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Transient Stability Improvement and Voltage Regulation in DFIG Based Wind Energy Systems Using Power System Stabilizer and STATCOM

Arumulla Ashwini
M.Tech Student (EPS),
JB Institute of Engineering and Technology
(UGC Autonomous), Hyderabad.

G.Rajashekar
Associate Professor,
Dept of EEE, J.B Institute of Engineering and Technology (UGC Autonomous), Hyderabad.

Abstract:

With the integration of wind power into power systems continues to increase, the impact of high penetration of wind power on power system stability becomes a very important issue. This paper investigates the impact of doubly fed induction generator (DFIG) control and operation on rotor angle stability. This Paper proposes a combination of Power System Stabilizer(PSS) and STATCOM based approach to improve the transient stability and regulation of bus voltages. Simulation study in the modified IEEE-39 bus New England system included with DFIG wind turbines ensures that the robustness and stabilizing performance of the proposed coordinated DFIG with PSS and STATCOM are much superior to those of the conventional DFIG with PSS under various severe disturbances and system uncertainties. Simulations are carried out PSAT software environment.

Key words: Doubly fed induction generator (DFIG), power system stabilizer (PSS), rotor angle stability, STATCOM, PSAT.

1. INTRODUCTION:

Due to environmental and economic issues that progressively have become dominant issues in our society, more efforts are placed in generating electricity from renewable energy sources. Among renewable energy technologies that are being developed, wind turbine technology is the fastest growing one in the world. Variable speed wind turbines (VSWTs) employing doubly fed induction generator (DFIG) is the most popular technology in currently installed wind turbines [1], [2]. With the continuous increase in penetration level of DFIG wind turbines, power system stability becomes an important issue which needs to be properly investigated. Considerable research efforts have been dedicated to address the wind power integration issues. Reference [3] indicates that by using power electronic converters, DFIG is able to control its own reactive power to operate at a given power factor (PF) or to control the generator terminal voltage.

However, the capability of DFIG voltage control (VC) cannot match that of the synchronous generator (SG) for the reason that its power converters have a limited capacity. Thus, the stability of the power system is affected in the unfortunate event that the VC requirement is beyond the capability of the DFIG [4]. The reactive power of DFIG can be enhanced by increasing the converters size. However, this solution increases the overall cost, which is one of the main advantages of DFIG over full power converter wind turbines [5].

In the previous works, the DFIG wind turbine with POD has been successfully applied to stabilize the power system oscillations. In [6], a PSS for wind turbine employing a DFIG is used for network damping enhancement. The tuning of PSS is based on eigen value analysis. In [7], the control of DFIG-based wind generation to augment the damping of inter-area oscillation is presented. The proportional integral-based damping controllers designed by the frequency response are added to the active and reactive power control loops. In [8], the multi-objective optimal controller design of a DFIG wind turbine for small signal stability improvement is presented. The objective function addressing the steady-state stability and dynamic performance at different operating conditions are implemented to optimize the controller parameters of both rotor and grid-side converters. In addition, the combined PSS and active damping controller design for a DFIG based on an optimized partial eigen structure assignment is presented in [9].

In [10], the DFIG rotor voltage control for system dynamic performance enhancement is proposed. The POD equipped with the DFIG based on a phase lead compensation is able to improve the network damping. Furthermore, the coordinated control of DFIG-based wind farms for power oscillation damping is presented in [11]. The POD equipped with DFIG wind turbine designed by modal analysis shows the satisfactorily damping effect. Besides, the coordinated control design between PSS of conventional synchronous generator and POD of DFIG wind generator considering wind power output variation is proposed in [12]. The parameters optimization of coordinated damping controllers is carried out based on an extended probabilistic small signal stability analysis. The study results show that the stabilizing effect of PSS without coordinated control is lower than that of the coordinated PSS and DFIG equipped with POD.

