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Coordinated control of TCPS and SMES for frequency regulation of interconnected restructured power systems with dynamic participation from DFIG based wind farm

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ABSTRACT

Among the several wind generation technologies, variable-speed wind turbines utilizing doubly fed induction generators (DFIG) are gaining momentum in the power industry. Increased penetration of these wind turbine generators displaces conventional synchronous generators which results in erosion of system frequency. With this assertion, the paper analyzes the dynamic participation of DFIG for frequency control of an interconnected two-area power system in restructured competitive electricity market. Frequency control support function responding proportionally to frequency deviation is proposed to take out the kinetic energy of wind turbine for improving the frequency response of the system. Impacts of varying wind penetration in the system and varying active power support from DFIG on frequency control have been investigated. The presence of thyristor controlled phase shifter (TCPS) in series with the tie-line and Superconducting Magnetic Energy Storage (SMES) at the terminal of one area in conjunction with dynamic active power support from DFIG results in optimal transient performance for PoolCo transactions. Integral gains of AGC loop and parameters of TCPS and SMES are optimized through craziness-based particle swarm optimization (CRPSO) in order to have optimal transient responses of area frequencies, tie-line power deviation and DFIG parameters.

1. Introduction

Growing environmental concerns and attempts to reduce dependency on fossil fuel resources are bringing renewable energy resources to the mainstream of the electric power sector. Among the various renewable resources, wind power is assumed to have the most favorable technical and economical prospects [1]. When deployed in small scale, as was done traditionally, the impact of wind turbine generators (WTGs) on power system performance is minimal. In contrast, when the penetration level increases, the dynamic performance of the power system can be significantly affected.

In the case of a DFIG, however, the inertia of the turbine is effectively decoupled from the system. The power electronic converter at the heart of the DFIG controls the performance and acts as an interface between the machine and the grid [2]. Hence, with the increased penetration of DFIG based wind farms, the effective inertia of the system “seen” by the grid will be reduced which results in increased rates of change of frequency (ROCOF) and contributing to reduce system robustness regarding the disturbances. In order to allow operating scenarios with large shares of wind power penetration, several utilities have put frequency control requirement on wind farms when revising their grid codes [3–5]. With recent technological developments [6–9], modern DFIG will not necessarily reduce the inertia of the system through inertia control or namely dynamic active power support, thereby, allowing their participation in frequency control and thus enabling safe increase in wind power penetration.

These recent reports [6–9] contributed the idea of utilizing a fraction of the rotational energy stored in the turbine blades of DFIG and fed to the grid with the help of power electronics based converter controllers. The torque set point of the converters can be changed by imposing another signal proportional to frequency deviation or the rate of change of frequency deviation (df/dt) for short-term/transient active power support. This helps in reducing the network frequency fall after a sudden generation deficit situation.

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An active power source with fast response such as SMES is expected to be the most effective stabilizer for frequency oscillations to compensate for the sudden load changes [10]. But the load frequency stabilization effect of SMES is restricted to the area in which it is located and almost has no frequency stabilization effect in another interconnected area [11]. Therefore, it would be desirable if an SMES unit located in an area is available for frequency stabilizations of other interconnected areas. For this, a thyristor controlled phase shifter (TCPS) [12,13], which is one type of flexible AC transmission systems (FACTS) devices, is located in series with the tie-line between two interconnected areas. The required active power modulations necessary for the LFC of both areas are carried out by TCPS as well as the SMES and the energy is commonly supplied by the SMES.

In the view of above discussions, the objectives of the paper are to examine the effect of coordinated control of TCPS–SMES for frequency stabilization of an interconnected two-area restructured hydrothermal power system with wind power penetration by DFIG.

The paper is organized in seven sections. In Section 2, the linearized model of an interconnected two-area restructured power system considering hydro/thermal generating units is presented. In Section 3, the linearized model of TCPS and SMES applicable for load frequency control is derived. The characteristics associated with DFIGs followed by underlying modeling concepts related to frequency control are presented in Section 4. Mathematical problem formulation and craziness-based particle swarm optimization are given in Section 5. In Section 6, the approach developed to analyze the impact of increased penetration of DFIGs on frequency control of the test system under different PoolCo transactions made between GENCOs and DISCOs in competitive electricity market is detailed. Conclusions that can be drawn from the analysis are presented in Section 7.

2. Linearized model of an interconnected two-area restructured power system

Fig. 1 shows the linearized model of an interconnected two-area restructured power system for the load frequency control in competitive electricity market. The control area is having conventional hydro/thermal power generating units along with DFIG based wind turbine generators. Hydro and thermal generating units are represented by traditional units' blocks given in [14].

