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Damping Enhancement of Multi Parallel-Operated Offshore PMSG Based Wind Turbine-Using STATCOM

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Abstract: This study presents a control scheme based on a STATCOM to achieve damping enhancement of a grid-connected offshore wind turbine and Onshore Ower System. The operating characteristics of each of the WTGs are simulated by using ermanent-magnet synchronous generator while the Onshore Power System is imulated by a Synchronous Generator (SG) and fed to transmission lines. A damping controller of the STATCOM is designed by using PI controller to contribute effective damping characteristics to the studied system under different operating conditions. A time-domain scheme is used for both non-linear system model and linearized system model and subject to various disturbances are employed to simulate the effectiveness of the proposed control scheme. It can be concluded from the simulated results that the proposed STATCOM joined with damping controller is very effective to stabilize the studied SG-based Onshore Power System under various disturbance conditions.

Key words: Dynamic stability, Permanent-Magnet Synchronous Generator (PMSG), Wind Turbine Generator (WTG), operating, ermanent-magnet synchronous

INTRODUCTION

Renewable energy is one of the hottest themes in the entire world today due to the fast consumption of fossil fuels. Some academic researchers have devoted that the 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 rectied to obtain a smooth dc-link voltage (Chen and Spooner, 1995). The Dynamic Model based on small-signal stability of a Wind Turbine (WT) using a direct-drive of PMSG with its power converters and controllers was proposed Wu *et al*. (2009). A new interconnecting method for two or more PMSG-based WTGs used in a wind farm was proposed by Nishikata and Tatsuta (2010) and the proposed scheme required only one externally commutated inverter and only one dc-link. A small-signal 47th-order analytical model for representing the operating characteristics of a ac grid to which direct-drive PMSG connected is widely varying strength and very weak grids was proposed by Strachan and Jovcic (2010). 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 (Muyeen *et al*., 2010). The control strategy of a hybrid wind farm containing 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 by Leon *et al.* (2010). 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 thir 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 (Zhang *et al*., 2011). A simple coordinated control of pitch angle and dc-link voltage of a PMSG-based WTG to smooth wind power fluctuations was proposed by Uehara *et al.* (2011). Regarding the applications of STATCOM to Power System stability improvement using STATCOM and the damping controller design of STATCOMs, the stability enhancement of power systems

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were presented by Chong *et al.* (2008). A variable-blade pitch of a WTG and design of an output feedback linear quadratic controller for a STATCOM to perform voltage control and mechanical power control under different operating conditions were studied by Gaztanaga *et al.* (2007). Controller design and system modeling for quick load voltage regulation and suppression of voltage flicker using a STATCOM were explored by Jain *et al.* (2006). A novel D-STATCOM Control algorithm for enabling separate control of positive and negative-sequence currents was proposed by Blazic and Papic (2006). Dynamic characteristics of a power system with a STATCOM and a Static Synchronous Series Compensator (SSSC) through digital simulations were compared by Norouzi and Sharaf (2005). The applications of a STATCOM to damp torsional oscillations of a series-capacitor compensated ac system were shown by Patil *et al.* (1998). The characteristics of using PSS, Static VAR Compensator (SVC) and STATCOM for damping undesirable interarea oscillations of a power system were compared by Mithulananthan *et al.* (2003). 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 proved to be good 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 identified that controlling of reactive power for all WTGs at the same time to supply adequate reactive power to the system is difficult. Hence, to guarantee good Power Quality (PQ) of the system, an additional VAR compensator is required. In this study, a STATCOM is proposed as a VAR compensator. This study focuses on modeling the characteristics of six parallel operated 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 PI controller connected to the common ac bus of the studied system is proposed.