The proposed coordinated PSS and POD can enhance the network damping under a wide range of operating conditions. Nevertheless, there are several uncertainties in power systems such as various generating and loading conditions, random wind power, and unpredictable network structure. The representation of such uncertainties by exact mathematic equations is the difficult problem in a design of power stabilizing controllers. The POD proposed in the previous works, which are designed without considering such uncertainties, may lose damping performance and fail to stabilize the system. The high robustness of POD and PSS against system uncertainties is highly anticipated.This paper focuses on the coordinated robust control of DFIG wind turbine with POD and synchronous generator with PSS for damping of power system oscillations taking system uncertainties into account. The inverse output multiplicative perturbation is used to represent system uncertainties without detailed mathematic equations. The structure of POD is the same as that of the conventional PSS, i.e., the practical second-order lead/lag compensator. The optimal tuning of POD and PSS parameters is automatically conducted by an improved firefly algorithm so that the robustness and damping performance are satisfied. The stabilizing effect and robustness of coordinated POD and PSS are evaluated in the modified IEEE-39 bus New England system.

2. WIND ENERGY CONVERSION SYSTEM:

In order to capture the maximal wind energy, it is necessary to install the power electronic devices between the wind turbine generator (WTG) and the grid where the electrical power delivered by the generator to the load can be dynamically controlled and the frequency is constant. The instantaneous difference between mechanical power and electrical power changes the rotor speed following the equation

$$J\frac{d\omega}{dt}=\frac{P_m-P_e}{\omega} \quad (4)$$

Where J is the polar moment of the inertia of the rotor

(neglecting friction coefficient B), ω is the angular speed of the rotor, Pm is the mechanical power produced by the turbine, and Pe is the electrical power delivered to the load. The input of a wind turbine is the wind and the output is the mechanical power turning the generator rotor [4].

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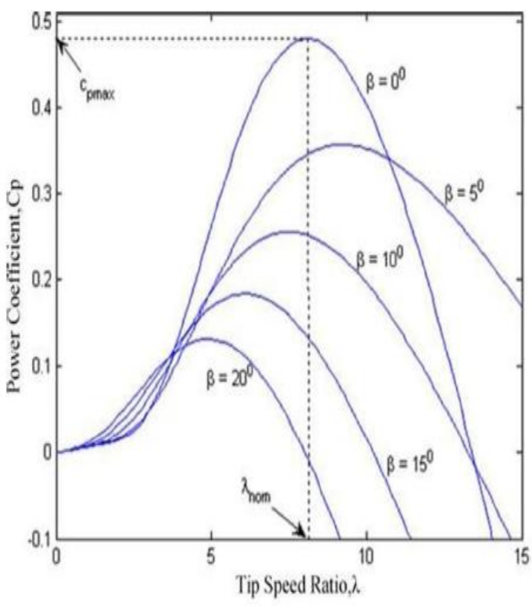
For a variable speed wind turbine, the output mechanical power available from a wind turbine could be expressed as

$$P_m = \frac{1}{2}\rho A C_P(\lambda, \beta) V_\omega^3 \quad (5)$$

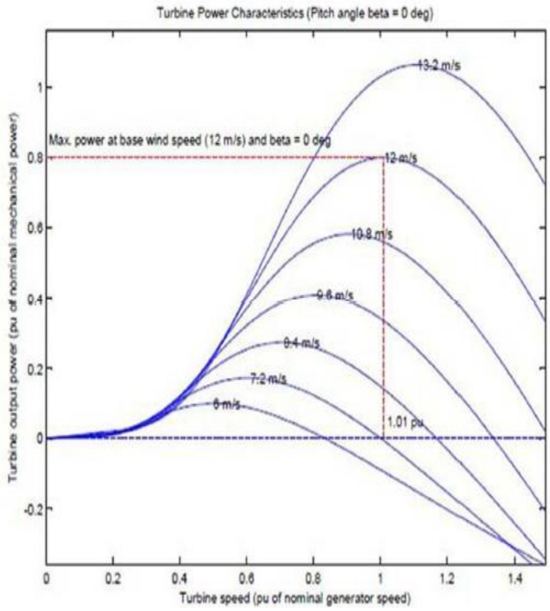
where ρ and A are the air density and the area swept by blades, respectively. Vw is the wind velocity (m/s), and CP is called the power coefficient, and is given as a nonlinear function of the tip speed ratio λ defined by

$$\lambda = \frac{\omega_r R}{V_\omega} \quad (6)$$

where R is the turbine blade radius, and r □ is the turbine speed. CP is a function of λ and the blade pitch angle β. The variable-speed pitch-regulated wind turbine is considered in this paper, where the pitch angle controller plays an important role. Fig. 1 shows the groups of CP - λ at different pitch angles and speed- power curves of the wind turbine used in this study at different wind velocities. It is noted from the figure that CP can be changed either by adjusting the pitch angle β or Tip speed ratio λ. Here considering constant pitch, In other words, the output power of the wind turbine can be regulated by the TSR control.



