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MATHEMATICAL MODELING AND TUNING OF STATCOM USING PSO FOR SSR DETUNING IN DFIG BASED SERIES COMPENSATED TRANSMISSION NETWORK

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Abstract: Today's energy-generating sector is seeing a significant growth in of the wind power globally. Typically wind plants are typically located in rural areas, hence long high-voltage transmission lines are necessitated to integrate them to the grid. Series capacitive compensation is a quick and cost-effective way to increase the power transfer capacities of the transmission line that connects the wind plant to the grid. The main contribution of this paper is the detection and mitigation of sub-synchronous resonance (SSR) in doubly fed induction generator (DFIG) based wind plants owing to the installation of series capacitors in the transmission line. This paper examines the effectiveness of a static synchronous compensator (STATCOM) to reduce the risk of sub-synchronous resonance (SSR). A detailed Eigen value analysis with time domain simulations is shown to demonstrate how STATCOM successfully lowers the SSR. After incorporating STATCOM, the fluctuations in electromagnetic torque of DFIG is greatly reduced.

Keywords: Sub-synchronous resonance, static-synchronous series capacitor, series compensation.

1. Introduction

As penetration and use of wind power is encouraged all over the globe, numerous wind plants in the USA, Australia, India, etc. continue to use induction generator (IG)-based wind turbines to allow variable speed operation. For instance, the USA, has an wind power installed capacity of 135.8 GW. IG-based wind plants in the US include the Stateline wind plant (300.96 MW) along the border of Washington and Oregon, the Fowler Ridge wind plant (300.3 MW) in Indiana, the Pioneer Prairie wind plant (301.95 MW) in Iowa, and the 321.75 MW Maple Ridge wind plant in New York[1]. Transmission lines are likely to be series compensated by capacitors to empower the transmission of enormous wind power in the grid, considering the growing emergence in the development of wind plants around the world [1]–[3]. This is a unique and cost-effective short-term solution. Using such a configuration of transmission line, it can transfer power at two frequencies. One is a power frequency, and the other is a natural frequency, which is owing to the degree of the series compensation utilized. Hence, an unexpected stability issue, specifically subsynchronous resonance SSR [4], in wind turbine-IGs [5]–[8], may be conceivably caused by the presence of series capacitors in the line. A thorough eigenvalue study on the prospect of SSR in a single-case IG-based wind farm is presented in [9] and validated by PSCAD simulations. Apart from eigenvalue analysis and time domain simulations, the frequency scanning method is also used to predict the prone frequency

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zone to examine the possibility of torsional oscillations and can also be used to show the tuning and detuning of SSR mode[10,11]. A frequency-based impedance model of a wind plant interfaced to a series-compensated line (SCL) is shown in [12]. To enhance the power generation capability of the wind-plants, based on the requirements type-1 to 4 induction generators can be configured. Due to intermittent nature of wind availability and far distance from the grid type-3 generators is largely preferred which avails the grid side and rotor side converters to facilitate the reliable operation. A very insightful article on the SSR interaction between a Type-3 wind farm (485 MW) and an adjoining 345-kV SCL in Texas, USA, was recently released by the North American Electric Reliability Corporation (NERC). [8]. A 150 MW Type-3 wind plant connected to a SCL in the Buffalo Ridge area is also alleged to have had an overvoltage scenario as a result of SSR [13].

A brief analysis is shown in [12] to demonstrate the probability of SSR interaction in a "doubly fed induction generator" (DFIG)- based wind plant and SCL. However using series capacitors are short term solution to facilitate the power flow, to allow the safe and reliable use of series capacitors numerous approaches are proposed in literature. As Flexible "AC Transmission System" (FACTS) devices can offer reliable and flexible operation even in prone conditions, a "static var compensator" (SVC), and "thyristor-controlled series compensator" (TCSC), have been proposed to diminish SSR in series compensated wind plants [6.7,14,15]. SSR phenomena majorly arise and observed by torque signal in multi mass system, a torque screening technique is used to diminish torsional interactions in wind plants, using "static-synchronous compensator" (STATCOM) [7]. STATCOM avails resilient operation as it compensated the dc storage energy though VSC to regulate PCC voltage. Due to this, it can regulate the PCC voltage and power flow in the network and has great potentiality over oscillations in the network. This paper presents a complete mathematical and time domain analysis of SSR in a DFIG-based SCL by considering different wind speeds and different compensation levels. The mitigation of SSR is shown by regulating the PCC voltage by reducing deviations owing SSR using a STATCOM. A complete mathematical modeling of STATCOM is shown to show the integration with existing network in d-q frame its parameters are tuned using particle swarm optimization (PSO) to increase the damping of SSR mode. A mathematical analysis along with modeling is presented, which predicts the unstable region of compensation degree and speeds of the wind turbine. Time-domain and eigenvalue analysis are shown to verify the efficacy of proposed approach.