CONFIGURATION OF THE STUDIED SYSTEM

Figure 1 shows the configuration of the studied system. The right-hand side of Fig. 1 represents the Synchronous Generator (SG)-based One-Machine Infinite

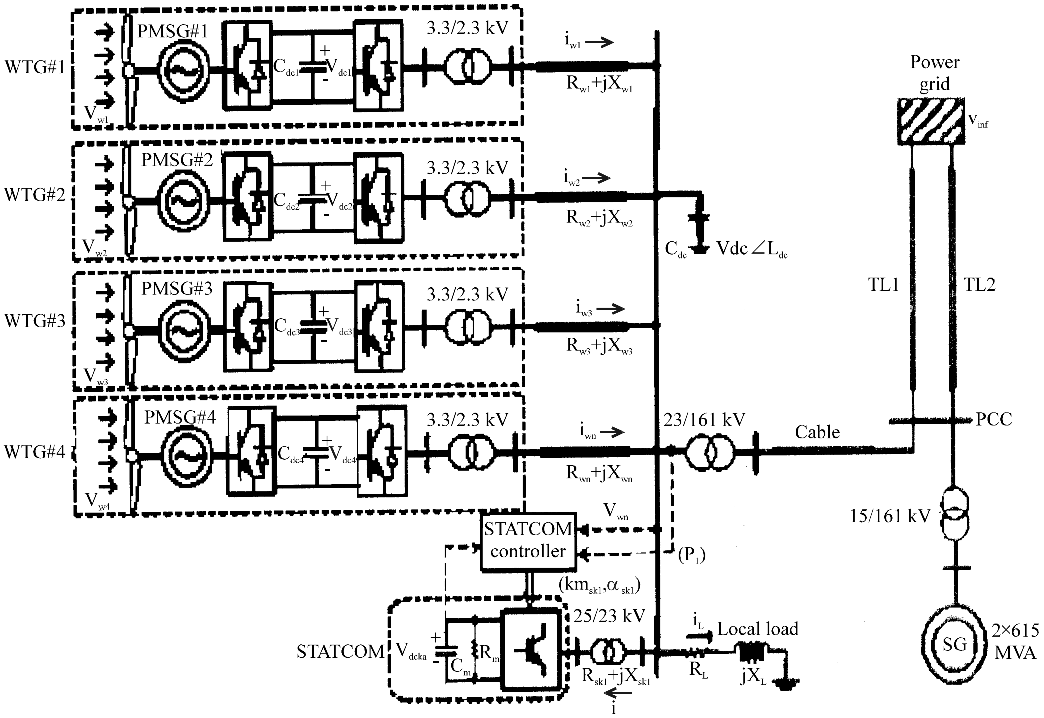

Fig. 1: Configuration of the studied SG-based OMIB System containing four parallel-operated PMSG-based WTGs with STATCOM

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 re-presented 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 capacitance C_{bus} is also connected to the common ac bus. The employed mathematical models of the studied system will be described.

Wind Turbine Model and Mass-Spring-Damper Model: The captured mechanical power (Watt) by a WT can be written by:

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

Where:

ρ = The air density
A_r = The blade swept area
V_w = The wind speed (m/sec)
C_p = The dimensionless power coefficient of the WT

The C_p can be expressed by:

$$C_p(\psi_k, \beta) = c_1\left(\frac{c_2}{\psi_k} - c_3.\beta - c_1.\beta^{c5} - c_6\right)\exp\left(\frac{c_7}{\psi_k}\right)$$

Where:

$$\frac{1}{\psi_k} = \frac{1}{\lambda+c_8.\beta} - \frac{c_9}{\beta^3+1}$$

$$\lambda = \frac{R_{blade}.\omega_{blade}}{V_w}$$

Where:

ω_{blade} = The blade angular speed (radians/sec)
R_{blade} = The blade radius (m)
λ = The tip speed ratio
β = The blade pitch angle (degrees)
C_1-C_9 = The constant coefficients for C_p

The wind speed V_w is modeled 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 C_p can be referred. The cut-in, rated and cut-out wind speeds of the studied WT are 4, 14 and 25 m sec^{-1}, respectively. When wind speed is <14 m sec^{-1}, $\beta = 0°$.