(a)



(b)

Fig. 1 (a) Characteristics of the WECS at different pitch angles. (b) Turbine power characteristics (pitch angle beta =0 deg).

3. STUDY AND SYSTEM MODELING:

A. Study System:

Fig. 2 delineates the modified IEEE-39 bus New England system [12] which is used as a study system. A synchronous generator is represented by a fourth-order model and equipped with a turbine governor type II [13] and an automatic voltage regulator (AVR) type III as depicted in Fig. 2, where vSG is a terminal voltage of synchronous generator, vf is a field voltage of AVR, vm is a measurement voltage of AVR, _uPSS is a stabilizing signal from PSS, vr is a regulator voltage, Tr and Te are measurement and field circuit time constants, respectively, Ke is a gain while T1z and T2p, time constants of regulator, and vmin f and vmax f are minimum and maximum field voltages, respectively. Note that, the initial field voltage v0f and initial bus voltage v0 are set at the initialization step. Additionally, if s0 is set to 1, the signal v=v0 is enabled. After the initialization of the AVR, the value of s0 is set to v0. Except G1 which is the equivalent external generator, the suitable synchronous generators for installation of PSSs are evaluated based on the

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sensitive PSS effect (SPE) method [14], [15]. This method can be used to find the suitable locations of PSSs for damping the power oscillations. The SPE is defined by

$$\mathrm{SPE} = \varphi_{\Delta P_g} \psi_{\Delta v_f} \frac{K_e}{T_e}$$

where '_Pg is the right eigenvector corresponding to the electrical power output deviation of synchronous generator (_Pg),=_vf is the left eigenvector corresponding to the filed voltage deviation (_vf), and Ke and Te are gain and time constant of AVR, respectively. The values of SPE of all synchronous generators are given in Table I. The high value of SPE indicates the suitable location of PSS which provides the high damping effect on the oscillation mode. As a result, the suitable locations of PSS are at G5, G7, and G9. In addition, it is assumed that three DFIG wind turbines W1, W2, and W3 with aggregate rated capacity of 200 MW are placed at buses 14, 16, and 17, respectively. Each DFIG is equipped with POD. The DFIG data are given in Appendix. Moreover, it is assumed that the power flow is in a heavy condition and severe disturbances such as three-phase short circuit occasionally take place in the system. These conditions cause local and inter-area oscillations with poor damping. To damp out the oscillations, the coordinated DFIG wind turbine with POD and PSS is applied.

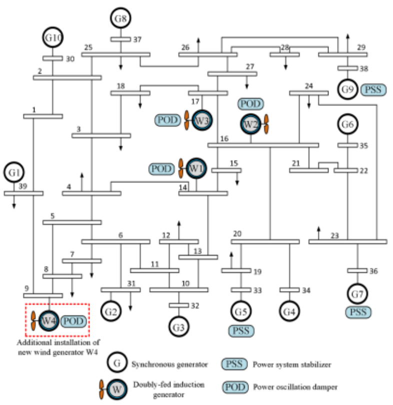

Fig. 2 Modified IEEE-39 bus New England system with DFIG wind turbines.

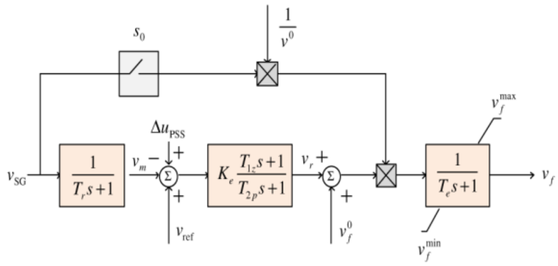

Fig. 3 AVR type III model.

B. DFIG Model:

The structure of DFIG wind turbine and control system is demonstrated in Fig. 4 [13]. The DFIG control is performed by controlling the rotor side converter. Based on the vector control technique, an independent control of active and reactive power can be achieved. Here, the converter is modeled by an ideal current source. The quadrature (q)-axis current of the rotor side converter (iqr) is applied to control the real power output via the rotor speed controller as shown in Fig. 4(a). On the other hand, the direct (d)-axis current (idr) is used to control the reactive power output via the voltage controller as shown in Fig. 4(b). The active power and reactive power injected into the grid of DFIG can be written in terms of the rotor currents as

$$p_e = \frac{x_s}{x_s + x_u} v i_{qr}$$

$$q_e = -\frac{x_u v i_{dr}}{x_s + x_u} - \frac{v^2}{x_u}$$

where pe and qe are active and reactive power outputs, respectively, xs is a stator self-reactance, xu is a magnetizing reactance, and v is a terminal voltage magnitude of DFIG terminal voltage.