The concept of a "DISCO participation matrix" (DPM) is used to make the easier visualization of contracts between GENCOs and DISCOs [15,16]. Each area is having two GENCOs and two DISCOs. Let GENCO1, GENCO2, DISCO1 and DISCO2 be in area1 and GENCO3, GENCO4, DISCO3 and DISCO4 be in area2. Unlike in the traditional AGC system, a DISCO asks/demands a *particular* GENCO or GENCOs for load power. Thus, as a particular set of GENCOs are supposed to follow the load demanded by a DISCO, information signals must flow from a DISCO to a particular GENCO specifying corresponding demands.

The demands are specified by cpf_s (elements of DPM) and the pu MW load of a DISCO. These signals which were absent in traditional AGC will carry information as to *which* GENCO has to follow a load demanded by *which* DISCO. apf_i (i = 1,2,3,4) are the Area Control Error (ACE) participation factors of different GENCOS.

3. Linearized model of TCPS and SMES applicable to AGC

3.1. Linearized model of TCPS applicable for AGC

The schematic of an interconnected two-area power system considering a TCPS in series with the tie-line is shown in Fig. 2.a. TCPS is placed near area 1. Resistance of the tie-line is neglected.

Without TCPS, the incremental tie-line power flow from area 1 to area 2 can be expressed as

$$\Delta P^0_{\mathrm{tie}12}(s) = \frac{T_{12}}{s}[\Delta\omega_1(s) - \Delta\omega_2(s)] \tag{1}$$

When a TCPS is placed in series with the tie-line, the current flowing from area 1 to area 2 can be written as

$$i_{12} = \frac{|V_1|\angle(\delta_1+\varphi) - |V_2|\angle(\delta_2)}{jX_{12}} \tag{2}$$

$$P_{\mathrm{tie}12} - jQ_{\mathrm{tie}12} = V_1^* i_{12} = |V_1|\angle-(\delta_1+\varphi)\left[\frac{|V_1|\angle(\delta_1+\varphi) - |V_2|\angle(\delta_2)}{jX_{12}}\right] \tag{3}$$

$$\therefore P_{\mathrm{tie}12} - jQ_{\mathrm{tie}12} = \frac{|V_1||V_2|}{X_{12}}\sin(\delta_1-\delta_2+\varphi) - j\frac{\left[|V_1|^2 - |V_1||V_2|\cos(\delta_1-\delta_2+\varphi)\right]}{X_{12}} \tag{4}$$

Separating the real parts of (4), we get

$$P_{\mathrm{tie}12} = \frac{|V_1||V_2|}{X_{12}}\sin(\delta_1-\delta_2+\varphi) \tag{5}$$

In (5), perturbing δ_1, δ_2 and φ from their nominal values $\delta^0{}_1$, $\delta^0{}_2$ and φ^0 yields:

$$\Delta P_{\mathrm{tie}12} = \frac{|V_1||V_2|}{X_{12}}\cos\left(\delta_1^0-\delta_2^0+\varphi^0\right)\sin(\Delta\delta_1-\Delta\delta_2+\Delta\varphi) \tag{6}$$

$(\Delta\delta_1-\Delta\delta_2+\Delta\varphi)$ is very small since, for a small change in real power load, the variation of bus voltage angles as well as the variation of TCPS phase angle are practically very small.

Hence, $\sin(\Delta\delta_1-\Delta\delta_2+\Delta\varphi) \approx (\Delta\delta_1-\Delta\delta_2+\Delta\varphi)$ Therefore,

$$\Delta P_{\mathrm{tie}12} = \frac{|V_1||V_2|}{X_{12}}\cos\left(\delta_1^0-\delta_2^0+\varphi^0\right)(\Delta\delta_1-\Delta\delta_2+\Delta\varphi) \tag{7}$$

$$\text{Let } T_{12} = \frac{|V_1||V_2|}{X_{12}}\cos\left(\delta_1^0-\delta_2^0+\varphi^0\right) \tag{8}$$

Thus, (7) reduces to

$$\Delta P_{\mathrm{tie}12} = T_{12}(\Delta\delta_1-\Delta\delta_2+\Delta\varphi) \tag{9}$$

$$\therefore \Delta P_{\mathrm{tie}12} = T_{12}(\Delta\delta_1-\Delta\delta_2) + T_{12}\Delta\varphi \tag{10}$$

where

$$\Delta\delta_1 = \int\Delta\omega_1 dt \text{ and } \Delta\delta_2 = \int\Delta\omega_2 dt \tag{11}$$

From (10) and (11), we get,

$$\Delta P_{\mathrm{tie}\,12} = T_{12}\left(\int\Delta\omega_1 dt - \int\Delta\omega_2 dt\right) + T_{12}\Delta\varphi \tag{12}$$

Laplace transformation of (12) yields

$$\Delta P_{\mathrm{tie}\,12}(s) = \frac{T_{12}}{s}[\Delta\omega_1(s) - \Delta\omega_2(s)] + T_{12}\Delta\varphi(s) \tag{13}$$

As per (13), tie-line power flow can be controlled by controlling the phase shifter angle $\Delta\varphi(s)$.

The phase shifter angle $\Delta\varphi(s)$ can be represented as: