Voltage Stability Improvement of Four Parallel Operated Offshore Wind Turbine Using Fuzzy Controller

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Abstract—**This paper presents the stability enhancement of four parallel-operated offshore Wind Turbine Generators (WTGs) is connected to an onshore power system using a Static Synchronous Compensator (STATCOM). The operating characteristics of each of the four WTGs are simulated by wind permanent magnet synchronous generator while the onshore power system is simulated by a Synchronous Generator (SG) fed to an infinite bus through two parallel transmission lines. A fuzzy controller for the proposed STATCOM is designed by using an adequate damping to the dominant modes of the SG. A frequency domain approach based on a linearized system model using Eigen value analysis is performed while a time domain scheme based on a linear system model subject to disturbances is also carried out. These papers present the voltage enhancement of the offshore wind turbine by using the fuzzy controller and maintain the voltage of 1p.u.**

Index Terms—**Dynamic stability, permanent-magnet synchronous generator (PMSG), static synchronous compensator, wind turbine generator (WTG).Fuzzy controller.**

I. INTRODUCTION

Renewable energy is one of the hottest themes in the entire world today due to the fast and huge consumption of fossil fuels. Some academic researchers have devoted to high-capacity offshore wind turbine generators (WTGs) connected to onshore substations through undersea cables. Currently, wind doubly-fed induction generators (DFIGs) and wind permanent-magnet synchronous generators (PMSGs) have been widely used in high-capacity offshore wind farms (OWFs). From the historical point of view, a direct-coupled, modular PMSG for variable-speed wind turbines was proposed and multiple single-phase outputs were separately rectified to obtain a smooth dc-link voltage. The dynamic model based on small-signal stability of a wind turbine (WT) using a direct-drive PMSG with its power converters and controllers was proposed in. A new interconnecting method for two or more PMSG-based WTGs used in a wind farm was proposed in, and the proposed scheme required only one externally commutated inverter and only one dc link.

A variable-speed WT-PMSG connected to the power grid through a fully controlled frequency converter has the reactive-power control ability to offer required reactive power of the fixed-speed WT generators connected in series or parallel to its terminals. The control strategy of a hybrid wind farm containing a large number of induction machine (IM)-based WTGs and very few PMSG-based WTGs to compensate the reactive power requirement of the IM during faults and mitigate power fluctuations during wind gusts was proposed in. An integration of a generator-side three-switch buck-type rectifier and a grid-side Z-source inverter as a bridge between the PMSG and the grid was proposed for a PMSG-based WTG while the experimental validation and simulation studies were carried out to examine the effectiveness of the proposed scheme . A simple coordinated control of dc-link voltage and pitch angle of a PMSG-based WTG to smooth wind power fluctuations was proposed.

Regarding the applications of STATCOM to power-system stability improvement, the stability enhancement of power systems using STATCOMs and the damping controller design of STATCOMs were presented in. A variable-blade pitch of a WTG and design of an output feedback linear quadratic controller for a STATCOM to perform mechanical power control and voltage control under different operating conditions were studied in [10]. Controller design and system modelling for quick load voltage regulation and suppression of voltage flicker using a STATCOM were explored in. A novel D-STATCOM control algorithm for enabling separate control of positive- and negative-sequence currents was proposed in. Dynamic characteristics of a power system with a STATCOM and a static synchronous series compensator(SSSC) through digital simulations were compared in. The application of a STATCOM to damp torsional oscillations of a series-capacitor compensated ac system was shown in.

