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Dynamic Stability Improvement of 'N' Parallel Operated PMSG Fed to a Power System Using a STATCOM

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Abstract: ***This paper presents the stability-improvement results of n parallel-operated offshore wind turbine generators (WTGs) connected to an onshore power system using a STATCOM. The operating characteristics of each of the four WTGs 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 osculating controller of the proposed STATCOM is designed. It can be concluded from the simulation results that the proposed STATCOM joined with the designed osculating controller can effectively improve the stability of the studied SG-based onshore power system under various disturbance conditions.***

Keywords: Stability, PMSG, STATCOM

1. 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 [2]. A new interconnecting method for two or more PMSG-based WTGs used in a wind farm was proposed in [3], 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

This paper focuses on modeling 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 STATCOM joined with the designed PID controller connected to the common ac bus of the studied system is proposed

Figure 1 shows the configuration of the studied system. The right-hand side of Figure 1 represents the synchronous generator (SG)-based one- machine in finite -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.

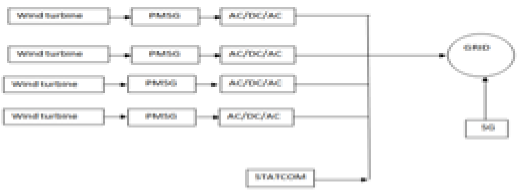


Figure 1: PMSG-based WTGs with STATCOM

2. Configuration of the Proposed System

Figure 1 shows the configuration of the studied system. The right-hand side of Figure 1 represents the synchronous generator (SG)-based one- machine in finite -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 -MVAR STATCOM 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 rep-resented 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.

Wind Turbine Model and Mass-Spring-Damper Model

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

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

Where p is the air density, A_r is the blade swept area, V_w is the wind speed (in meters per second), and is the dimensionless power coefficient of the WT. The C_P can be expressed by

$$C_p(\lambda_k, \beta) = c_1 \left(\frac{c_2}{\lambda_k} - c_3 \cdot \beta - c_4 \cdot \beta^{c_5} - c_6 \right) \exp\left(-\frac{c_7}{\lambda_k} \right)$$

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,

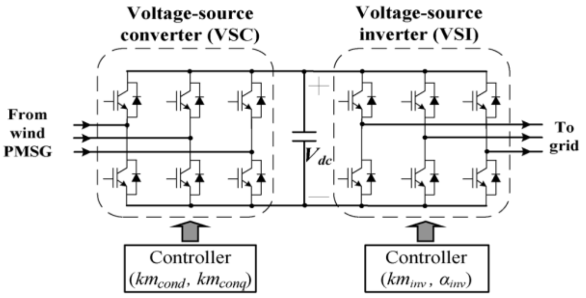


Figure 2: Model of power converters of the studied wind PMSG

β is the blade pitch angle (in degrees), and are the constant coefficients for C_p. The wind speed is modeled as the algebraic sum of a base wind speed, a gust wind speed, a ramp C_p wind speed, and a noise wind speed [18] while the expression of C_p can be referred to [19]. The cut-in, rated, and cut-out wind speeds of the studied WT are 4, 14, and 25 m/s, respectively. When wind speed Vw Is lower than Vw>14m/s,.When Vw>14 m/s, the pitch-angle control system activates and β increases accordingly. Each WT is directly coupled to the rotorshaft of a wind PMSG and it can be represented by a two-inertia reduced-order equivalent mass-spring-damper model

$$2H_h p(\omega_h) = T_m - K_{hg}\theta_{hg} - D_{hg}\omega_h \quad (5)$$
$$2H_g p(\omega_g) = K_{hg}\theta_{hg} + D_{hg}\omega_h - T_e \quad (6)$$
$$p(\theta_{hg}) = \omega_b(\omega_h - \omega_g) \quad (7)$$

Permanent-Magnet Generator and Power Converters

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 [16] and [17]

$$v_{qs} = -r_s i_{qs} + \frac{p\psi_q}{\omega_b} + \frac{\omega_r}{\omega_b}\psi_d \quad (8)$$
$$v_{ds} = -r_s i_{ds} + \frac{p\psi_d}{\omega_b} - \frac{\omega_r}{\omega_b}\psi_q \quad (9)$$

where φis the per-unit flux linkage, is the per–unit stator winding voltage, I_s is the per-unit stator winding current, is the per-unit magnetization reactance, is the per-unit leakage per-unit rotational speed, and is the per-unit base speed. The power converter of each wind PMSG consists of a voltage source converter (VSC) and a voltage-source inverter (VSI) as shown in Figure 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. Reactance, is the per-unit magnetization current, is the STATCOM Model.