The leftover paper is structured as follows. Section 2 describes the mathematical modeling of various subsystems including IG model, SCL, DC link model. Section 3 describes a STATCOM controller modeling and its controller parameters using particle swarm optimization. The objective functions and constraints are also defined in same section. Section 4 includes eigenvalue and simulation results of STATCOM at prone conditions for DFIG based SCL. Section 5 makes conclusion of the work.

2. Mathematical Modeling of proposed System

The frame of study system is reformed from IEEE "first benchmark model" (FBM) for SSR studies as shown in Fig. 1. DFIG based wind plant is interfaced with SCL by using 069/161kV generator step-up transformer (GSUT).

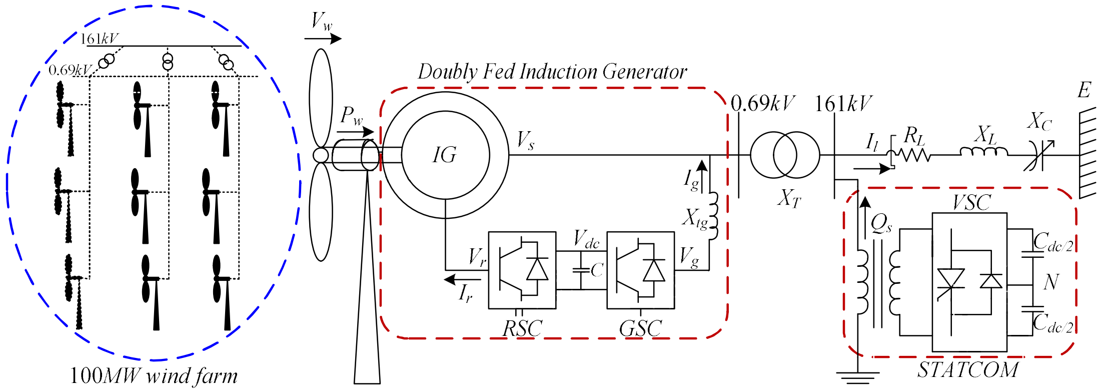


Fig. 1 IEEE FBM interfaced with100 MW wind plants

A DFIG based wind farm is scaled to 100MW by aggregation of 50 2MW turbine generator units and is connected to a 161-kV series compensated line. The combined characteristics 50 wind turbine- generator is assumed by a coequal lumped machine. This consideration is considered by from presence of available literature that imply that the grouping of wind plants provides an acceptable approximation for system interconnection analysis [16-19]. For mitigation of SSR, STATCOM is interfaced at PCC which consist of coupling transformer, voltage source converter and dc-capacitors.

Mathematical model of each sub-section IG model, SCL model, DC link model and torsional dynamic model is formed and later combined to form overall system.

2.1 SCL model

A widely used "synchronous reference frame" is used to present IG [20]. In the same reference frame, the SCL model can be presented as,

$$\frac{d}{dt}\begin{bmatrix} v_{cq} \\ v_{cd} \\ i_{ql} \\ i_{dl} \end{bmatrix} = \begin{bmatrix} 0 & -w_e & X_c & 0 \\ \omega_e & 0 & 0 & X_c \\ \frac{1}{X_L} & 0 & \frac{-R_L}{X_L} & -\omega_e \\ 0 & -\frac{1}{X_L} & \omega_e & \frac{-R_L}{X_L} \end{bmatrix} \begin{bmatrix} v_{cq} \\ v_{cd} \\ i_{ql} \\ i_{dl} \end{bmatrix} + \omega_B \begin{bmatrix} 0 \\ 0 \\ \frac{v_{tq} - E_{Bq}}{X_L} \\ \frac{v_{td} - E_{Bd}}{X_L} \end{bmatrix} \quad \textbf{(1)}$$

Where v_{cq} and v_{cd} are the out of and in phase integrant of the capacitor voltage, i_{ql} and i_{dl} are the out of and in phase integrant of line current, v_{tq} and v_{td} are the out of and in phase integrant of the terminal voltage, E_{Bq} and E_{Bd} are out of and in phase integrant of the infinite bus voltage, ω_B and ω_e are the base speed and "synchronous reference frame" speed (377 rad/s).

The state vector associated with the SCL is denoted by X_n and defined as

$$X_n = \left[v_{cq}, v_{cd}, i_{ql}; i_{dl}\right]^T . \quad \textbf{(2)}$$

2.2 IG Model

A 6th order differential model [21] is used to present type-3 IG with rotor side converter and grid side converter. Both converters are linked with DC link capacitor. The model is described by,

$$\dot{X}_g = AX_g + BU_g \tag{3}$$

Where,

$$X_g = \left[i_{qs}, i_{ds}, i_{os}, i_{qr}, i_{dr}, i_{0r}\right]^T$$
$$U = \left[v_{qs}, v_{ds}, v_{0s}, v_{dr}, v_{qr}, v_{0r}\right]^T \tag{4}$$

