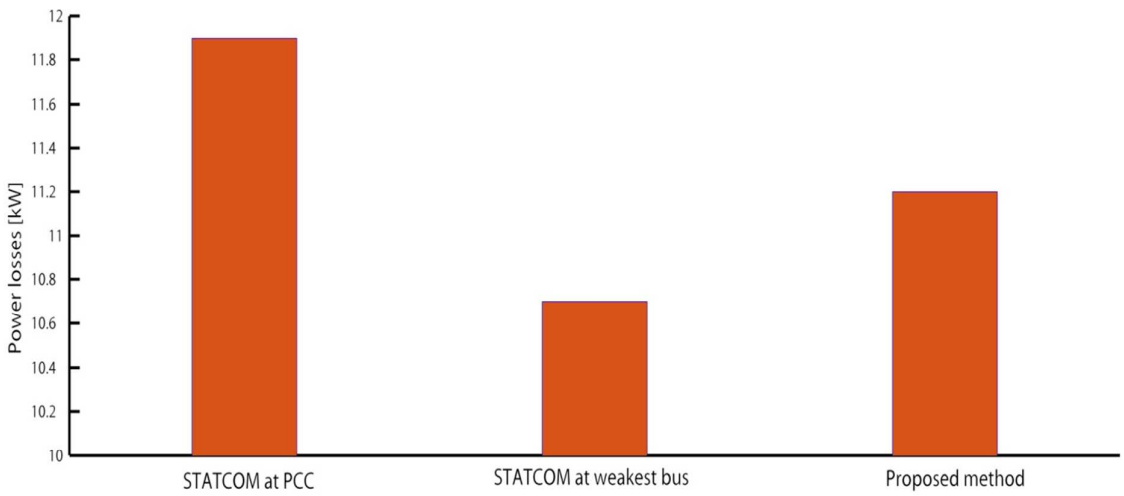

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Fig. 6 a Reactive power margin of load buses

b Power losses in STATCOM

As per the grid code, an event in the system which creates 0.15 p.u at the PCC of WF is the worst case. The effectiveness of STATCOM should be such that the WF should sustain the voltage dip and

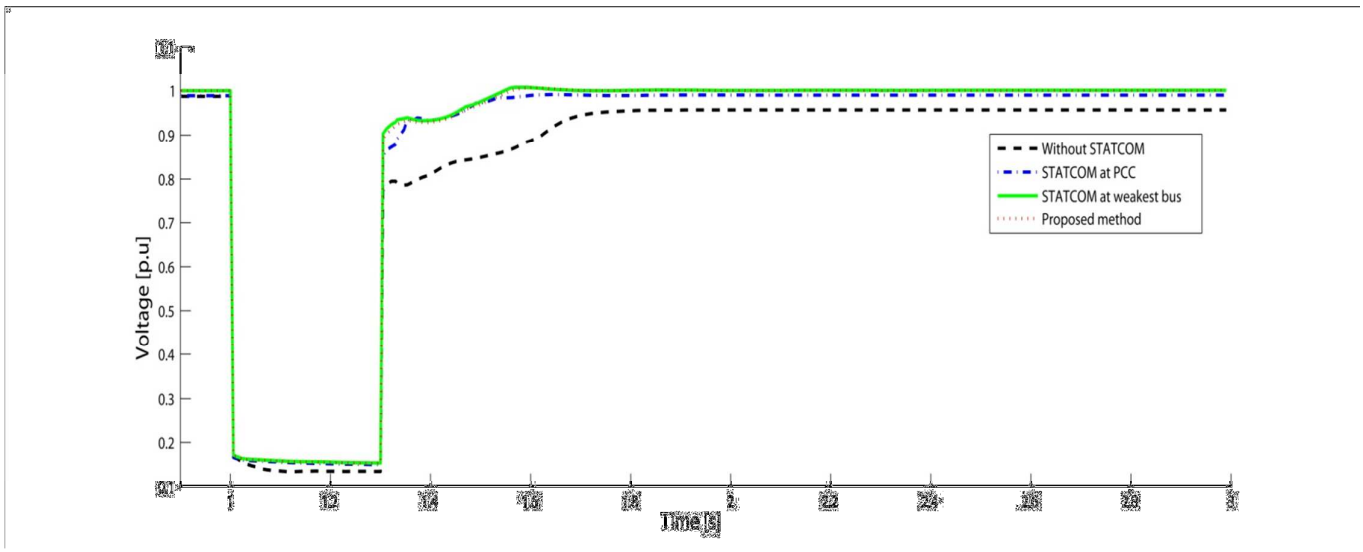
assist the network by injecting reactive current till the voltage recovers to a certain value (0.15 p.u to 0.85 p.u within 3000 ms).A three phase short circuit fault at bus 5 is created and cleared after 300 ms. Table 3 exhibits the recovery time of voltage at PCC. It is observed that, the STATCOM speeds up the recovery of the voltage after clearance of fault. Moreover, the voltage returns to its pre fault value within stipulated time period specified by the grid code. Fig. 7a, shows the profile of voltage recovery. The short circuit fault causes the voltage of PCC drop to 0.13 p.u in the critically loaded system without STATCOM. The WF is disconnected from the grid by under voltage relay. If the STATCOM is connected, the voltage at PCC is increased to 0.15 p.u. Therefore, the wind turbines retain their connectivity to the grid under fault conditions.