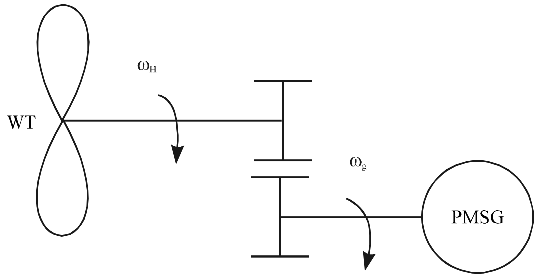

Fig. 2: Two-inertia reduced-order equivalent Mass-Spring-Damper Model of each WT coupled to the rotor shaft of a wind PMSG

When V_w>14 m sec^{-1}, 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 The per-unit (pu) equations of motion for the two-inertia reduced-order WT Model are expressed by:

$$2H_{hp}(w_h)=T_m-K_{hg}\theta_{hg}-D_{hg}w_h$$
$$2H_g p(w_g)=K_{hg}\theta_{hg}+D_{hg}w_h-T_e$$
$$p(\theta_{hg})=w_h(w_h-w_g)$$

Where:

p = The differential operator with respect to time t
H_h and H_g = The inertias of the hub and the PMSG, respectively
W_m and W_g = The angular speeds of the hub and the PMSG, respectively
D_{hg}, K_{hg} and θ_{hg} = The mechanical damping coefficient, spring constant and rotor angle difference between the hub and the PMSG, respectively
T_m and T_e = The mechanical input torque and the electromagnetic torque of the PMSG, respectively

Power converters: 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 (Fig. 3).

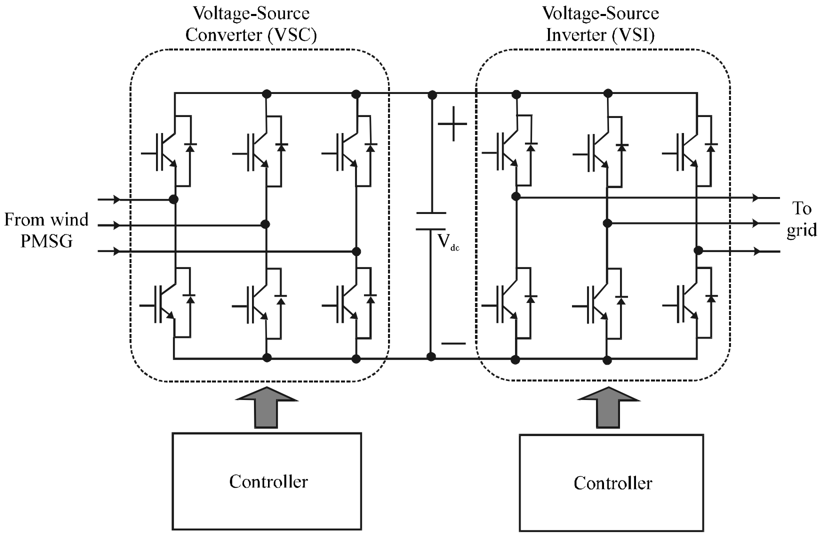

Fig. 3: Model of power converters of the studied wind PMSG

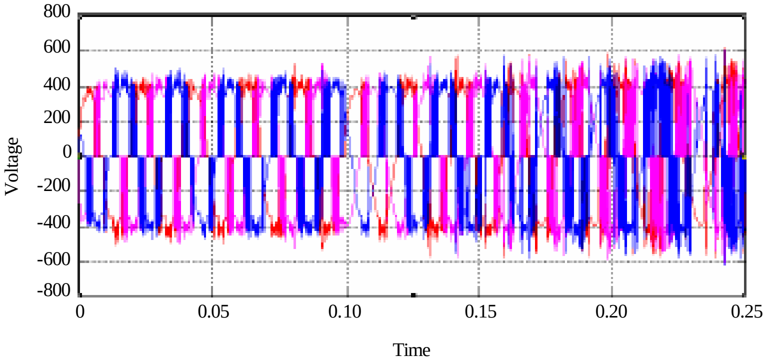

Fig. 4: Output voltage waveform for grid side without STATCOM

DESIGN OF A PI DAMPING CONTROLLER FOR THE STATCOM

The design procedure for the PI damping controller is easily understandable, systematic and useful. One of the main advantages of this design approach is that the proposed PI damping controller can be easily designed by exactly assigning the dominant modes of the studied system to the desire locations of the complex plane. In fact, PI controllers have been practically applied to industry process control and various systems or devices. The main drawback of this method in a real system comes from the fact that the parameters of the controller must be carefully tuned since uncertainty could exist in the studied systems. To perform this task, advanced knowledge for setting up such PI controllers is required to avoid errors or an Auto Turning Method has to be employed. It is common that commercial controllers offer autotuning functions. The operators can start the autotuning functions via some buttons and/or menu choices on the PI controllers. The controllers then automatically execute preplanned experiments on the uncontrolled processes or the control systems depending on the autotuning method implemented. Although, other robust control techniques can be more effective than PI controllers, PI controllers still can be practically employed in various control systems with acceptable accuracy. Moreover, a robust controller requires much time to design since system uncertainties have to be included in the design process while robust controllers are not widely applied to practical systems.

Time-domain simulations: In this study, researchers have investigated about stability problem with various six parallel operated PMSG Wind Turbine and load. In this study, researchers have two sections one with STATCOM and another one without STATCOM. Researchers have two separate outputs which show the different and voltage and current improvement respectively. Researchers have divided the output for load side and also for grid side. The recovery for the output is shown in Fig. 4-9 for without STATCOM.

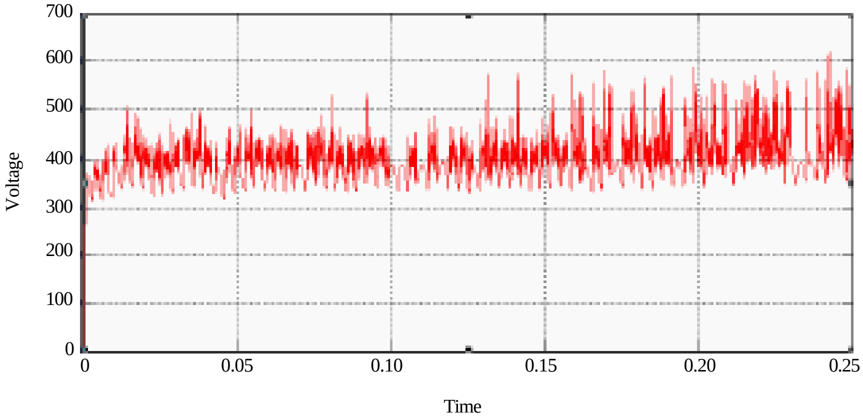

Fig. 5: Output waveform for load side without STATCOM

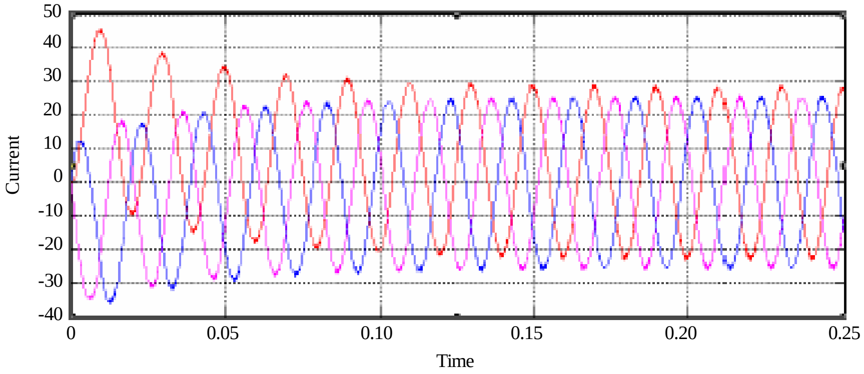

Fig. 6: Output current waveform for grid side without STATCOM

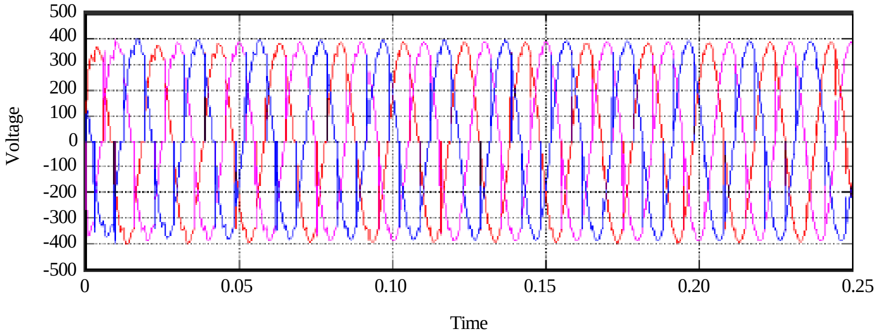

Fig. 7: Output voltage waveform for grid side with STATCOM

This study utilizes the non-linear system model developed to compare the damping characteristics contributed by the proposed STATCOM joined with the designed PI damping controller. To examine the effectiveness of the proposed damping control scheme, this study uses DC load which is connected to the power grid and at T = 0.1 sec to 0.2 the circuit breaker connected to STATCOM is closed and at that particular time the harmonics is recovered and voltage is also improved. Although, this type of loads are connected in power systems, it is most useful to test stability of power systems. Hence, it is worth using different type of loads for testing the transient responses of the studied systems. If the studied systems are stable when this loads are 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 adding of various load such as R, RL load and DC load. It is assumed that the studied system operates under the operating conditions used in plots the