$$A = -B\begin{bmatrix} r_s & \frac{\omega_e}{\omega_b}X_{ss} & 0 & 0 & \frac{\omega_e}{\omega_b}X_M & 0 \\ -\frac{\omega_e}{\omega_b}X_{ss} & r_s & 0 & -\frac{\omega_e}{\omega_b}X_M & 0 & 0 \\ 0 & 0 & r_s & 0 & 0 & 0 \\ 0 & \frac{\omega_e-\omega_r}{\omega_b}X_M & 0 & r_r^{'} & \frac{\omega_e-\omega_r}{\omega_b}X_{rr}^{'} & 0 \\ -\frac{\omega_e-\omega_r}{\omega_b}X_M & 0 & 0 & -\frac{\omega_e-\omega_r}{\omega_b}X_{rr}^{'} & r_r^{'} & 0 \\ 0 & 0 & 0 & 0 & 0 & r_r^{'} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{X_{ss}}{\omega_b} & 0 & 0 & \frac{X_M}{\omega_b} & 0 & 0 \\ 0 & \frac{X_{ss}}{\omega_b} & 0 & 0 & \frac{X_{ss}}{\omega_b} & 0 \\ 0 & 0 & \frac{X_{ls}}{\omega_b} & 0 & 0 & 0 \\ \frac{X_{ss}}{\omega_b} & 0 & 0 & \frac{X_{rr}^{'}}{\omega_b} & 0 & 0 \\ 0 & \frac{X_{ss}}{\omega_b} & 0 & 0 & \frac{X_{rr}^{'}}{\omega_b} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{X_{lr}^{'}}{\omega_b} \end{bmatrix}^{-1}$$

2.3 DC-link Capacitor Model

The capacitor in the dc link present between converters of DFIG is described by a differential term as

$$Cv_{dc}\frac{dv_{dc}}{dt} = P_r - P_g \tag{5}$$

2.4 Torsional Dynamic Model

The shaft mechanism of turbine-IG system is represented by two-mass model as

$$\frac{d}{dt}\begin{bmatrix}\Delta\omega_t\\ \Delta\omega_r\\ T_g\end{bmatrix}=\begin{bmatrix}\frac{-D_t-D_{tg}}{2H_t} & \frac{D_{tg}}{2H_t} & \frac{-1}{2H_t}\\ \frac{D_{tg}}{2H_g} & \frac{-D_g-D_{tg}}{2H_g} & \frac{1}{2H_g}\\ K_{tg}\omega_e & -K_{tg}\omega_e & 0\end{bmatrix}\begin{bmatrix}\Delta\omega_t\\ \Delta\omega_r\\ T_g\end{bmatrix}+\begin{bmatrix}\frac{T_m}{2H_t}\\ \frac{-T_e}{2H_g}\\ 0\end{bmatrix} \quad \textbf{(6)}$$

Where ω_t and ω_r are the turbine and IG rotor speed in pu, correspondingly. T_g is the shaft torque of the multi-mass model. H_t and H_g are the inertia coefficients of the turbine and IG correspondingly. D_t and Dg are the mechanical dampening constants of the turbine and IG correspondingly; D_{tg} is the dampening constant of the intermediate shaft; K_{tg} is the shaft stiffness. T_m and T_e are the mechanical torque of the turbine and electrical torque of the IG correspondingly. Here T_e is defined as

$$T_e=\frac{X_m}{2\omega_B}((I_{qs}+I_{qr})-(I_{ds}+I_{dr})) \quad \textbf{(7)}$$

The state vector associated with the shaft system is denoted by X_t

$$X_t=\left[\Delta\omega_t,\Delta\omega_r,T_g\right]^T \quad \textbf{(8)}$$

Modeling of STATCOM

STATCOM is shunt FACTS controller which can injects the current to PCC node through coupling transformer from voltage sourced converter [22]. As SSR instability is also reflected in DFIG terminal voltage, the STATCOM is interfaced at interconnection of DFIG and transmission line to regulate the PCC voltage. The dc-side capacitor acts as energy source and dc capacitor voltage is modulating signal. Its equivalent circuit of STATCOM along with coupling transformer is shown in Fig.2. The differential equation of the STATCOM is developed in "synchronously rotating reference" frame as below.

$$L_{st}\frac{d}{dt}I_{Dst}=V_{Ds}-R_{st}I_{Dst}+\omega_s L_{st}I_{Qst}-E_{Dst} \quad \textbf{(9)}$$

$$L_{st}\frac{d}{dt}I_{Qst}=V_{Qs}-R_{st}I_{Qst}-\omega_s L_{st}I_{Dst}-E_{Qst} \quad \textbf{(10)}$$

$$C_{dc}\frac{d}{dt}V_{dc}=I_{dc}-\frac{V_{dc}}{R_{sw}} \quad \textbf{(11)}$$

Where,

$E_{Dst}=mV_{dc}\sin(\alpha)$, $E_{Qst}=mV_{dc}\cos(\alpha)$ and $I_{dc}=mI_{Dst}\sin(\alpha)+mI_{Qst}\cos(\alpha)$.