Fig. 7b, illustrates the rotor speed of 250 kW SCIG. Wind speed is assumed to be constant (12m/s) in transient conditions. Hence, the mechanical power input from the turbine is constant. The SCIG cannot export the active power to the network due to low voltage at PCC. As a consequence, the rotor of SCIG accelerates due to a fault and becomes instable. The STATCOM improves the voltage recovery and LVRT of SCIG. It is demonstrated that, the proposed method makes SCIG speed to settle down faster than other strategies. Fig.7c, shows the rotor speed of 2 MW DFIG. The rotor develops some oscillations and reaches its pre fault speed after several seconds. Although the DFIG is stable after a fault, it cannot assist the grid by injecting reactive current.

The induction motor draws reactive power from the grid and thereby worsening the recovery of voltage. If the voltage falls below 0.65 p.u, the motors are tripped by under voltage relay. This feature has a positive impact on the stability. On the other hand, when shallow dips are initiated by remote faults, the motor remains in the system consuming VAR during post fault period. Fig. 8 shows the reactive current drawn by IM at bus1 during a short circuit fault in bus 5 for 300 ms. The voltage drops to 0.6 p.u, the under voltage relay disconnects the motor as shown in Fig. 8a. If a voltage dip of 0.82 p.u occurs, the motor draws reactive power even after the fault is cleared. Fig. 8b, clearly demonstrates the need for an additional VAR source to ensure quick recovery of voltage.

Table 3 Recovery time of voltage at PCC

Location of STATCOM	Pre-Fault Voltage (p.u)	Recovery Time (Sec)
Without STATCOM	0.986	2.00
PCC	0.999	1.55
Weakest bus	0.988	1.59
Proposed method	0.999	1.56



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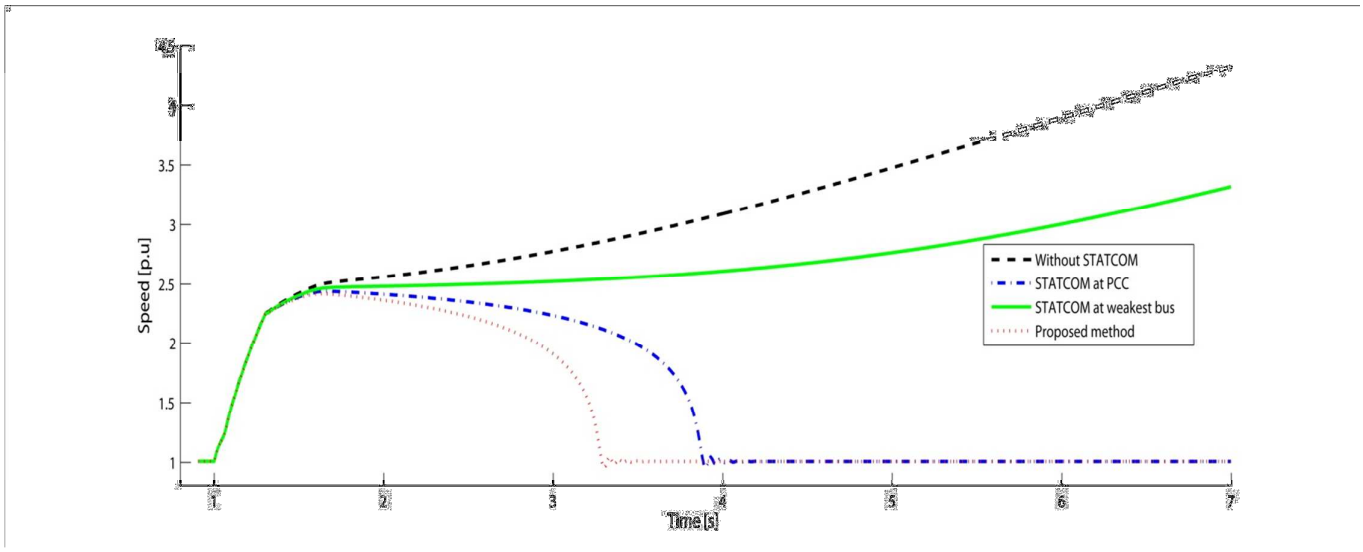