The characteristics of using PSS, static VAR compensator (SVC), and STATCOM for damping undesirable inter area oscillations of a power system were compared in. These days, with the fast advance of high-capacity power-electronics technology, large commercial wind turbine generators can be practically employed to contribute high generated power to power systems, where wind PMSGs with full back-to-back converters have proven to be good choices for high-power WTGs. Basically, the grid-side converter of the PMSG-based WTG can be operated as a STATCOM. Many manufacturers also provide this option even for the case when the WTG is not running. But in a real PMSG-based OWF, it has several PMSG-based WTGs operating together, and it is difficult to control reactive power of all WTGs at the same time to supply adequate reactive power to the system. Hence, to guarantee Good power quality (PQ) of the system, an additional VAR Compensator is required. In this paper, a STATCOM is proposed as a VAR compensator. This paper focuses on modelling the characteristics of four 5-MW PMSG-based WTGs fed to an

SG-based power system to examine the effect of large power penetration to the SG. For improving the damping of the SG of the OMIB system, a STSCOM joined with the designed FUZY controller connected to the common ac bus of the studied system is proposed.

II. CONFIGURATION OF THE STUDIED SYSTEM

Fig. 1 shows the configuration of the studied system. The right-hand side of Fig. 1 represents the synchronous generator (SG)-based one-machine infinite-bus (OMIB) system. Two parallel-operated 615-MVA SGs are connected to an infinite bus (or a power grid) through two parallel transmission lines (TL1 and TL2) and a 15/161-kV step-up transformer. Four parallel-operated PMSG-based WTGs and a 5-MVARSTATCOM are connected to the common offshore ac bus that is fed to the point of common coupling (PCC) of the OMIB system through a step-up transformer of 23/161 kV and a cable(undersea and underground cables). Each 5-MW WTG is represented by a PMSG with an ac/dc converter, a dc link, a dc/ac inverter, and a step-up transformer of 3.3/23 kV. While the shaft of the wind PMSG is directly driven by a variable-speed WT. the four PMSG-based WTGs, the STATCOM, and a local load are connected to a common ac bus through connection lines and transformers. The equivalent capacitanceC_{bus} is also connected to the common ac bus. The employed mathematical models of the studied system will be described.

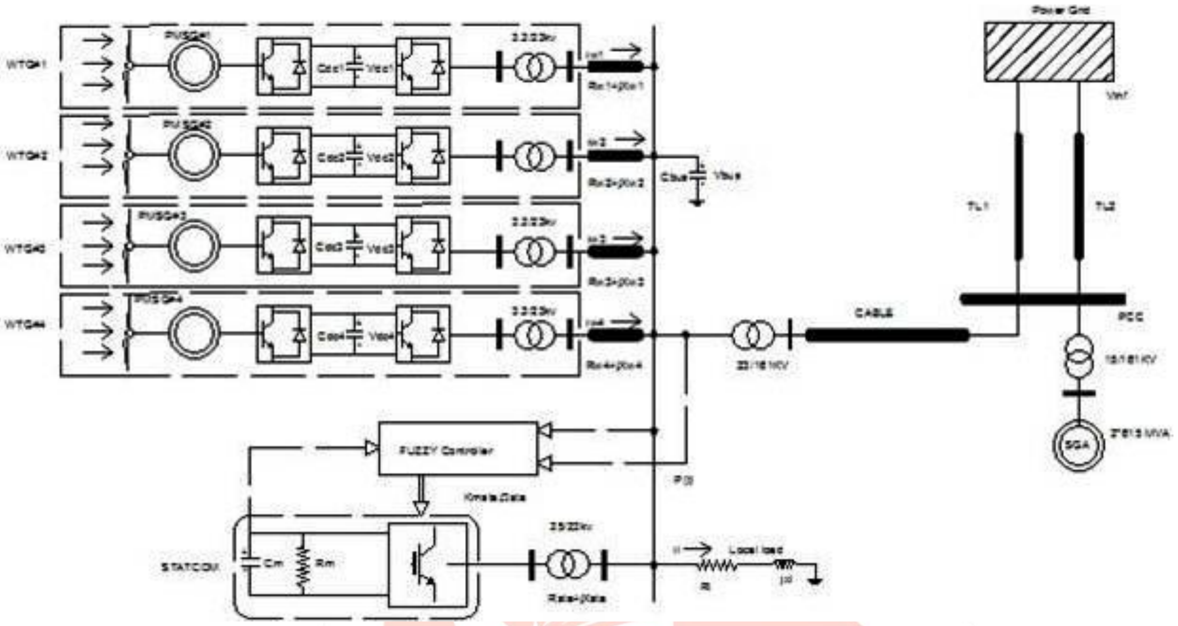


Fig.1.Configuration of the studied SG-based OMIB system containing four parallel-operated PMSG-based WTGs with FUZZY CONTROLLER.

A Wind Turbine Model And Mass Spring Damper Model

The captured mechanical power (in watts) by a WT can be written by,

$$P_m = \frac{1}{2}\rho.A_r.V_W^3.C_p(\lambda, \beta) \tag{2.1}$$

Where ρ is the air density,(kg/m^3) is the blade swept area(m^2), V_w is the wind speed (in meter per second), and is the dimensionless power coefficient of the WT. The can be expressed by

$$C_p(\psi_k) = C_1(\frac{C_2}{\psi_k} - C_3.\beta - C_4.B^{C^5} - C_6)\exp(-\frac{C_7}{\psi_k}) \tag{2.2}$$

Where

$$\lambda = \frac{R_{blade} \cdot W_{blade}}{V_w} \tag{2.3}$$

Where W_{blade} is the blade angular speed (in radians per second),R_{blade} is the blade radius (in meters), is the tip speed ratio,

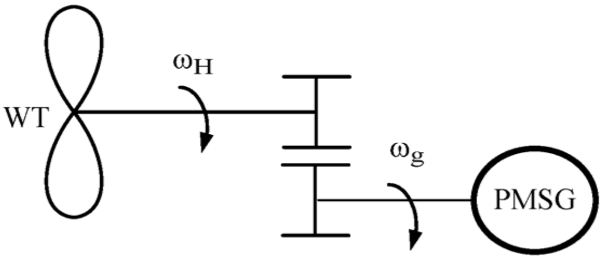


Fig.2. Two-inertia reduced-order equivalent mass-spring-damper model of each WT coupled to the rotor shaft of a wind PMSG

β is the blade pitch angle (in degrees), and C_1- C_2 are the constant coefficients for C_p. The wind speed V_w is modelled as the algebraic sum of a base wind speed, a gust wind speed, a ramp wind speed, and a noise wind speed while the expression of Cp can be referred. The cut-in, rated, and cut-out wind speeds of the studied WT are 4, 14, and 25 m/s, respectively. When wind speed V_w is lower than 14 m/s, β=0^° When 14 m/s, the pitch-angle control system activates and β increases accordingly. Each WT is directly coupled to the rotor shaft of a wind PMSG and it can be represented by a two-inertia reduced-order equivalent mass-spring-damper model shown in Fig. 2

B Permanent Magnet Generator And Power Convertor

The p.u d –q axis equivalent circuit model of the studied wind PMSG, where the q -axis is fixed on the machine rotor and rotates at rotor speed, can be expressed by

$$V_{qs} = -r_s i_{qs} + \frac{p\psi_q}{\omega_b} + \frac{\omega_r}{\omega_b}\psi_d \tag{2.4}$$

$$V_{ds} = -r_s i_{ds} + \frac{p\psi_d}{\omega_b} + \frac{\omega_r}{\omega_b}\psi_q \tag{2.5}$$

Where

$$\psi_q = -(X_{mq} + X_{is}) i_{qs} = -X_q i_{qs} \tag{2.6}$$

$$\psi_d = -(X_{md} + X_{is}) i_{ds} + X_{md\, i'_m} = X_d i_{ds} + X_{md}\, i'_m \tag{2.7}$$

Where ψ is the per-unit flux linkage, $V_s$is the per–unit stator winding voltage, is the per-unit stator winding current, X_m is the per-unit magnetization reactance, is the per-unit leakage reactance, i_m is the per-unit magnetization current, is the per-unit rotational speed, and W_b is the per-unit base speed.

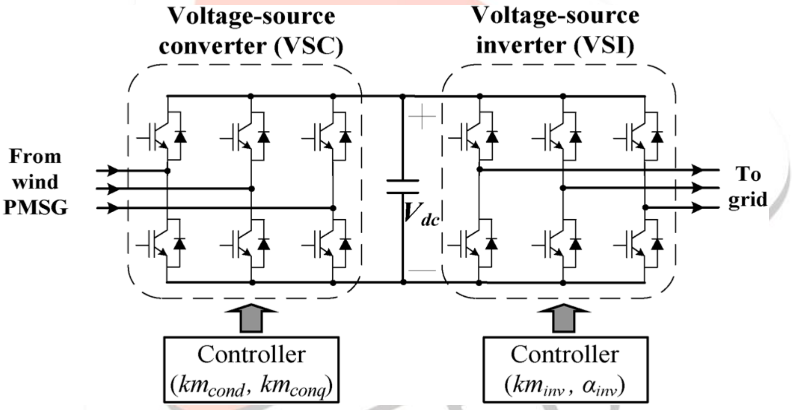


Fig. 3. Model of power converters of the studied wind PMSG.

The power converter of each wind PMSG consists of a voltage source converter (VSC) and a voltage-source inverter (VSI) as shown in Fig. 3. The VSC or the VSI consists of six insulated- gate bipolar transistors (IGBTs). The common dc link with a large capacitor is connected between the VSC and the VSI. The operation of the VSC and the VSC is properly decoupled by the dc-link capacitor and, hence, the VSC and the VSI have independent controllers.

The input d – q axis per-unit voltages of the voltage-source converter (VSC) converter of a wind PMSG can be expressed by V_{cond}=km_{cond} V_{dc} and V_{conq}=km_{conq} V_{dc} , respectively, where V_{dc} is the dc-link voltage while km_{cond} and km_{conq} are the d-and q-axis modulation indices of the VSC converter, respectively. The output d–q axis per unit voltages of the VSC inverter of a wind PMSG can be written by V_{invd}=km_{inv}sin (α_{inv}) and V_{invq}=km_{inv}cos (α_{inv}), respectively, where km_{inv} and α_{inv} are the modulation index and the phase angle of the VSC inverter, respectively. The fundamental control block diagram of the VSC converter and the VSC inverter of each of the wind PMSGs can be referred to Fig. 3. Fig. 3 shows that α_{inv} is responsible to control the rotor speed of the wind PMSG ω_r, and km_{inv} is used to control the output reactive power of the PMSG (Q), km_{conq} is employed to control the dc-link voltage V_{dc}, and km_{conq} is utilized to control the stator-winding voltage of the PMSG (Vs).

C. STATCOM Model

The per-unit q-and d-axis output voltages of the proposed STATCOM shown in Fig. 1 can be written by, respectively

$$v_{qsta} = V_{desta} \,.\, km_{sta} \,.\, \cos(\Theta_{bus} + \alpha_{sta}) \tag{2.8}$$

$$v_{dsta} = V_{desta} \,.\, km_{sta} \,.\, \sin(\Theta_{bus} + \alpha_{sta}) \tag{2.9}$$

Where V_{qsta} and V_{dsta} are the per-unit q- and d-axis voltages at the output terminals of the STATCOM, respectively; km_{sta} and α_{sta} are the modulation index and phase angle of the STATCOM, respectively; Θ_{bus} is the voltage phase angle of the common ac bus, and V_{desta} is the per-unit dc voltage of the dc capacitorC_m. The per-unit dc voltage-current equation of the dc capacitor C_m can be described by

$$(C_m)p(V_{desta}) = \omega b[(I_{desta}/R_m)] \tag{2.10}$$

Where

$$I_{desta} = i_{qsta} . km_{sta} . \cos(\Theta_{bus} + \alpha_{sta}) + i_{dsta} . km_{sta} . \sin(\Theta_{bus} + \alpha_{sta}) \tag{2.11}$$

The per-unit dc current flowing into the positive terminal of V_{desta},R_m is the per-unit equivalent resistance considering the equivalent electrical losses of the STATCOM, and i_{qsta} and i_{dsta} are the per-unit q- and d-axis currents flowing into the terminals of the STATCOM, respectively. The fundamental control block diagram of the employed STATCOM including a proportional-integral-derivative (PID) damping controller is shown in Fig. 5. The per-unit dc voltage V_{desta} is controlled by the phase angle α_{sta} while the voltage V_{sta} is varied by changing the modulation index km_{sta}. Based on the conclusions the size of STATCOM in this paper is chosen as 5 MVAR that is equal to 25% of the capacity of the studied OWF. The procedure to calculate parameters of the proposed STATCOM is referred.

III. DESIGN OF FUZZY CONTROLLER

The tHere fuzzy controller is designed with two inputs i.e. generator frequency and its derivative and a single output i.e. Alpha. The advantage of this controller is that it doesn't required detailed information about the system. Mamdani Fuzzy Model is use for the purposed fuzzy controller and "if-Then" rules use for inference engine. There is fuzzy variable corresponding to each controller input and these inputs are fuzzified by using membership function and crisp output is calculated using Centre of area (COA) method. Proper membership functions are defined for output variables too. Membership functions for input variables i.e. ω and its derivative$\frac{d\omega}{dt}$are given in Fig5&Fig6.

The proper range for each term and the number of membership functions can be defined based on designer experiments and the system configuration. Membership functions of dω/dt are symmetrical but those of ω are defined in different way. It is because of the behaviour of machine speed and can be known by simulation results. Fig 7 shows the output membership functions of alpha angle of voltage source converter which is used to build controller crisp output from the fuzzy outputs of inference engine. The deffuzzification method used for this purpose is COA.

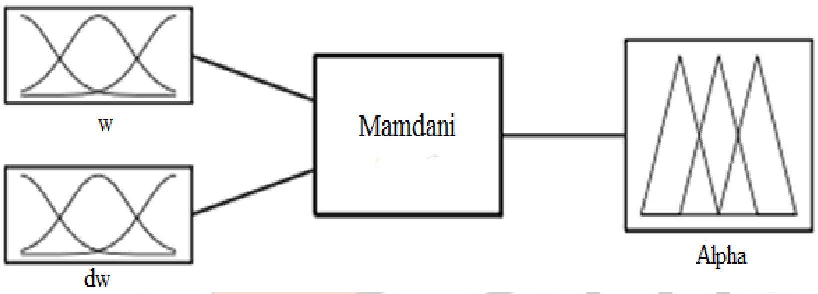


Fig.4. Two input single output FLC

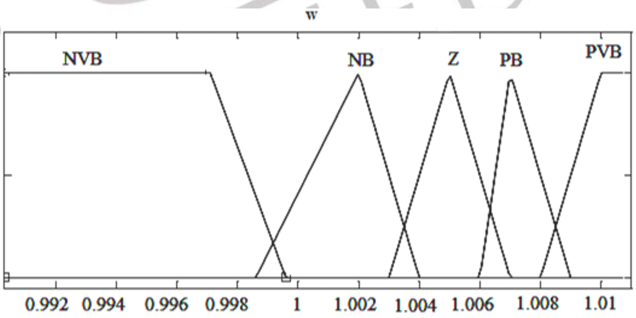


Fig.5. input membership function of ω

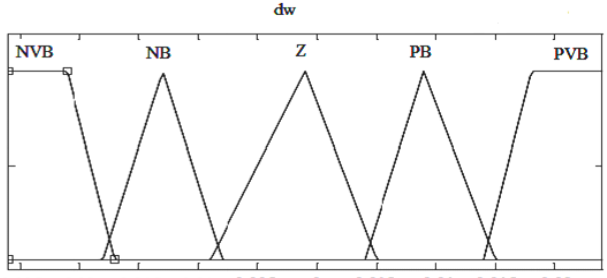


Fig.6. input membership function of $\frac{d\omega}{dt}$

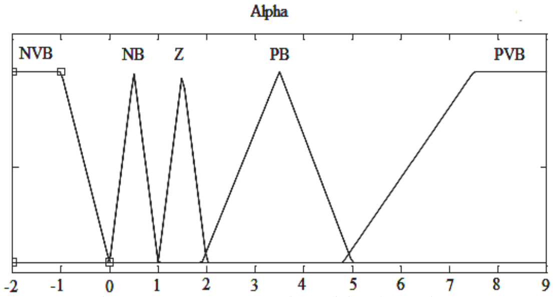


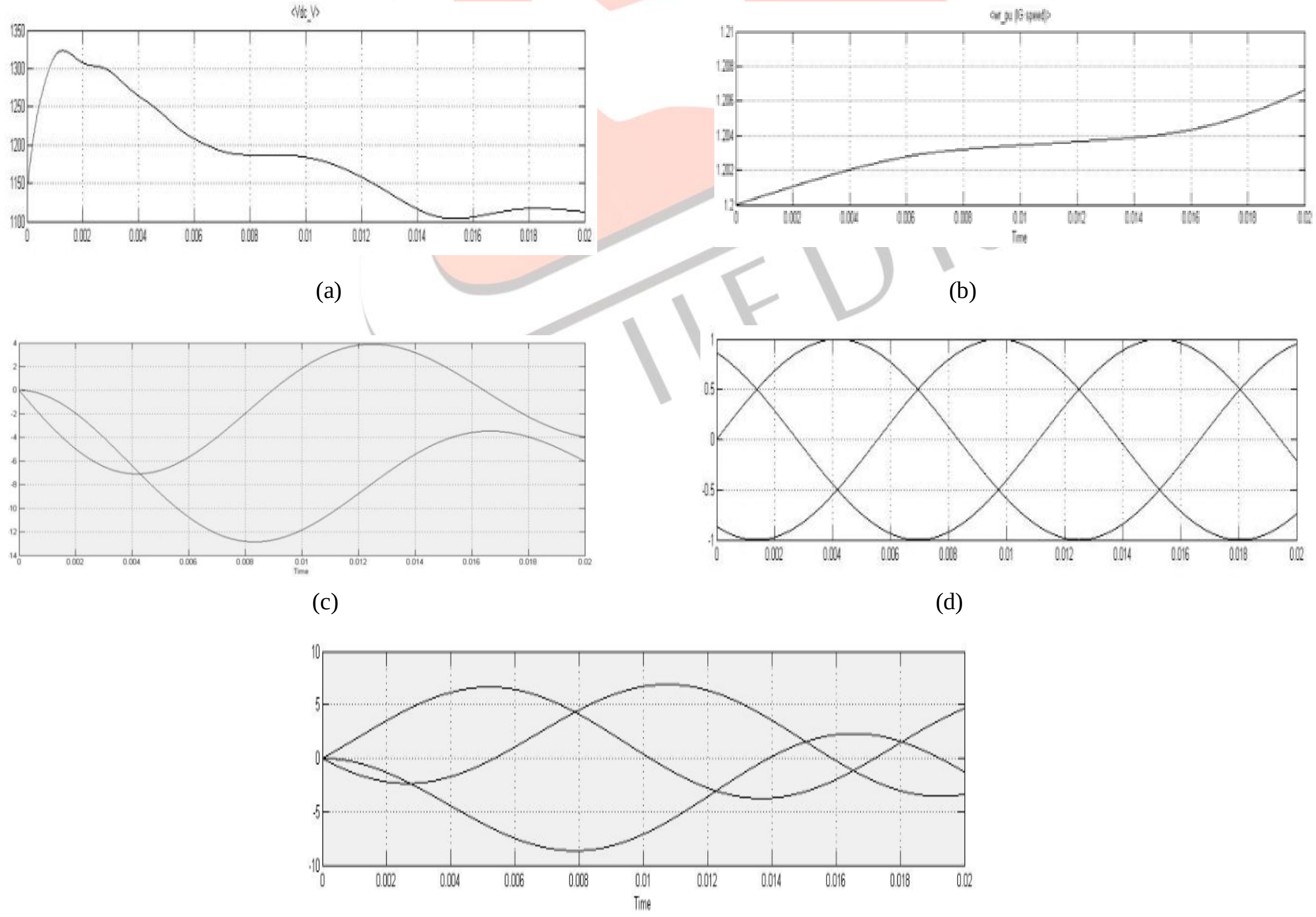
Fig.7. Output membership function α

The logic behind rule can be easily derived. For example,
R1:if (power factoe angle is very very small) then (firingangle is veryvery small) (1).
R2: if (power factoe angle is very small) then (firingangle is very small) (1).
R3: if (power factoe angle is small) then (firingangle is small) (1).

The logic is that when frequency is high and it's rising fast, the system is in critical condition because the input mechanical power of generators is more than output electrical power. Therefore the STATCOM should inject big capacitive current into the network hence alphashould be small. By this action the transmittable power capacity of the line whichSTATCOM installed will be increased and the transient stability will be improved. Other conditions can be analysed in a similar way.

IV. RESULT AND DISCUSSION

The performance of the proposed system through mat lab/Simulink, are discussed. Power system stability can be defined as the ability to remain in equilibrium during normal operating conditions and to regain an acceptable equilibrium after being subjected to a physical disturbance with most system variables bounded. For example, squirrel cage induction generator connected directly to the grid has intrinsically more damped oscillation modes. Generators of the variable speed wind turbines are decoupled from the grid by a power converter .In a stability analysis it is important to define where the wind farm is located, what generator technology is used, and how strong the power system is where the wind farm is connected. The impact of wind generation under different voltage levels or in various penetration percents can cause a poor behaviour of the power system A squirrel cage induction generator connected directly to the grid helps to enhance the stability of the system. However, the contribution to the stability is limited.



(a)

(b)

(c)

(d)

(e)

Fig 6.1 Shows the output (a) Stator Voltage,(b) Turbine Speed,(c) Real Power Output of Offshore Wind,(d) Output Voltages of Offshore Wind Turbine,(e) Output Current of Offshore Wind Turbine

The stator voltage values in four parallel operated Permanent Magnet Synchronous Generator (PMSG) values are shown in Fig6.1 (a) It is also included the power quality problems like as voltage sag, swell and large disturbances.Fig6.1 (b) shows the increased in turbine speed. The speed of the wind turbine is mainly depending of the variation of the wind. Fig6.1(c)shows The STATCOM joined with the designed Fuzzy controller can supply proper reactive power to the system and offer better damping characteristics to the modes of the SG to quickly damp out the inherent oscillations.Fig6.1(d) shows the voltage profile of the system can also be improved by the proposed STATCOM with the Fuzzy controller. The terminal voltage is increased from 0.8 to 1 pu. The output current of the offshore wind turbine connected to the grid shown in Fig 6.1(e)

V. CONCLUSION

The voltage stability enhancement of four parallel-operated PMSG-based WTGs connected to SG-based OMIB system. The Proposed STATCOM model was connected to the common ac bus of the four WTGs to supply adequate reactive power and offer proper damping. A fuzzy controller has been designed for the STATCOM using modern control theory of the SG on the desired locations on the complex plane. It can be concluded from the simulation results that the proposed Fuzzy logic based STATCOM controller has the ability to improve the Voltage Enhancement of the multiple PMSG-based WTGs connected to an SG-based power system.

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