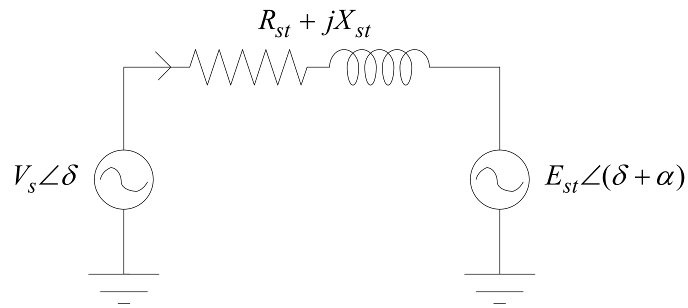


Fig.2 Simplified elementary circuit of STATCOM

The in-phase and out of phase elements of the STATCOM power output can be written as,

$$P_{st} = V_{Ds}I_{Dst} + V_{Qs}I_{Qst} \quad \textbf{(12)}$$

$$Q_{st} = -V_{Ds}I_{Qst} + V_{Qs}I_{Dst} \quad \textbf{(13)}$$

Referring to Q axis, V_{Qs} is same as V_s and V_{Ds} is taken zero. The in-phase current I_P and out of phase current I_R injected by STATCOM at the PCC can be written as,

$$I_P = \frac{P_{st}}{V_s} = I_{Qst} \quad \textbf{(14)}$$

$$I_R = \frac{Q_{st}}{V_s} = I_{Dst} \quad \textbf{(15)}$$

STATCOM controller modeling

The proposed STATCOM controller regulates the PCC voltage and dc capacitor voltage using the modulation index (m) and the phase angle difference (α) as shown in Fig 3.

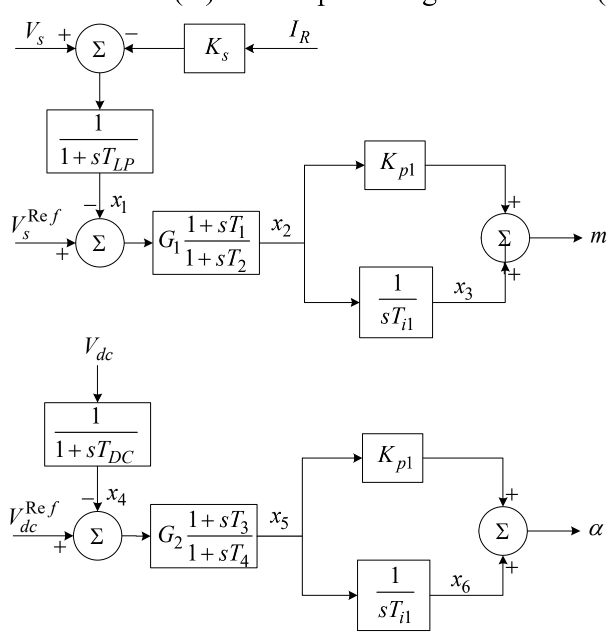


Fig.3 Modeling of STATCOM controller

Here as shown in Fig. 3 voltage droop K_s is added to PCC voltage regulation. As shown the phase angle α is based on the error of VSC dc capacitor voltage and derived from lead-lag and PI controller. Two low pass filters are added in the same to avoid the high-frequency elements from the voltage signals.

The working of the controller is based on differential equations as below.

$$T_{LP}\frac{d}{dt}\left(\Delta x_1\right)=\Delta V_s-K_s\Delta I_R-\Delta x_1 \quad \textbf{(16)}$$

$$G_1T_1\frac{d}{dt}\left(\Delta x_1\right)+T_2\frac{d}{dt}\left(\Delta x_2\right)=G_1\left(V_s^{Ref}-\Delta x_1\right)-\Delta x_2 \quad \textbf{(17)}$$

$$T_{i1}\frac{d}{dt}\left(\Delta x_3\right)=\Delta x_2 \quad \textbf{(18)}$$

$$T_{DC}\frac{d}{dt}\left(\Delta x_4\right)=\Delta V_{dc}-\Delta x_4 \quad \textbf{(19)}$$

$$G_2T_3\frac{d}{dt}\left(\Delta x_4\right)+T_4\frac{d}{dt}\left(\Delta x_5\right)=G_2\left(V_{dc}^{Ref}-\Delta x_4\right)-\Delta x_5 \quad \textbf{(20)}$$

$$T_{i2}\frac{d}{dt}\left(\Delta x_6\right)=\Delta x_5 \quad \textbf{(21)}$$

The interlinking among existing study system and STATCOM controller is presented as in below Fig. 4.