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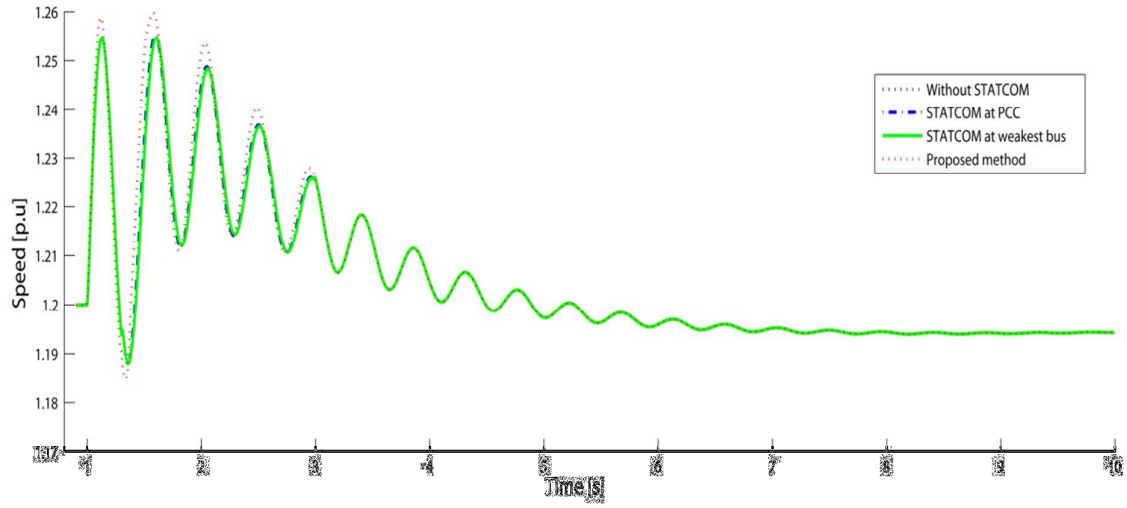

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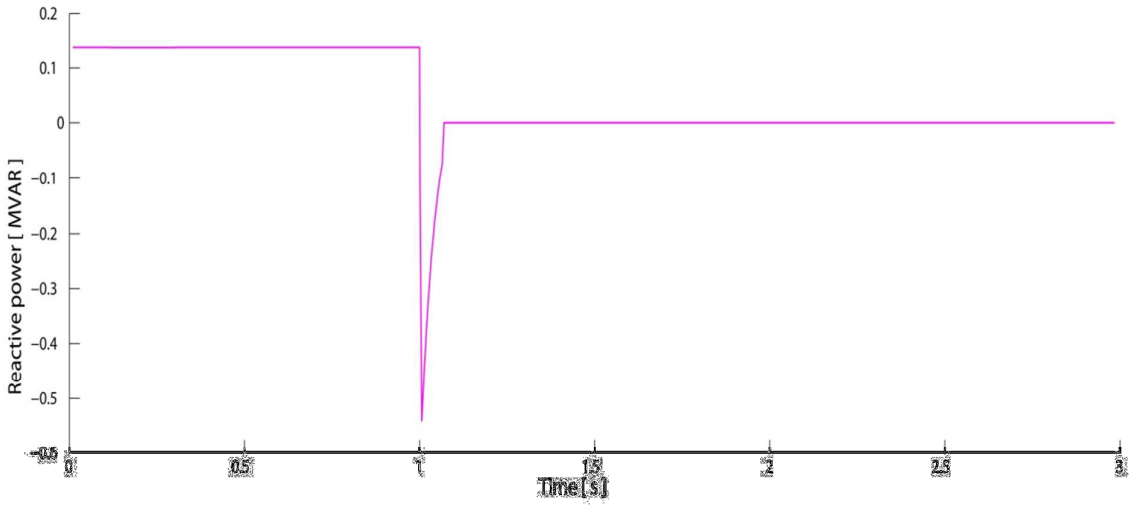
Fig.7 a Voltage at PCC
b Rotor speed of SCIG
c Rotor speed of DFIG