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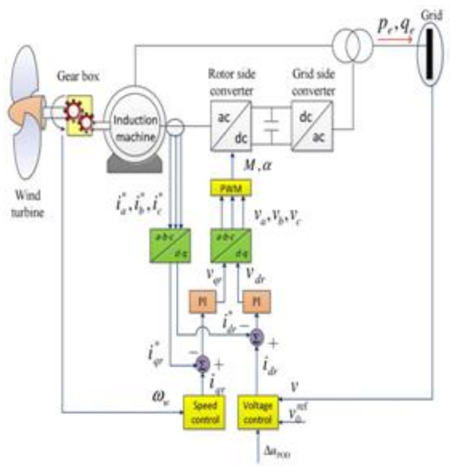

Fig. 4 Configuration of DFIG wind turbine and control system.

4. PSS AND POD MODEL:

Fig. 5 shows the POD structure which is a second-order lead/lag compensator with single input. The POD consists of a stabilizer gain Kstab, a washout filter with time constant Tw ¼ 10 s, and two-phase compensator blocks with time constants T1, T2, T3, and T4. The washout block ensures that the POD output is zero in the steady state. The input signal is the electrical power output deviation of DFIG (_PDFIG,). The output signal _uPOD is subject to an anti-windup limiter where vmin s and vmax s are minimum and maximum of _uPODð_0:1 p.u.Þ, respectively. Kstab determines the amount of damping introduced by POD while the phase compensator block provides the appropriate lead/lag compensation of the output signal. Note that, the structure of POD is similar to that of conventional PSS.

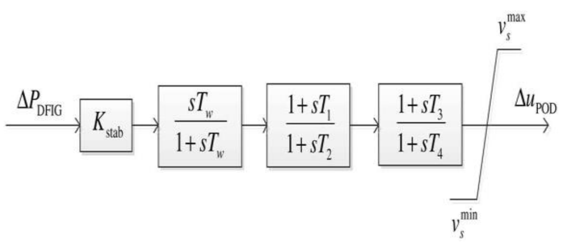

Fig. 5 Structure of POD.

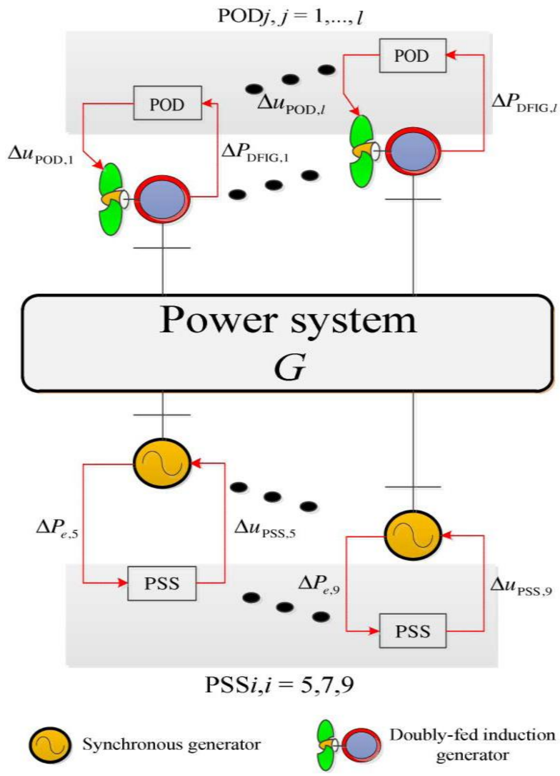

Fig. 6 Power system with POD and PSS.

5. STATCOM:

A STATCOM [6], [12], also known as an advanced static VAR compensator, is a shunt connected FACTS device. It generates a set of balanced three-phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle. A typical application of a STATCOM is for voltage support. In this paper, the STATCOM is modeled as a IGBT PWM converter with a dclink capacitor. The objective of the STATCOM is to regulate the voltage at the PCC rapidly in the desired range and keep its dc-link voltage constant. It can enhance the capability of the wind turbine to ride through transient disturbances in the grid. The overall control scheme of the STATCOM is shown in Fig. 5.