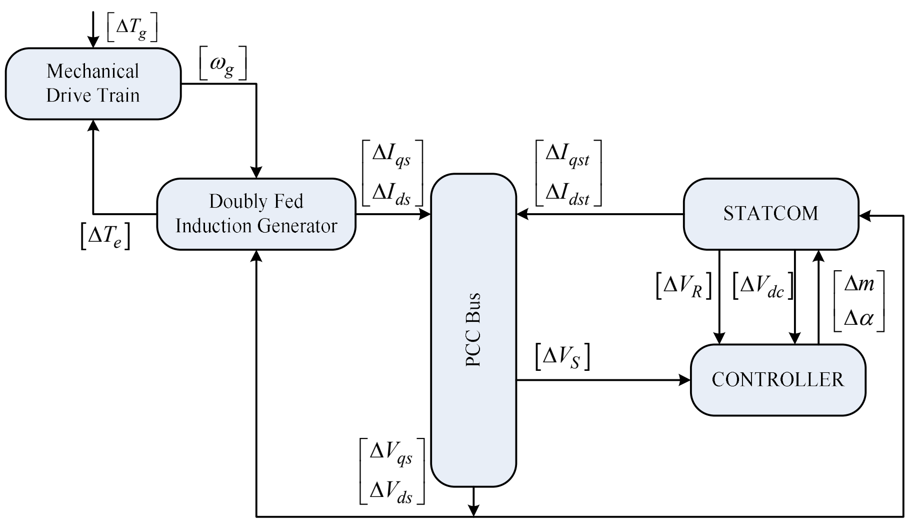


Fig.4 Interconnection among the subparts of study system

Simultaneous tuning of STATCOM controller parameters using PSO

The simultaneous tuning of STATCOM for increasing the damping of eigen modes, Particle Swarm Optimization (PSO) is implemented here considering different objective function [23]. PSO uses large number of particles placed in the multidimensional space of function. The particles share their positions with each other and resettled by the best path by updating their positions and velocities to find optimum solution in iterative process. Each particle in the swarm is composed of D-dimensional vectors and these are the current location, the last best solution and the velocity. The Particles will update their speeds and locations in each iteration by Eqns. (22) and (23) respectively. [24,25].

$$V_{i,iter+1} = w*V_{i,iter} + c_1*r_1*(P_{i,iter}^{best} - X_{i,iter}) + c_2*r_2*(G_{iter}^{best} - X_{i,iter}) \quad (22)$$

$$X_{i,iter} = X_{i,iter} + V_{i,iter+1} \quad (23)$$

Where, $V_{i,iter}$ and $X_{i,iter}$ represents the velocity vector and the position vector respectively of i[th] particle at iteration 'iter', $P_{i,iter}^{best}$ and G_{iter}^{best} are personal best and global best position of i[th] particle at 'iter' correspondingly. The term w indicates the inertial weight and it is responsible for dynamically adjusting the velocity of the particles. Typically, the value of w is in the range of 0.4 to 0.9. The constants, c_1 and c_2 are acceleration coefficients and their values usually selected in the range of 0 to 4.

A set of STATCOM Controller parameters are calculated by parameter optimization approach by minimizing the objective functions along with satisfying the operating constraints. Here the controller parameters are tuned by increasing the damping ratio of eigenvalues of the study system.

The damping ratio defines the rate of decay of the amplitude of oscillations in the range of -1 to 1 and it is given by

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad \textbf{(24)}$$

Tuning of STATCOM parameters is done by minimizing the objective function as below.

$$J = \min\{1 - \xi_i\} \quad \textbf{i=1,2,…,n} \quad \textbf{(25)}$$

Minimization of J with below operating constraints will help to identify the STATCOM parameters' value to improve system stability.

$$\begin{aligned} K_{i1}^{\min} &\le K_i \le K_i^{\max} \\ T_{i1}^{\min} &\le T_{i1} \le T_{i1}^{\max} \\ K_{i2}^{\min} &\le K_{i2} \le K_{i2}^{\max} \\ T_{i2}^{\min} &\le T_{i2} \le T_{i2}^{\max} \end{aligned} \quad (26)$$

Where K_{i1} and K_{i2} are the gain of STATCOM, T_{1i}, T_{2i} are and time constants of lead-lag block of STATCOM. The procedure of implementing the PSO algorithm for simultaneous tuning of parameters of STATCOM is as given below in flowchart shown in Fig. 5[24].

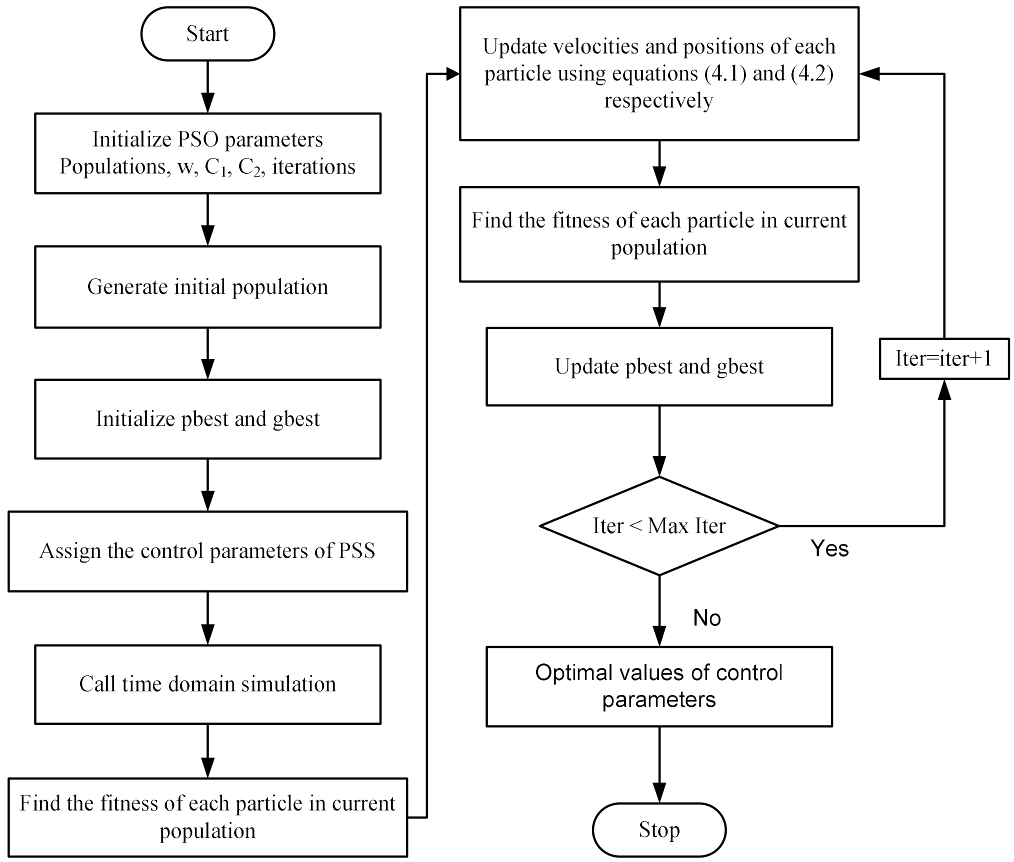


Fig.5 Flowchart of PSO based simultaneous tuning of STATCOM Parameters.

The optimal parameters of STATCOM controller using objective function are listed in Table 1.

Table 1 List of STATOM controller's parameter tuned by PSO

Parameters	K_{p1}	T_{i1}	K_{p2}	T_{i2}
Objective Function $J = \min\{1-\xi_i\}$	77.2704	0.0077	70.5708	4.5586e-4

Results and Discussion

To mitigate the SSR oscillations in DFIG based wind turbine the parameters of the STATCOM controller are optimized using PSO. Using this a state space model of complete system is developed on MATLAB software. To evaluate the designed STATCOM's performance with study system, small signal analysis is done with different cases. In first case, wind speed is assumed constant at 9 m/s and compensation level is varied with 10%, 25%, 50%, 60%, 75% & 90%. The loci of SSR mode is presented along with waveform of electrical torque T_e. Eigen values of proposed system without STATCOM are shown in Table 4.1. In the second case, compensation level is held at 50% and wind speed is varying at 7 m/s to 11 m/s. The list of eigen values and transient simulations are shown for verification.

Table 2 and Table 3 shows the eigen modes (E.M.) of the system without STATCOM. It replicates that SSR mode at K is 75% and 90% compensation level and wind speed less than 8 sec are unstable due to high oscillations presents in electrical torque T_e. Fig.6 shows waveforms of T_e at all compensation levels and concludes the same.

Table 2 List of Eigen Values for different Compensation Levels (without STATCOM)

	Without STATCOM (fixed wind speed (9 m/s))					
K	**10%**	**25%**	**50%**	**60%**	**75%**	***K* =90%**
E.M. 1	-6.41±469.54i	-7.20±523.65i	-8.40±584.74i	-8.86±604.68i	-9.54±631.72i	-10.22±656.20i
E.M. 2	-5.55±284.52i	-5.55±230.63i	-4.63±169.53i	-3.29±149.28i	3.14±122.88i	9.98±109.39i
E.M. 3	-2.18±96.61i	-2.83±96.86i	-4.94±97.69i	-6.78±98.34i	-13.98±98.27i	-21.60±87.94i
E.M. 4	-0.99±5.72i	-0.99±5.73i	-1.01±5.73i	-1.03±5.73i	-1.06±5.71i	-1.10±5.68i

Table 3 List of Eigen Values for different wind speedsd (without STATCOM)

	Without STATCOM (fixed *K*=75%)				
V_w	**7 m/s**	**8 m/s**	**9 m/s**	**10 m/s**	**11 m/s**
E.M. 1	-9.55±631.72i	-9.52±631.72i	-9.49±631.71i	-9.46±631.7i	-9.44±631.7i
E.M. 2	3.14±122.88i	-4.38±122.27i	-6.29±122.86i	-7.14±123.14i	-7.62±123.29i
E.M. 3	-13.99±98.28i	-5.9±62.79i	-2.53±30.32i	-5.38±27.5i	-5.38±58.79i
E.M. 4	-1.06±5.72i	-1.36±5.29i	-1.41±3.18i	-0.32±4.78i	-0.18±6.08i

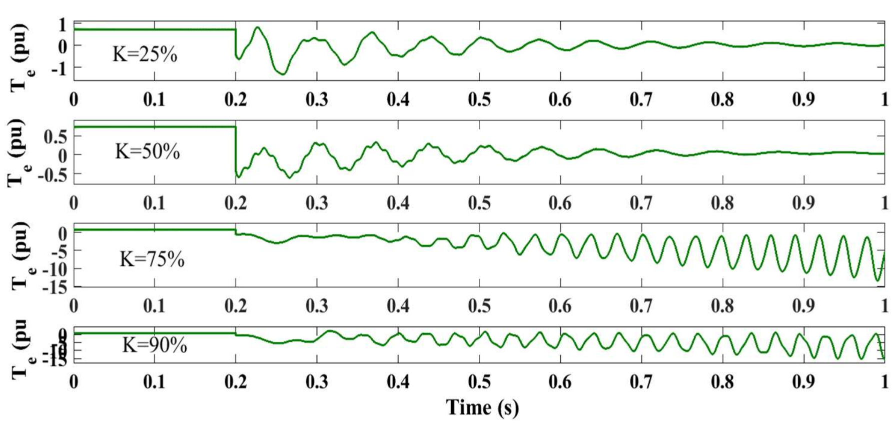


Fig. 6 Response of T_e at different compensation level

Case a) Wind speed is assumed constant 9 m/s & comp. level (K) is varied from 10% to 90%

Table 4 and Table 5 shows the lists of Eigen values of the system considering STATCOM whose parameters are optimized using PSO and considering Eigen values as an objective function. Result shows that Eigen values for comp. level 75% and 90% becomes stable as well as the system becomes more stable for other compensation levels. Damping to the Mode 2 which is SSR mode is significantly improved.

Comparison of SSR mode without STATCOM and with STATCOM are shown in Fig 7., which shows effect of STATCOM inclusion helps in improvement of stability through loci of Eigen values.

Table 4 List of Eigen Values for different Compensation Levels (with STATCOM)

	With STATCOM (*fixed wind speed*)					
K	10%	25%	50%	60%	75%	90%
E.M. 1	-5.85±477.64i	-5.53±536.98i	-4.6±605.02i	-4.14±627.61i	-3.39±658.66i	-2.63±687.27i
E.M. 2	-5.57±276.92i	-5.56±218.66i	-5.87±152.84i	-6.1±131.26i	-6.69±101.78i	-7.96±74.73i
E.M. 3	-7.17±23.6i	-7.19±24i	-7.22±24.82i	-7.2±25.2i	-7.1±25.84i	-6.69±26.39i
E.M. 4	1.06±2.69i	1±2.69i	0.89±2.7i	0.83±2.7i	0.73±2.69i	0.61±2.67i

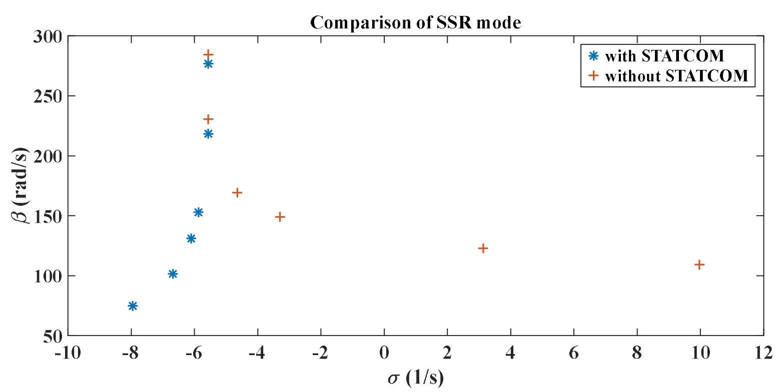
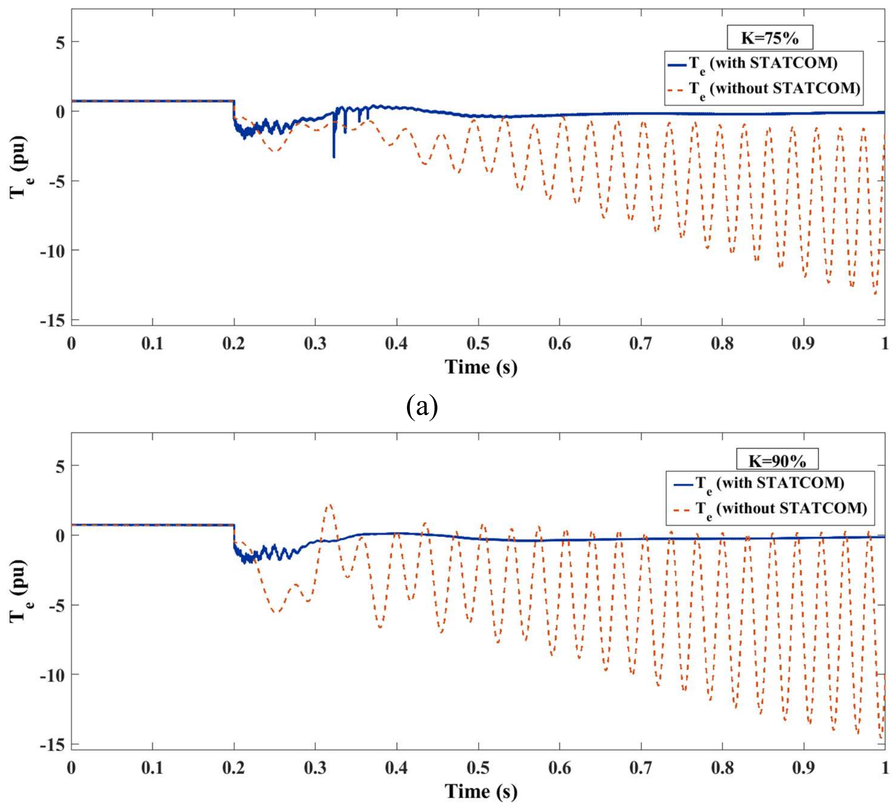