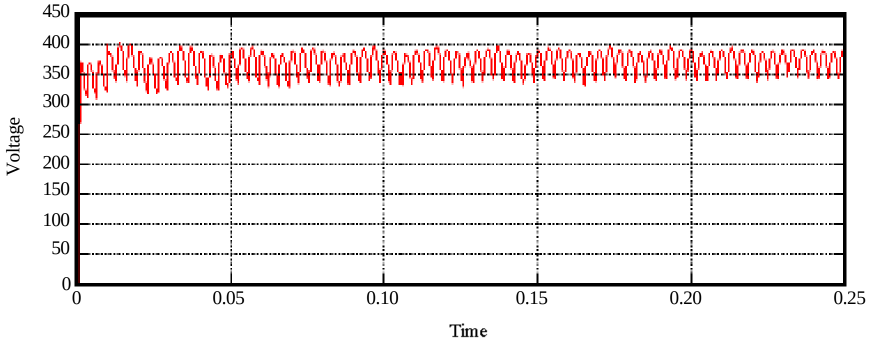

Fig. 8: Output voltage waveform for load side with STATCOM

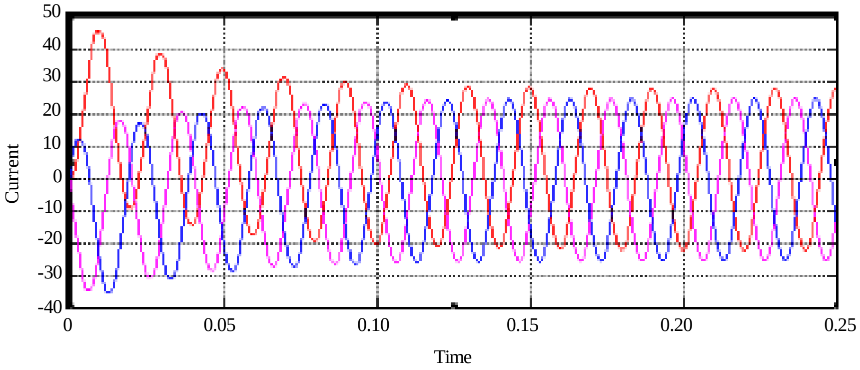

Fig. 9: Output current waveform for grid side with STATCOM

comparative transient responses of the studied system with and without the designed PI damping controller. Since, six parallel-operated PMSG-based WTGs have identical parameters and operating conditions of that are justified and transient responses of the studied system with the proposed STATCOM joined with the designed PI damping controller can be recovered to the prefault steady-state operating conditions. It also shows that the proposed STATCOM joined with the designed PI damping controller can supply proper reactive power to the system and offer better damping characteristics to 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 PI 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 PI damping controller.

From the various outputs, researchers have noted that grid side voltage and load side voltage has some harmonics and voltage reduction when STATCOM is in open condition. This have been improved and recovered while connecting STATCOM in generation side.

CONCLUSION

This study has presented the stability improvement of multi-parallel-operated PMSG-based WTGs connected to an SG-Based System. The STATCOM is proposed and is connected to the common ac bus of the WTGs to enhance damping. STATCOM joined with the designed PI damping controller on suppressing inherent SG oscillations and improving system stability under different operating conditions. From simulation result, researchers have concluded that the proposed STATCOM joined with the PI 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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