



# Coordination of SVC and PSS for stability enhancement of DFIG-based offshore wind farm connected to a multi-machine system

Vipin Patel<sup>1</sup>, Varun Kumar<sup>2</sup>, Dilip Kumar<sup>3</sup>

<sup>1</sup>Student, Kamla Nehru Institute of Technology, Sultanpur, Uttar Pradesh

<sup>2,3</sup>Assistant Professor, Kamla Nehru Institute of Technology, Sultanpur, Uttar Pradesh

## ABSTRACT

*This paper present implementation of Static Var Compensator (SVC) & a Power System Stabilizer (PSS) to improve the transient stability of a DFIG-based offshore wind farm (OWF) connected to a multi-machine system. In wind farm connected grids, maintain the stability of grid and wind farm during transient disturbances is a serious issue. Due to grid faults wind DFIG trip and synchronous machines start oscillation due insufficient damping. To check out the stability of proposed system a three-phase to ground (LLLG) fault has been taken at bus number six of three machine nine bus system. The test system is modelled and simulated in MATLAB/Simulink platform. In absence of SVC during three phase to ground fault DFIG trip due to reduction in its terminal voltage below a critical value. But in presence of SVC wind farm protection system does not trip DFIG due reactive power support. And in presence of both SVC & PSS synchronous machine oscillations are also damped, hence settling time and over shoot of system also reduced.*

**Keywords:** *The offshore wind farm, Transient stability, Doubly fed induction generator, Static var compensator, Power system stabilizer.*

## 1. INTRODUCTION

Due to lot off development in power electronic devices and wind DFIG, a large amount of wind energy is integrated with power grids. Doubly Fed Induction Generator (DFIG) based wind energy conversion system is most efficient and economical due to reduced converter cost, less harmonic injection into grid, less switching losses and capability of better active and reactive power control. But wind DFIG is very sensitive to grid faults because the stator winding of DFIG is directly connected to the grid. Grid faults leave bad impact on wind DFIG like under voltage, over voltage, over speed of rotor etc due to which its protection system trip DFIG. There are several ideas given by researchers to solve this problem. In [1] to improve the stability of wind farm connected power system PSSs and SVC is used. SVC is used in [2] for voltage control of DFIG connected to a grid. The performance of STATCOM & SVC is compared in wind farm connected grid [3-4]. Stability of wind farm connected multi-machine system is improved by using STATCOM and SVC based fuzzy controller [5]. In [6] sub-synchronous resonance (SSR) mitigation has done of a series compensated wind farm by using FACTS devices. PID controller based STATCOM is used for stability enhancement of DFIG-based offshore wind farm connected three machine nine bus system [7]. Speed oscillation and voltage fluctuation mitigate by PSS & UPQC in [8]. The performance of SVC, STATCOM & SSSC is compared in a wind farm integrated system [9]. In [10] comparative study has done in between PSS, SVC & STATCOM controller for damping the power system oscillations.

This paper is organized as below. System configuration and test system model are introduced in section II. Simulation results of test system without controller, with SVC and with SVC+PSS for three phase to ground fault with full description presented in section III. The section IV consist important conclusions of this paper.