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

$$v_{qsta} = V_{dcsta} \cdot km_{sta} \cdot \cos(\theta_{bus} + \alpha_{sta}) \quad (12)$$
$$v_{dsta} = V_{dcsta} \cdot km_{sta} \cdot \sin(\theta_{bus} + \alpha_{sta}) \quad (13)$$

Where V_{qsta} and are the per-unit -and -axis voltages at the output terminals of the STATCOM, respectively; K_{msta} 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_{dcsta} is the per-unit dc voltage of the dc capacitor C_m[24]. The per-unit dc voltage-current equation of the dc C_m capacitor can be described by

$$(C_m)p(V_{dcsta}) = \omega_b \left[I_{dcsta}(V_{dcsta}/R_m) \right] \quad (14)$$

where

$$I_{dcsta} = i_{qsta} \cdot km_{sta} \cdot \cos(\theta_{bus} + \alpha_{sta}) + i_{dsta} \cdot km_{sta} \cdot \sin(\theta_{bus} + \alpha_{sta}) \quad (15)$$

is the per-unit dc current flowing into the positive terminal of V_{dcsta}, is the per-unit equivalent resistance considering the equivalent electrical losses of the STATCOM, and I_{dsta} and I_{qsta} are the per-unit -and -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 Figure 5. The per-unit dc voltage V_{dcsta} is controlled by the phase angle α_{sta} while the voltage is varied by changing the modulation index K_{msta}. Based on the conclusions of [25] and [26], the size of the STATCOM in this paper is chosen as 5MVAR that is equal to 25% of the capacity of the studied OWF. The procedure to calculate parameters of the proposed STATCOM is referred to in [26].

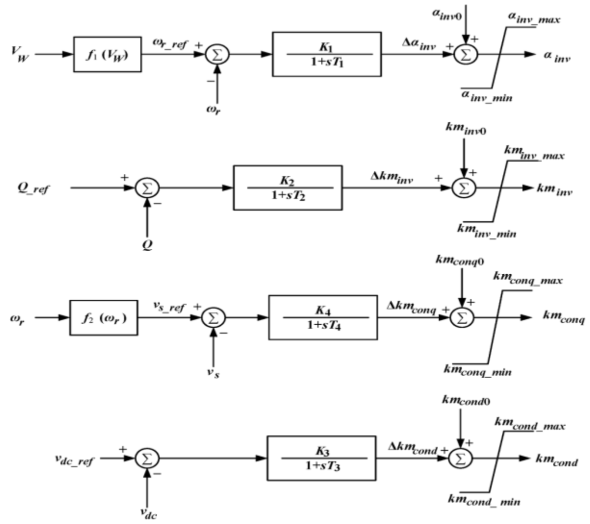


Figure 4: Control block diagram of the VSC converter and the VSC inverter of each of the wind PMSGs

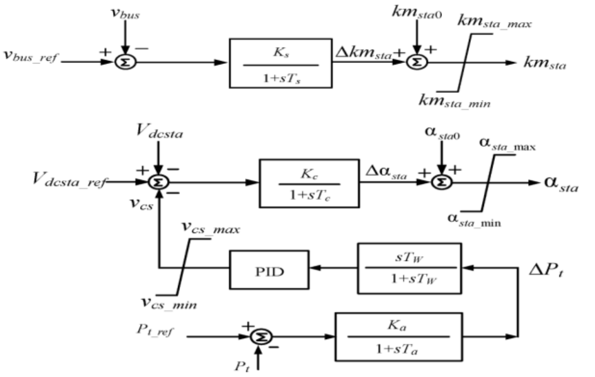
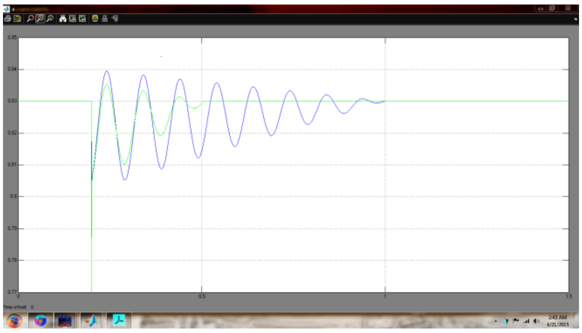
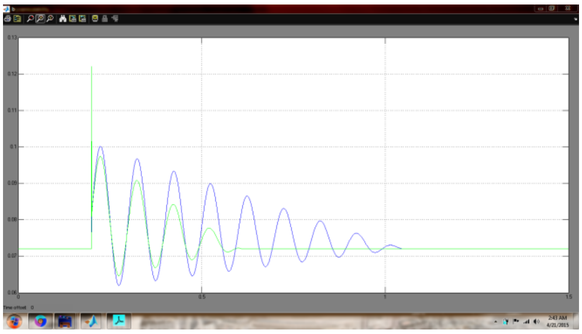