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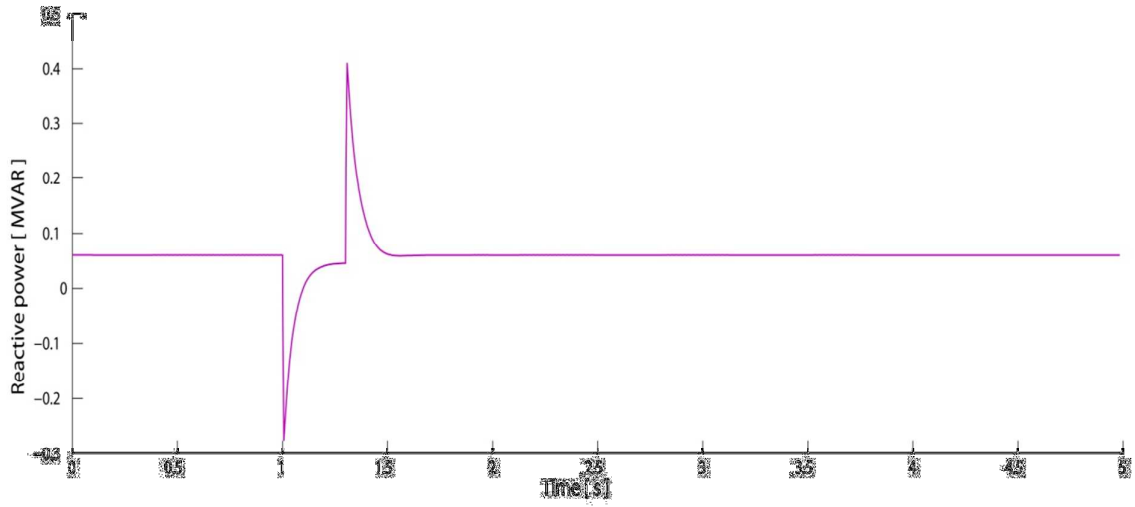

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Fig.8 Reactive power drawn by an induction motor at bus 1
a During 0.6 p.u voltage dip
b During 0.8 p.u voltage dip

4.3 Assessment of STATCOM rating

Simulation results show that the LVRT requirements demand higher rating of STACOM in order to comply with the grid code. During fault conditions, the STATCOM may be overloaded with typical range of 150-200%, which is termed as overload capacity. Technically the amount of reactive power needed for voltage recovery would be fulfilled by this over current rating. The voltage rating of the STATCOM will be same for all capacities for the given location of the network, whereas the current decides rating of power semiconductor devices used in the converter [25].

Load flow studies reveal that during critically loaded condition, the test system consumes 16.26 MVAR from the external grid without STATCOM. It is well known that, the behaviour of wind generators after fault is of paramount importance for deciding the rating of dynamic VAR source. As shown in Fig. 9 the DFIG absorbs reactive power until RSC is reconnected. Inadequate compensation of capacitors causes the SCIG to draw huge amount of reactive power during a fault. It is clear that, the Type –B machines put less reactive power demand during voltage recovery compared to Type-A. The maximum current delivered by the STATCOM is determined when the terminal voltage is at minimum (8).

$$I_{STATCOM\_MAX} = S_{STATCOM}/V_{pcc\_min} \quad (8)$$

$I_{STATCOM\_MAX}$ = Maximum current of STATCOM in A

$S_{STATCOM}$= Rating of STATCOM in VA

V_{pcc_min} = Minimum voltage at PCC in volts

The available reactive current depends on instant active current

$$I_{STATCOM\_REACTIVE} = \sqrt{((I_{STATCOM\_RATED})^2 \_ (I_{STATCOM\_ACTIVE})^2)} \quad (9)$$

$I_{STATCOM\_RATED}$ =Rated current of STATCOM

$I_{STATCOM\_ACTIVE}$ = Active component of $I_{STATCOM}$ required to maintain the DC link voltage at rated value

$I_{STATCOM\_REACTIVE}$ = Reactive component of $I_{STATCOM}$ required to inject reactive power in to the system