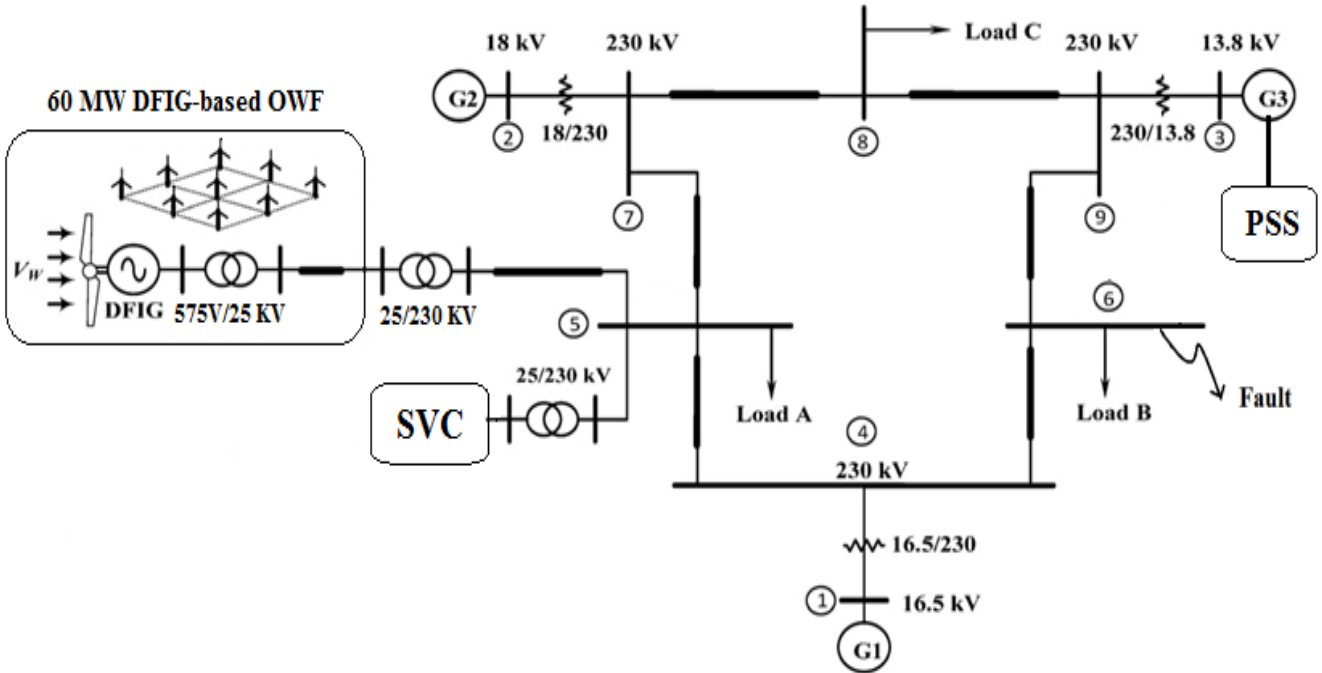
## 2. TEST SYSTEM

Fig. 1 represents the configuration of the studied system. The test system consist three machine nine bus, three loads Load A of 125MW & 50MVAR at bus 5, Load B of 90MW & 30MVAR at bus 6 and Load C 100MW & 35 MVAR at bus 8, 60MW offshore

wind farm, 50MVAR SVC and a multi band PSS. The offshore wind farm & SVC are connected at bus 5 and PSS is connected with excitation system of generator 3. The mathematical models of the studied system are described as follows.

**A. Aggregate Model of Wind Farm**

The offshore wind farm is represented by fully aggregated model, which consist an equivalent aggregated DFIG coupled with an equivalent aggregated variable speed wind turbine (VSWT) through an equivalent gearbox [7].



**Fig. 1 Single-line diagram of the studied offshore wind farm connected multi-machine system with SVC AND PSS**

The equivalent power rating of wind farm is given as [11]-

$$S_{eq} = \sum_{i=1}^n S_i \tag{1}$$

$$P_{eq} = \sum_{i=1}^n P_i \tag{2}$$

Where  $S_i$  and  $P_i$  are MVA rating and real power of the individual generator respectively,  $i$  is an index and  $n$  is the number of the generators.

**B. Wind Turbine**

The aerodynamic efficiency of variable speed wind turbine (VSWT) is better than fixed speed wind turbine. And the several advantages of VSWT are improved power quality, increased energy capture and reduced mechanical stress on wind turbine. The output power of VSWT is given as [7]-

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

Where  $P_m$  is the wind turbine output power (W),  $V_w$  is the wind speed,  $A$  is the cross-sectional area of the wind turbine ( $m^2$ ),  $\rho$  is the air density ( $kg/m^3$ ),  $C_p$  is dimensionless power coefficient and given by-

$$C_p(\psi_k, \beta) = C_1 \left( \frac{C_2}{\psi_k} - C_3 \beta - C_4 \beta^5 - C_6 \right) \exp\left(-\frac{C_7}{\psi_k}\right) \tag{4}$$

Where-

$$\frac{1}{\psi_k} = \frac{1}{\lambda + C_8\beta} - \frac{C_9}{\beta^3 + 1} \quad (5)$$

$$\lambda = \frac{R_{bld} \cdot w_{bld}}{V_w} \quad (6)$$

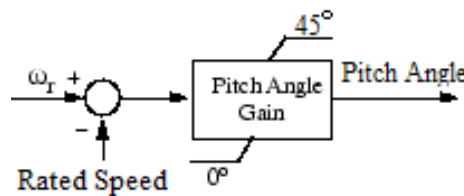
Where  $R_{bld}$  is the wind turbine rotor radius (m),  $w_{bld}$  is the blade angular speed (rad/s),  $C_1$ -  $C_9$  are the constants for power coefficient  $C_p$ ,  $\lambda$  is the tip speed ratio,  $\beta$  is blade pitch angle.

The mechanical torque of wind turbine is given as-

$$T_m = (\frac{1}{2} \rho \cdot \pi R_{bld}^3 \cdot C_p \cdot V_w^2) / \lambda \quad (7)$$

**C. Pitch Angle Control**

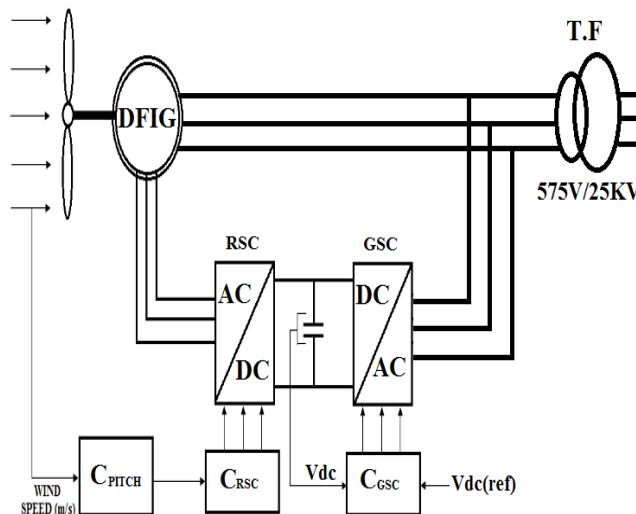
The basic need of pitch angle control is to control the wind turbine output power. The cut out, rated & cut in speeds of wind turbine are 24 m/s, 14 m/s, & 4 m/s respectively [7]. The pitch angle is maintained at zero degree until the speed reaches 12 m/s and increase in proportional to the speed deviation from 12 m/s. The pitch angle is change in between 0 to 45 degrees.