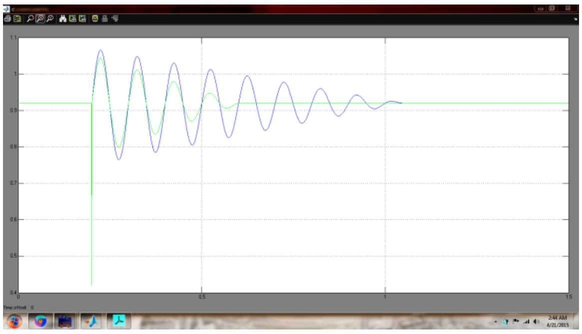
Figure 5: Control block diagram of the employed STATCOM including the designed PID damping controller

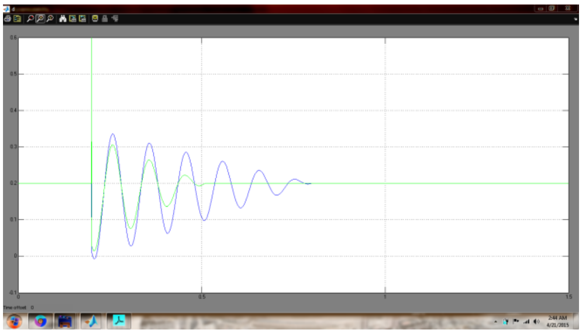
3. Time-Domain Simulations

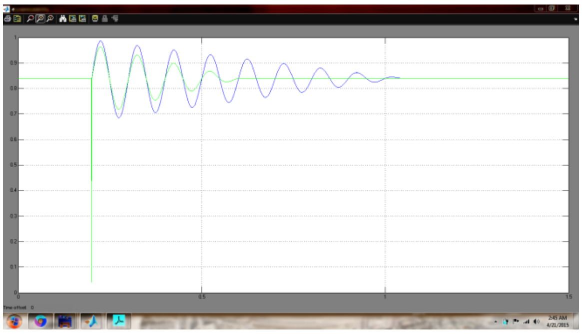
This section utilizes the nonlinear system model developed in Section II to compare the damping characteristics contributed by the proposed STATCOM joined with the designed PID damping controller. To examine the effectiveness of the proposed damping control scheme, this paper uses a three-phase short-circuit fault suddenly applied to the power grid at t=2s, and the fault is cleared at T=2.1 s. Although this type of fault seldom occurs in practical power systems, it is the most critical and the most severe fault to test stability of power systems. Most transient stability studies or evaluations employ such three-phase short-circuits faults applied to the studied systems to check whether the studied systems can withstand such severe system impacts. Besides, a three-phase short-circuit fault imposes the most severe duty on power circuit breakers while this type of fault is also used to determine the circuit-breaker ratings. Hence, it is worth using a three-phase short-circuit fault for testing the transient responses of the studied systems. If the studied systems are stable when this severe fault is suddenly applied and is cleared by some protective relays, it means that the studied systems have the ability to remain in stable operation when the systems are subject to other faults, such as single line-to-ground fault, line-to-line fault, etc. It is assumed that the studied system operates under the operating conditions used in Table I. Figure 7 plots the comparative transient responses of the studied system with and without the designed PID damping controller. Since four parallel-operated PMSG-based WTGs have identical parameters and operating conditions, only the active power and the reactive power of WTG#1 are shown in Figure 7. It is clearly observed from the comparative transient simulation results shown in Figure 7 that all transient responses of the studied system with the proposed STATCOM joined with the designed PID damping controller can be recovered to the pre fault steady-state operating conditions around 6/7.5 s. When the fault occurs, large amplitudes on all quantities shown in Figure 7 can be clearly found. It also shows that the proposed STATCOM joined with the designed PID damping 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 of the SG. It shows that better damping characteristics can be effectively contributed by the designed PID damping controller of the STATCOM to suppress oscillations of the SG. A voltage profile of the studied system can also be improved by the proposed STATCOM with the designed PID damping controller.