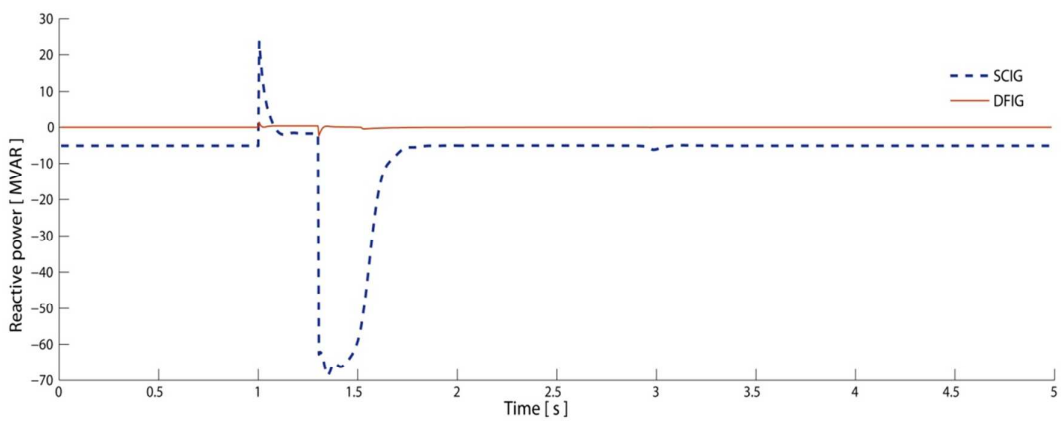

Fig. 9 Reactive power consumption of DFIG and SCIG during a fault

Fig. 10 gives the active and reactive current delivered by the STATCOM. In order to keep the DC link voltage constant during a fault, the STATCOM draws active current from the supply. The available reactive current output of STATCOM reduces as indicated in (9). The inverter can still withstand the overload and the capacity of transformer should be chosen to accommodate this power flow. Many manufacturers declare 200% overloading capacity of STATCOM for 2 or 3 seconds. Thus, the flexibility of overloading of STATCOM can be availed.

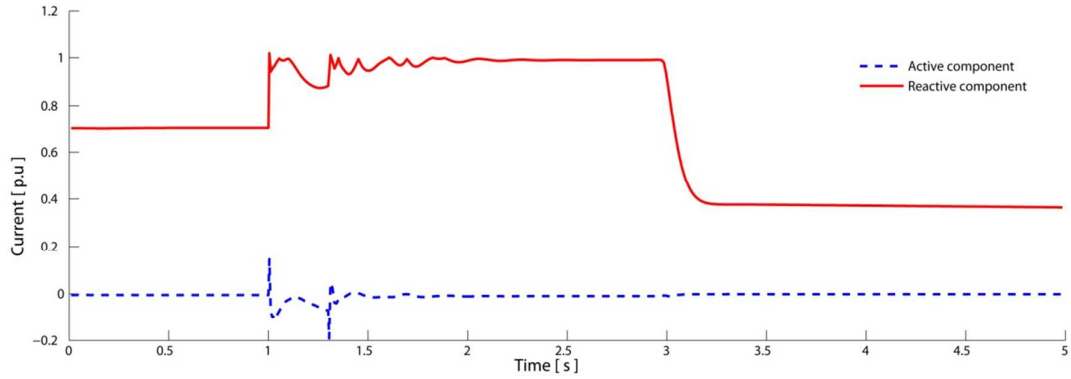

Fig. 10 Reactive and active currents of STATCOM

To start with, 50% rating of STATCOM (14.175 MVAR) is connected at the weakest bus and PCC as per dispersed placement strategy. There is no change in Q_{margin} of load buses due to reduction of STATCOM rating. It is observed that, the WF can comply with the grid code with 50% rating of STATCOM by utilizing its transient overload capacity.

5. Conclusion

The focus of this work is to evaluate the transient stability of SCIG and DFIG based wind farms using STATCOM. The loads are modelled according to the real time data and their impact on stability of power system has been analysed. The optimal location of the STATCOM is determined by considering two criteria; steady state voltage regulation and dynamic voltage stability. In the simulation study, considerable improvement in loadability of distribution feeders and fast voltage recovery of voltage after a severe fault shows the effectiveness of dispersed placement strategy.

The transient overload capacity of STATCOM can be exploited for determination of suitable rating for LVRT capability of wind farms. Moreover, DFIG based wind farms demand less reactive power during post fault period. This feature reduces the reactive power burden of STATCOM thus its rating. In conclusion, the LVRT operation of DFIG and SCIG based wind farms can be achieved with reduced rating of the STATCOM.

Acknowledgement

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Appendix

Parameters of transmission line

Conductor = ACSR- Panther, Resistance = 0.274 Ohm/km, Reactance = 0.377 Ohm/km

Table 4 Details of connected load

Bus	General load (MW)		Induction motor (HP)	
	Industry 0.9 L.P.F*	Domestic 0.85 L.P.F	Industry 0.9 L.P.F	Agriculture pump 0.8 L.P.F
1	0.0376	0.017	475	116
2	0.0709	4.133	474	6722
3	3.276	2.552	2393	2647
4	2.160	3.203	1428	1904
5	1.649	3.503	1110	1429
Total	7.194	13.408	5880	12818

* Lagging power factor

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