**Fig. 2 Pitch Angle Control System**

**D. Doubly Fed Induction Generator**

The major components of DFIG-based wind turbine are shown in fig. 3. Doubly fed induction generator consist a slip ring induction machine and two forced-commutated IGBTs based voltage source converters. The rotor windings of DFIG are connected to LV side of a 575V/25KV transformer through slip rings, rotor side converter (RSC), DC-link capacitor and grid side converter (GSC). And the stator windings of DFIG are also connected to the same LV side of step up transformer. The capacitor between RSC & GSC acts as DC voltage source. The controllers  $C_{GSC}$ ,  $C_{RSC}$  &  $C_{PITCH}$  use to generate the control commands for GSC, RSC & turbine blade pitch mechanism respectively.



**Fig. 3 Structure of DFIG Wind Turbine**

The control block diagram of grid side converter (GSC) is shown in fig. 4. The grid side converter is used to regulate the voltage of DC-link capacitor irrespective of magnitude & direction of the rotor power flow. We use Stator Voltage Oriented Control (SVOC) method for decoupled control of DC-link voltage and reactive power flow.

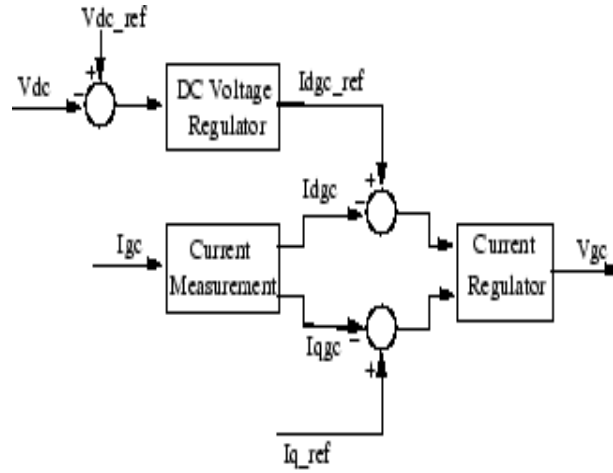


Fig. 4 Control block diagram of GSC

Fig. 5 shows the control block diagram of rotor side converter (RSC). Stator Flux Orientated Control (SFOC) method is used to control the voltage or the reactive power at grid terminal. SFOC is a synchronously rotating reference frame in which direct- axis is oriented along the stator flux vector position. By adjusting the currents  $i_{qr}$  &  $i_{dr}$  we can achieve the desired active & reactive power.

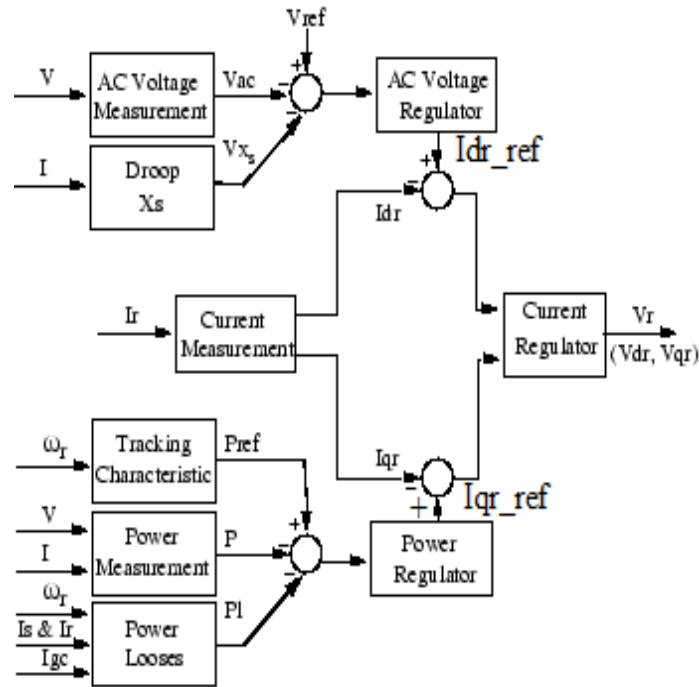


Fig. 5 Control block diagram of RSC

### E. Multi Machine System

In this paper classical model of multi machine system is used for power system stability study. The classical model is the simplest model and required minimum data in stability studies. The multi-machine system has three synchronous generators, nine buses and three constant loads. The line data and generators parameters of multi-machine system referred to [12]. The synchronous machines are represented by two-axis model. The rotational speed is approximate to rated speed 1 pu. For stability study we consider only transient effects and sub transient effects are neglected.