Fig.7 Comparison of loci of SSR mode at different compensation levels with and without STATCOM



(b)

Fig. 8 Comparison of response of T_e at peak compensation level (a) at 75% compensation level, (b) 90% compensation level

The eigenvalue results can be corroborated from the time domain response of electrical torque signal of DFIG as shown in Fig. 8. The red line denotes the without STATCOM signal which is highly oscillatory in behaviour. Whereas the blue color line shows the response with STATCOM and is found stable at both compensation levels.

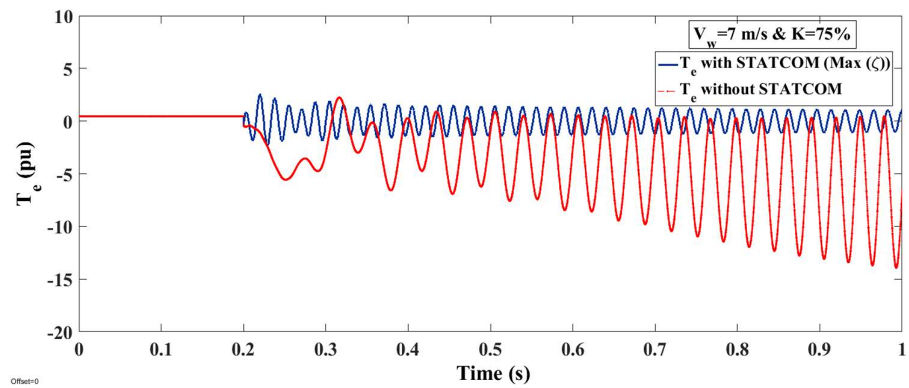
Case b) Fixed Comp. level is taken and wind speed is increased from 7 m/s to 11 m/s

In Table 3 at 7 m/s Mode 2 is found stable which is due to oscillatory SSR characteristics. The efficacy of proposed STATCOM is evaluated with same prone condition in this subsection. Table 4.4 show list of Eigen values with incorporation STATCOM. The SSR mode has been found stable in at all wind speed level. Stability of unstable mode 2 is also significantly improved. Fig. 9 shows waveform of electric torque T_e with both objective functions. In which mitigated waveforms are decreasing in nature compare to waveform of torque without STATCOM as shown in Fig. 9.

Table 5 List of Eigen Values for different wind speeds (with STATCOM)

	Without STATCOM (fixed K=75%)				
V_W	**7 m/s**	**8 m/s**	**9 m/s**	**10 m/s**	**11 m/s**
E.M. 1	-1.14±657.94i	-1.14±657.94i	-1.14±657.94i	-1.14±657.93i	-1.15±657.93i

E.M. 2	-6.7±103.37i	-6.7±103.37i	-6.7±103.37i	-6.7±103.37i	-6.7±103.37i
E.M. 3	-9.48±2.35i	-9.48±2.35i	-9.48±2.35i	-9.48±2.35i	-9.48±2.35i
E.M. 4	-0.87±6.02i	-0.87±6.02i	-0.87±6.02i	-0.87±6.02i	-0.87±6.02i



(b)

Fig. 9 Comparison of response of T_e at low wind speed at 75% compensation level

Conclusion

This paper presents an extensive comparison analysis of proposed STATCOM controller for SSR detuning in DFIG-based SCL. The probability of SSR is evaluated with varying wind speed and capacitive compensation levels through eigenvalue studies. To mitigate SSR a STATCOM controller is proposed to dampen SSR oscillation by regulating the PCC and dc capacitor voltage of VSC. The PI controller parameters of STATCOM are tuned by PSO to maximize the damping ratio of eigen mode. From eigenvalue and time domain results it has verified that even at light wind and peak compensation levels proposed STATCOM controller is effectively detuning the SSR.

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