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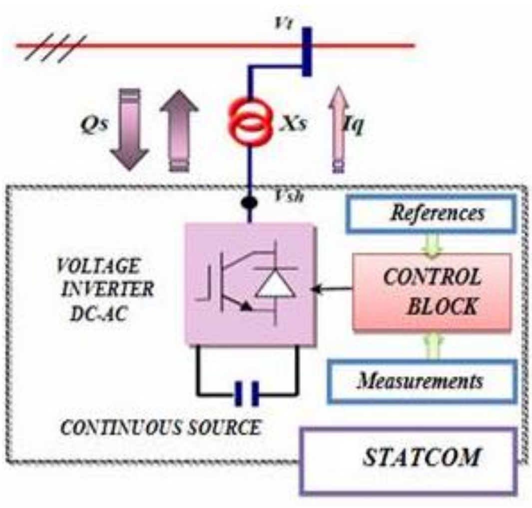

Fig.7 Equivalent circuit of ideal PV cell

In its most basic form, the STATCOM configuration consists of a VSC, a dc energy storage device; a coupling transformer connected in shunt with the ac system, and associated control circuits. Fig.3, shows the basic configuration of STATCOM with wind turbine driven SCIG connected directly to the grid. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the STATCOM output voltages allows effective control of active and reactive power exchanges between the STATCOM and the ac system.

In general, STATCOM and (battery) energy storage systems have been used independently to improve power system operations, and integrating these devices provides an opportunity to improve overall small-signal and transient stability of the power system. Considerable research has addressed the integration of either STATCOM or battery energy storage into the power network, with less attention devoted to the integration of STATCOM and battery energy storage as a system, and the development of dedicated control systems that simultaneously manage bidirectional real and reactive power flow for multi-machine power system applications.

Ali [8] and Muyeen et al. [9] have indicated that the integration of STATCOM and battery along with other types of energy storage is more effective than the STATCOM alone in wind power systems. Chakraborty et al. [13] have provided a review and application regarding the practical realization of STATCOM/battery integration, especially in connection with intermittent renewable energy sources. Baran et al. [14] have shown that the combined STATCOM and battery can be used to smooth intermittent wind farm power and compensate reactive power simultaneously through simulation studies.The VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes:

1) Voltage regulation and compensation of reactive power

2) Correction of power factor

3) Elimination of current harmonics.

The design approach of the control system determines the priorities and functions developed in this analysis. In this paper, the STATCOM is used to regulate voltage at the point of connection. The control is based on discrete PWM and only requires the measurement of the rms voltage at the load point, reference voltage near the grid and dc voltage near the STATCOM VSC converter. The wind energy generating system is connected with grid having the nonlinear load. The performance of the system is measured by switching the STATCOM at time s in the system and how the STATCOM responds to the step change command for increase in additional load at 1.0 s is shown in the simulation. When STATCOM controller is made ON, without change in any other load condition parameters, it starts to mitigate for reactive demand as well as harmonic current. The dynamic performance is also carried out by step change in a load, when applied at 1.0 s. This additional demand is fulfill by STATCOM compensator. Thus, STATCOM can regulate the available real power from source.

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6. SIMULATION RESULTS:

The simulation circuit of proposed RSC circuit is shown in Fig.12. The simulation circuit of perturb and observe MPPT method is shown in Fig.13. The simulation circuit of Incremental Conductance MPPT method is shown in Fig.14.