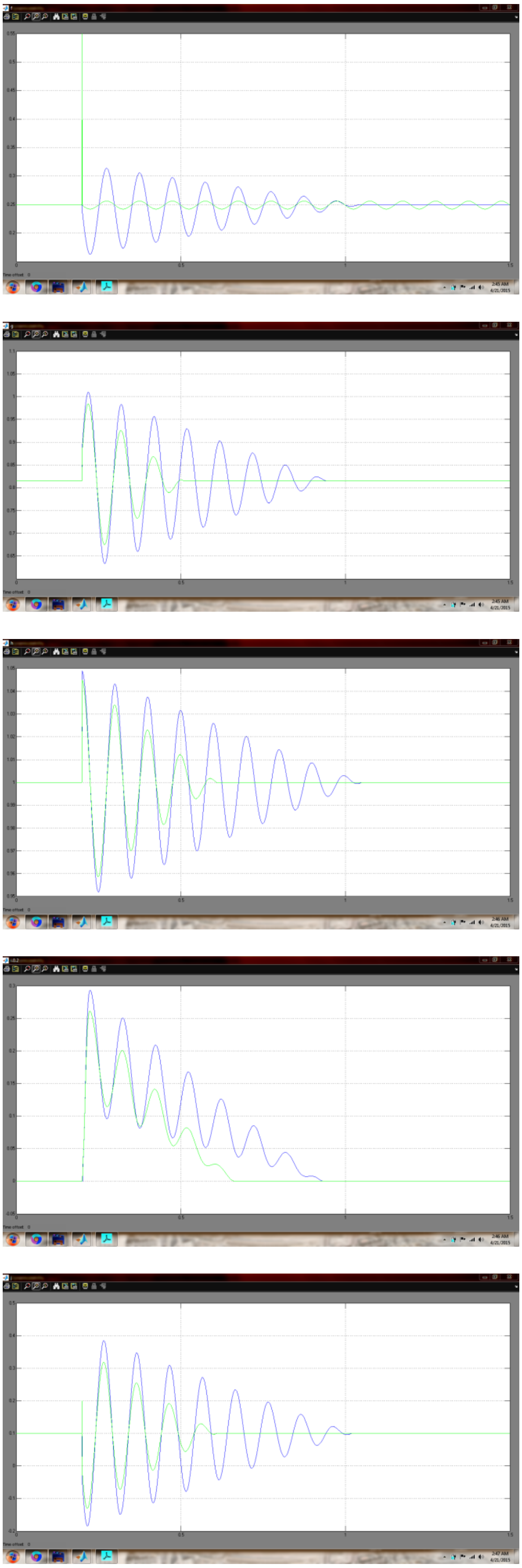












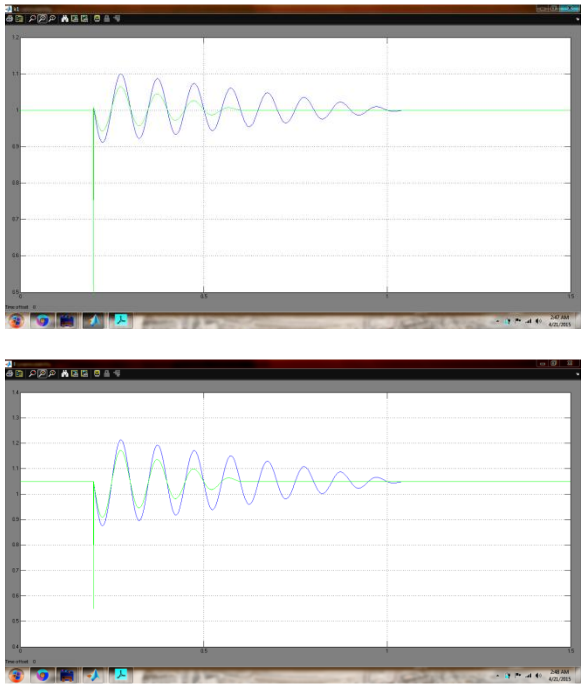


Figure 7: Transient responses of the studied system with and without the designed PID STATCOM damping controller subject to a three-phase short-circuit fault. (a)Pi.(b)Qi.(c)Psystem.(d)Qsystem.(e)Psg.(f)Qsg.(g)δ.(h) Wrsg.(i)Q_{sta}.(j)P_{sta}.(k)V_{pcc}. (l)V_{bus}.

4. Conclusion

This paper has presented the stability improvement of four parallel-operated PMSG-based WTGs connected to an SG-based OMIB system. The STATCOM is proposed and is connected to the common ac bus of the four WTGs to supply adequate reactive power and offer proper damping. A PID damping controller has been designed for the STATCOM using modal control theory to assign the mechanical mode and the exciter mode of the studied SG on the desired locations on the complex plane. Root-loci plots under various operating conditions and time-domain transient simulations of the studied system subject to a three-phase short-circuit fault at the power grid have been systematically performed to demonstrate the effectiveness of the proposed STATCOM joined with the designed PID damping controller on suppressing inherent SG oscillations and improving system stability under different operating conditions. It can be concluded from the simulation results that the proposed STATCOM joined with the designed PID damping controller has the ability to improve the performance of the studied multiple PMSG-based WTGs connected to an SG-based power system under different operating conditions.

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