The pu differential equations for synchronous generator is given as [12]-

$$T_{d0}' \frac{d}{dt} (e'_q) = -e'_q - (X_d - X'_d) i_d + E_{fq} \quad (8)$$

$$T_{q0}' \frac{d}{dt} (e'_d) = -e'_d + (X_q - X'_q) i_q \quad (9)$$

$$\frac{d\delta}{dt} = \omega - 1 \quad (10)$$

$$T_J \frac{d\omega}{dt} = -D\omega + P_m - P_e \quad (11)$$

Where  $T'_{d0}$  &  $T'_{q0}$  are transient time constants,  $e'_q$  &  $e'_d$  are rotor voltages,  $X_d$  &  $X_q$  are d-axis & q-axis synchronous reactance's,  $X'_d$  &  $X'_q$  are d-axis & q-axis transient synchronous reactance's,  $i_d$  &  $i_q$  are d-axis & q-axis stator currents,  $E_{fq}$  is field voltage,  $\delta$  is rotor angle,  $\omega$  is rotor speed,  $T_J$  is moment of inertia,  $D$  is damping coefficient,  $P_m$  is mechanical power input,  $P_e$  is electrical power output.

### F. Static Var Compensator

SVC is basically a shunt connected FACTS device. SVC is used in power system network for voltage support, transient stability enhancement, power oscillation damping and to increase the loadability. SVC consist Thyristor-Switched Capacitor (TSC), Thyristor Controlled Reactor (TCR) and filter. Single line diagram of SVC is shown in Fig. 6.

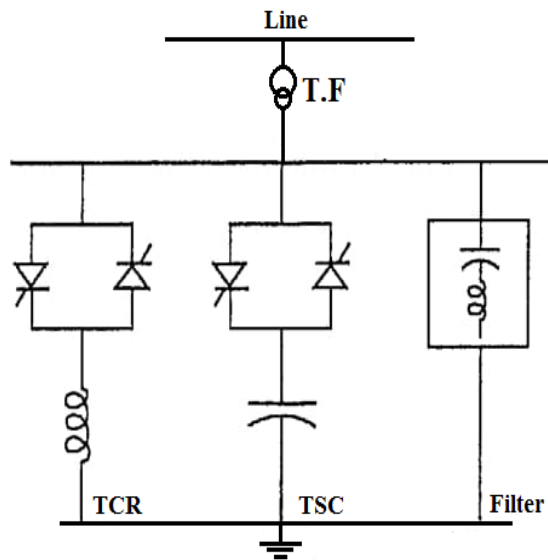


Fig. 6 Single line diagram of SVC

In the studied system SVC operates in voltage regulation mode with reference voltage ( $V_{ref}$ ). When system voltage goes below reference voltage, SVC supply reactive power and when system voltage goes above reference voltage, SVC absorbs reactive power.

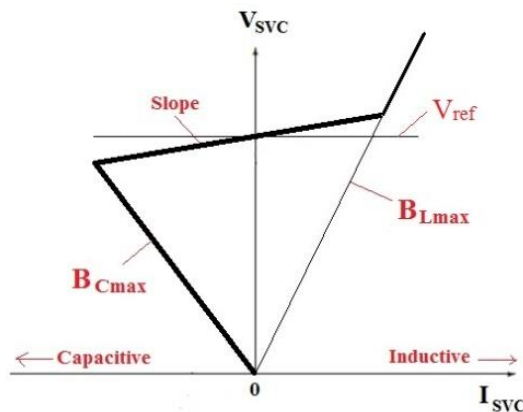


Fig. 7 V-I characteristic of SVC

Voltage-current characteristic of SVC is shown in fig.7. The mathematical equations of SVC is given as [12]-

$$Q_L = \frac{2\beta - \sin 2\beta}{\pi\omega L} V^2 \tag{12}$$

$$Q_C = \omega C V^2 \tag{13}$$

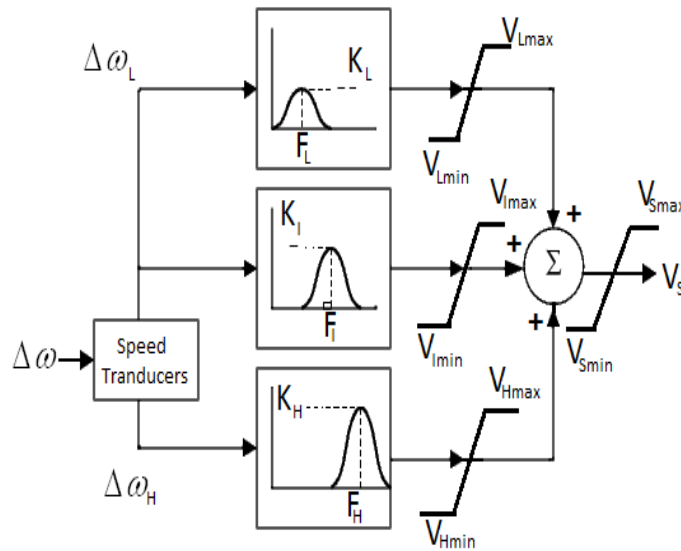
$$Q_{SVC} = Q_C - Q_L = \left(\omega C - \frac{2\beta - \sin 2\beta}{\pi\omega L}\right) V^2 \tag{14}$$

$$X_{SVC} = \frac{\pi\omega L}{2\beta - \sin 2\beta - \pi\omega^2 LC} \tag{15}$$

Where  $Q_L$  the reactive power absorbed by TCR,  $Q_C$  the reactive power supplied by TSC,  $Q_{SVC}$  reactive power injected by SVC,  $X_{SVC}$  the equivalent reactance of SVC,  $\beta$  the conducting angle,  $\omega$  angular frequency,  $L$  the inductance of TCR,  $V$  the system voltage,  $C$  the capacitance of TSC.

**G. Power System Stabilizer (PSS)**

The disturbances occurring in power system network produce electromechanical oscillation (power swing) in synchronous machines. These oscillations must be effectively damped to maintain the power system stability. The power system stabilizers used to minimize the power swing by modulating the generator excitation. PSS provide an additional signal ( $V_s$ ) for excitation system of synchronous machine by using speed deviation or terminal frequency or acceleration power ( $P_a = P_m - P_e$ ) as input signal. In studied system speed deviation  $\Delta\omega$  used as input signal of MB-PSS.



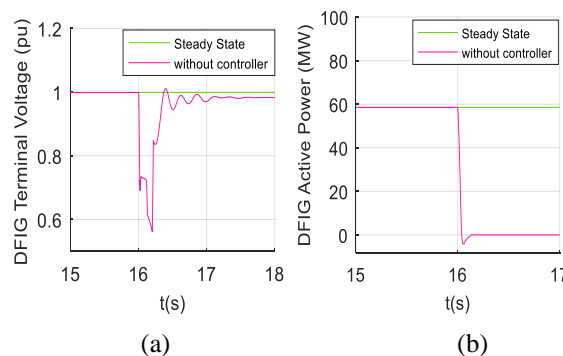
**Fig. 8 Control block diagram of MB-PSS**

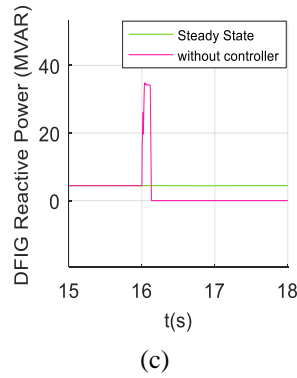
The control block diagram of multiband power system stabilizer is shown in Fig. 8. The electromechanical oscillations are mainly four type- local oscillation (frequency range 0.8 Hz to 4 Hz), Interplant oscillation (frequency range 1 Hz to 2 Hz), Inter area oscillation (frequency range 0.4 Hz to 0.8 Hz) and global oscillation (typical frequency 0.2 Hz).To damped such a wide range of electromechanical oscillations, we use MB-PSS.

**3. SIMULATION RESULTS**

This section present the simulation results of studied system under three phase to ground fault at bus 6. A three-phase to ground fault is suddenly applied to bus at  $t = 16$  s and is cleared at  $t = 16.2$  s. This is a critical fault and mostly occurs in practical power system. Hence we can use this type of fault to check whether the studied systems can withstand such fault or not. If studied systems are stable during such faults, it means that the studied system have ability to remain stable when they are subject to other faults such as single line-to-ground fault, line-to-line fault, double line-to-ground fault etc.

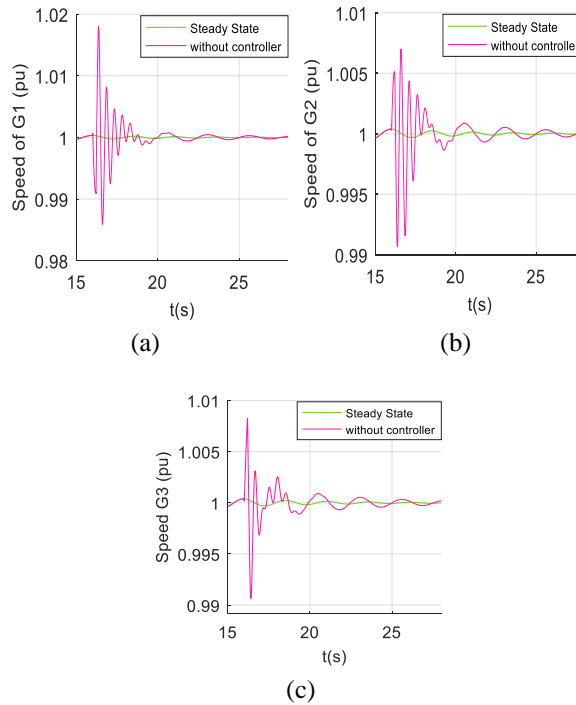
The simulation results of the studied system are obtained from MATLAB/Simulink platform. A 50 MVAR SVC is use to stabilize the wind farm. When both SVC & PSS used parallel; they also damp the power oscillation during fault. The simulation results of studied system without controller, with SVC and with SVC+PSS for three phases to ground fault are shown below.





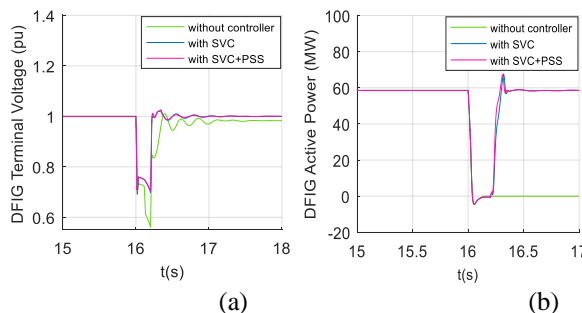
**Fig. 9 DFIG Parameters during Steady State & Fault without any Controller (a) DFIG terminal voltage (b) DFIG Active Power (c) DFIG Reactive Power**

The fault impedance of fault breaker is ( $Z_f = 1\Omega$ ) and ground impedance is ( $Z_g = 0.001\Omega$ ). The DFIG protection system is designed to trip for AC under voltage 0.75 pu, AC over voltage 1.1 pu, rotor under speed 0.3 pu and rotor over speed 1.5 pu. In steady state condition the DFIG terminal voltage is 0.998 pu. When system is subjected to LLLG fault, DFIG terminal voltage drops to 0.59 pu, hence DFIG trip at 16.11 sec. Fault is cleared in 0.2 sec but due to tripping of DFIG, its terminal voltage reduces to 0.98 pu. DFIG supply 58.50 MW active power & 4.50 MVAR reactive power in steady state and in fault condition it trips.



**Fig. 10 Speed of Generators during Steady State & Fault without any Controller (a) Speed of G1 (b) Speed of G2 (c) Speed of G3**

The speed of synchronous generators G1, G2 & G3 are shown in Fig. 10. In steady state condition speed of synchronous generators is 1 pu. But after fault without any controller, DFIG trips and synchronous generators start oscillation & take 14 to 16 sec to reach its steady state operating speed due to insufficient damping.



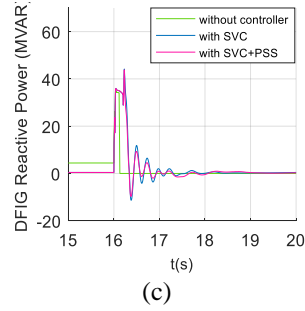


Fig. 11 DFIG Parameters during Fault without Controller, with SVC & with SVC+PSS (a) DFIG terminal voltage (b) DFIG Active Power (c) DFIG Reactive Power

Without controller, when system is subjected to LLLG fault DFIG trips because its terminal voltage reduce below 0.75 pu. In presence of SVC DFIG maintain

Table I Values of several parameters of studied system

Parameters	In Steady State	In Fault Condition Without Controller	In Fault Condition with SVC+PSS
DFIG Terminal Voltage (pu)	0.998	0.981	1.00
DFIG Active Power (MW)	58.50	Trip	58.53
DFIG Reactive Power (MVAR)	4.43	Trip	0.41
DFIG Rotor Speed (pu)	1.21	1.52	1.21
Generators G1, G2 and G3 Settling time (sec)		14–16	3–4
Rotor Angle Deviation $\delta_{12}$ (degree)		68	64
Rotor Angle Deviation $\delta_{13}$ (degree)		67	62
Reactive Power Supplied by SVC (MVARs)			25.90

its terminal voltage more than 0.75 pu, due to reactive power support of SVC and also DFIG active power supply increase from 58.50 MW to 58.53 MW & reactive power supply reduce from 4.5 MVAR to 0.4 MVAR. Hence power factor of DFIG also improved. In presence of both SVC+PSS DFIG does not trip and oscillations are also minimized.

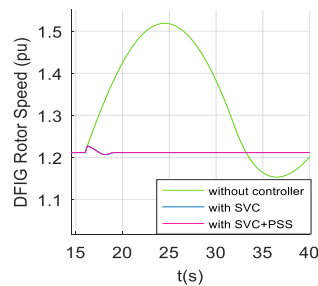
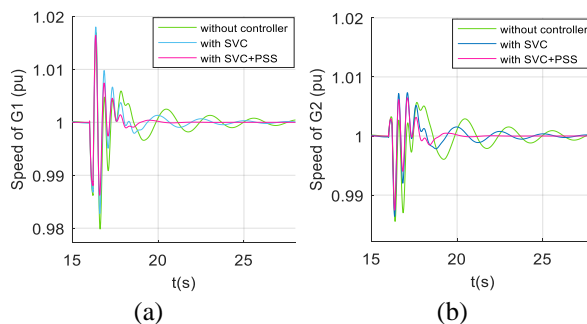
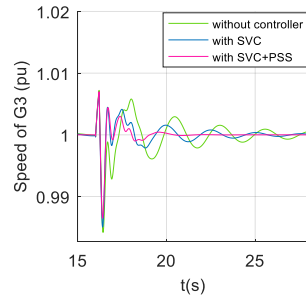


Fig. 12 DFIG Rotor Speed

The rotor speed of DFIG is shown in fig. 12. Without controller DFIG rotor speed increase up to 1.52 pu and with SVC it maintain at 1.21 pu.

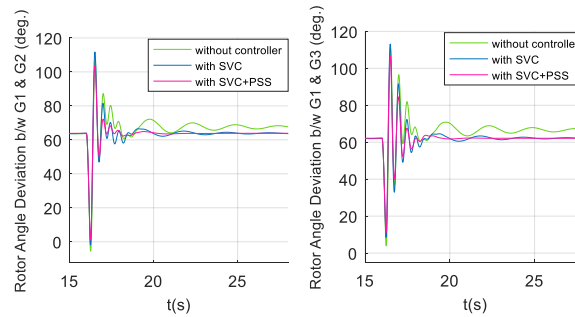




(c)

**Fig. 13 Speed of Generators during Fault without Controller, with SVC & with SVC+PSS (a) Speed of G1 (b) Speed of G2 (c) Speed of G3**

The speeds of synchronous generators are shown by fig. 13(a), (b) & (c). Without any controller synchronous generators take 14 to 16 sec to achieve steady state speed due to insufficient damping. And in presence of both damping controllers SVC & PSS oscillation damped. And hence alternators settle in 3 to 4 sec.

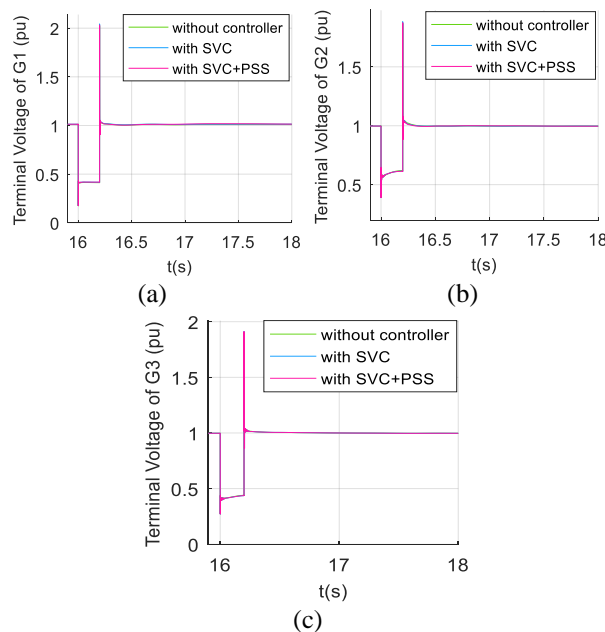


(a)

(b)

**Fig. 14 Rotor Angle Deviation of Generators during Fault without Controller, with SVC & with SVC+PSS (a) Rotor Angle Deviation b/w G1 & G2 (b) Rotor Angle Deviation b/w G1 & G3**

Fig. 14 shows the rotor angle deviation of synchronous generators. In absence of damping controllers rotor angle deviation  $\delta_{12}$  &  $\delta_{13}$  are 68 degree & 67 degree respectively. And in presence of SVC & PSS  $\delta_{12}$  reduce form 68 degree to 64 degree &  $\delta_{13}$  reduce from 67 degree to 62 degree and system stabilized in 4 sec.



(a)

(b)

(c)

**Fig. 15 Terminal Voltage of Generators during Fault without Controller, with SVC & with SVC+PSS (a) Terminal Voltage of G1 (b) Terminal Voltage of G2 (c) Terminal Voltage of G3**

The terminal voltages of synchronous generators are shown in fig. 15(a), (b) & (c). In presence of SVC & PSS the terminal voltages of G1, G2 & G3 are maintain at 1.01 pu, 1.00 pu & 0.997 pu respectively.

SVC operates in voltage control mode and supply reactive power according to voltage of bus 5. The reactive power supplied by SVC is shown in fig.16. SVC supplied 25.90 MVAR reactive power except fault duration.

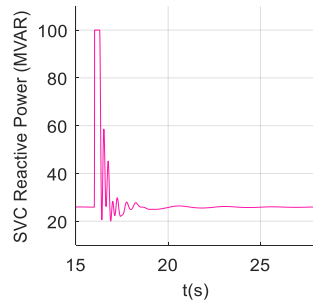


Fig. 16 Reactive Power Supplied by SVC

#### 4. CONCLUSION

This paper has presented the stability improvement of a DFIG-based offshore wind farm connected to a multi-machine system using SVC & PSS. The wind farm and SVC both are connected at bus 5 of multi-machine system. SVC supply reactive power to the system and maintain stable operating condition for DFIG. And to improve the damping of system PSS is used at generator G3. Both SVC & PSS operate symmetrically to enhance the performance of DFIG-based offshore wind farm connected to a multi-machine system.

#### 5. APPENDIX

Brief explanation of input data to model the system in MATLAB/Simulink:

Multi Machine Data [12]:

##### Branch Data:

From-end bus	To-end bus	Resistance (in per unit)	Reactance (in per unit)	Half of the admittance (in per unit)	Non-standard ratio of transformer
4	5	0.010	0.085	0.088	-
4	6	0.017	0.092	0.079	-
5	7	0.032	0.161	0.153	-
6	9	0.039	0.170	0.179	-
7	8	0.0085	0.072	0.0745	-
8	9	0.0119	0.1008	0.1045	-
1	4	0.0	0.0576	-	1.0
2	7	0.0	0.0625	-	1.0
3	9	0.0	0.0586	-	1.0

##### Generator Data:

Generator	Bus	$T_J$	$R_a$	$X_d$	$X'_d$	$X_q$	$X'_q$	$T'_{d0}$	$T'_{q0}$	D
s1	1	47.28	0.0	0.1460	0.0608	0.0969	0.0969	8.96	-	0.0
2	2	12.80	0.0	0.8958	0.1198	0.8645	0.1969	6.00	0.535	0.0
3	3	6.02	0.0	1.3125	0.1813	1.2578	0.2500	5.89	0.600	0.0

**Doubly Fed Induction Generator Data [13]:**

S.N	Parameter	Values
1	Capacity ( = 40 Turbines x 1.5 MW each)	60 MW
2	Voltage	575 V
3	No. of Poles	6
4	Inertia Constant	5.04
5	Stator Resistance (in per unit)	0.0070
6	Stator Inductance (in per unit)	0.171
7	Rotor Resistance (in per unit)	0.005
8	Rotor Inductance (in per unit)	0.156
9	Magnetizing Inductance (in per unit)	2.9

**SVC Data:**

Power Rating	50 MVA
Mode of Operation	Voltage Control
Voltage Rating	25 kV

**6. REFERENCES**

- [1] X. Y. Bian, Yan Geng, Kwok L. Lo, Yang Fu and Q. B. Zhou, “Coordination of PSSs and SVC Damping controller to Improve Probabilistic Small-Signal Stability of Power System with Wind Farm Integration”, IEEE Trans. Power Syst., vol. 31, no. 3, May. 2016.
- [2] Z. Elhassan, Yang Li and Yi Tang, “Simplified voltage control of paralleling doubly fed induction generators connected to the network using SVC”, Int. Trans. Elect. Energ. Syst., 2014.
- [3] R. M. M. Pereira, C. M. M. Ferreira and F. p. M. Barbosa, “Comparative Study of STATCOM and SVC Performance on Dynamic voltage Collapse of an Electric power System with Wind Generation”, IEEE Trans. Power Syst., vol. 12, no. 2, March. 2014.
- [4] M. A. Kamarposhti, M. Shaker, T. Tayyebifar and M. Firoozian, “Performance Comparison of STATCOM & SVC in Reactive Power Control Strategy for Wind Farm” in J. World. Elect. Eng. Tech., June 2014.
- [5] M. G. Hemeida, Hegazy Rezk and Mohamed M. Hamada, “A comprehensive comparison of STATCOM versus SVC-based fuzzy controller for stability improvement of wind farm connected to multi-machine power system” Electr. Eng DOI 10.1007/s00202-017-0559-6.May 2017.
- [6] R. K. Verma, S. Auddy and Ysni Semesedini, “Mitigation of Subsynchronous Resonance in a series-Compensated Wind Farm Using FACTS controllers” IEEE Trans. Power Syst., vol. 23, no. 3, July 2008.
- [7] Li Wang, and Dinh-Nhon Truong, “Stability Enhancement of DFIG-Based Offshore Wind Farm Fed to a Multi-Machine System Using a STATCOM”, IEEE transactions on power systems 2013.
- [8] S. R. Aali and D. Nazarpour, “Transient Stability Enhancement of Wind Farm by PSS and UPQC” Taylor & Francis, 11 Feb. 2015.
- [9] R. Sarrias, C. Gonzalez, L. M. Fernandez, C. A. Garcia and F. Jurado, “Comparative Study of the Behavior of a Wind Farm Integrating Three different FACTS Devices,” J Elect. Eng. Tech. Vol.9, 2014.
- [10] N. Mithulananthan, C. A. Canizares, J. Reeve and G. J. Rogers, “Comparison of PSS, SVC and STATCOM controllers for Damping power System Oscillations”, IEEE transactions on power systems, Vol. 18, no. 2, May 2003.
- [11] L. M. Fernandez, F. Jurado, J. R. Saenz, “Aggregated dynamic model for wind farms with doubly fed induction generator wind turbines,” Renewable Energy, vol. 33, pp. 129-140, January 2008.
- [12] Xi-Fan Wang, Yonghua Song and Malcolm Irving, “Morden Power System Analysis”, ISBN 978-0-387-72852-0, 2008.
- [13] B. Pokharel and Wenzhong Gao, “Mitigation of disturbances in DFIG-based wind farm connected to weak distribution system using STATCOM” in Proc. IEEE North American Power Symposium, pp. 1-7, 26-28 Sept. 2010.