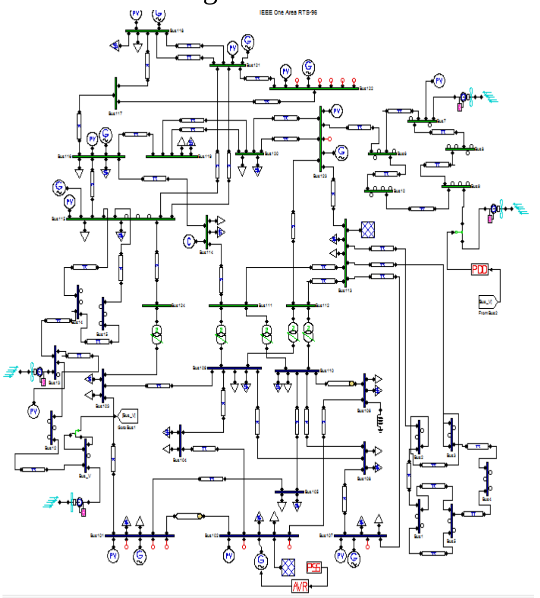

Fig. 8 Simulation Circuit of IEEE-39 Bus System with AVR, PSS and POD

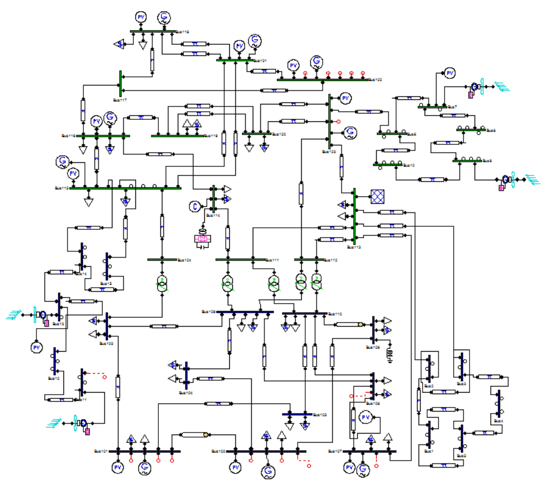

Fig. 9 Simulation Circuit of IEEE-39 Bus System with STATCOM

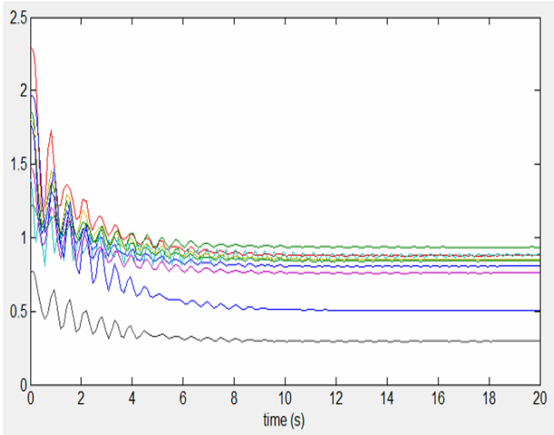

Fig. 10 Generator Angles in Conventional System

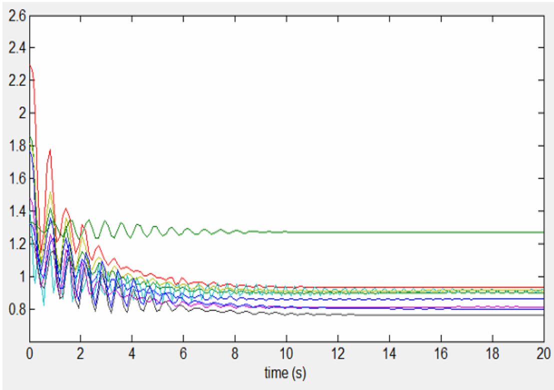

Fig. 11 Generator Angles in Proposed System

7. CONCLUSION:

A new robust coordinated control design of DFIG with POD and PSS considering system uncertainties is proposed for stabilization of low-frequency electromechanical oscillations in a power system with wind power generators. The inverse output multiplicative perturbation is used to model unstructured uncertainties in power systems without the requirement of exact mathematical representation. The parameters optimization of the practical second-order lead/lag compensator based-POD and PSS is carried out so that both robustness against system uncertainties and stabilizing performance can be augmented. To obtain the optimized parameters, the improved firefly algorithm is applied to solve the problem automatically. Simulation study in a modified IEEE-39 bus New England system confirms that the robustness and stabilizing effect of the proposed robust

POD and PSS are much superior to those of the conventional POD and PSS under various faults, wind speeds, unpredictable network structures, and heavy power flow conditions. Moreover, the proposed design can be applied to evolving power network such as in case of an installation of new wind generator. The redesign of coordinated POD and PSS can be conducted so that the new POD effectively works well with the former PODs and PSSs. By the proposed technique, the DFIG wind turbine equipped with POD not only capably coordinates with PSS for contributing the damping function, but also provides a new sophisticated service in the future smart grid.

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