COORDINATED DESIGN OF A MB-PSS AND STATCOM CONTROLLER TO ENHANCE POWER SYSTEM STABILITY

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ABSTRACT

This paper solves the problem of power system stabilization by using the advanced static synchronous shunt compensator STATCOM to increase the damping of electromechanical oscillations of the power system and regulates the system voltage by absorbing or generating reactive power to the system. Also, a multi-band power system stabilizer MB-PSS is developed in this paper to get a moderate phase advance at all frequencies of interest in order to compensate for the inherent lag between the field excitation and the electrical torque induced to ensure robust oscillation damping. A combined control of STATCOM with MB-PSS is proposed also in this paper to give more increase of the oscillation damping that improves power system stability. The application of these controllers is applied to the multi-machine two-area power system using Matlab Toolbox.

Keywords: STATCOM, MB-PSS, Power System Stability, Oscillation Damping.

Nomenclature

\(\psi_d, \psi_q\)  direct and quadrature axis component of stator flux
\(e_d, e_q\)  direct and quadrature axis component of stator voltage
\(i_d, i_q\)  direct and quadrature axis component of stator current
\(r_s\)  stator resistance
\(E_d', E_q'\)  direct and quadrature axis transient voltage
\(\psi_{kd}, \psi_{kq}\)  direct and quadrature axis damper flux linkage
\(E_d\)  exciter voltage
\(K_G\)  speed governor gain
\(D\)  the percentage of steady-state speed regulation or unit droop
\(T_V\)  the time constant of the vessel steam flow
\(P_0\)  the steady-state vessel pressure
\(Q_0\)  the steady-state mass flow out of the vessel
\(V_{vessel}\)  the volume of the vessel
\(K_{vessel}\)  the density change due to pressure changes in constant temperature
\(V_{steam}\)  the specific volume of steam
\(T_0\)  the vessel temperature
\(P_2, P_1\)  the boundaries of the smallest pressure interval
1. INTRODUCTION

Since 1960s, low frequency oscillations have been observed when large power systems are interconnected by relatively weak tie lines. These oscillations may sustain and grow to cause system separation if no adequate damping is available [1-5]. Nowadays, the conventional power system stabilizer CPSS is widely used by power system utilities. Generally, it is important to recognize that machine parameters change with loading make the machine behavior quite different at different operating conditions. Since these parameters change in a rather complex manner, a set of stabilizer parameters, which stabilizes the system under a certain operating condition, may no longer yield satisfactory results when there is a drastic change in power system operating conditions and configurations. Hence, power system stabilizers PSSs should provide some degree of robustness to the variations in system parameters, loading conditions, and configurations. \( H_\infty \) optimization techniques [2] have been applied to robust PSS design problem. However, the importance and difficulties in the selection of weighting functions of \( H_\infty \) optimization problem have been reported. In addition, the additive and/or multiplicative uncertainty representation cannot treat situations, where a nominal stable system becomes unstable after being perturbed [3]. Moreover, the pole-zero cancellation phenomenon associated with this approach produces closed loop poles whose damping is directly dependent on the open loop system [4].

On the other hand, the order of the \( H_\infty \)-based stabilizer is as high as that of the plant. This gives rise to complex structure of such stabilizers and reduces their applicability. Kundur et al. [4] have presented a comprehensive analysis of the effects of the different CPSS parameters on the overall dynamic performance of the power system. It is shown that the appropriate selection of CPSS parameters results in satisfactory performance during system upsets. In addition, Gibbard [5] demonstrated that the CPSS provide satisfactory damping performance over a wide range of system loading conditions. Robust design of CPSSs in...
multi-machine power systems using genetic algorithm is presented in Ref. [6-7], where several loading conditions are considered in the design process. Although PSSs provide supplementary feedback stabilizing signals, they suffer a drawback of being liable to cause great variations in the voltage profile and they may even result in leading power factor operation under severe disturbances [8-9]. MB-PSS is based on multi-frequency variables that this stabilizer can obtain to cope with all low, intermediate, and high frequencies oscillations [10, 11]. The MB-PSS is developed in such a manner that it can be capable of introducing moderate phase advance at all oscillations frequencies of interest in order to compensate for the inherent lag between the field excitation and the electrical torque [7].

The recent advances in power electronics have led to the development of the flexible alternating current transmission systems FACTS. Generally, a potential motivation for the accelerated use of FACTS devices is the deregulation environment in contemporary utility business. Along with primary function of the FACTS devices, the real power flow can be regulated to mitigate the low frequency oscillations and enhance power system stability. Recently, several FACTS devices have been implemented and installed in practical power systems [12]. In the literature, a little work has been done on the coordination problem investigation of excitation and FACTS-based stabilizers. Refs. [13-17] present a coordinated PSS and SVC control for a synchronous generator. However, the proposed approach uses recursive least squares identification, which reduces its effectiveness for on-line applications. Rahim and Nassimi [15] presented optimum feedback strategies for both SVC and exciter controls. However, the proposed controller requires some or all states to be measurable or estimated. Moreover, it leads to a centralized controller for multi-machine power systems, which reduces its applicability and reliability. Noroozian and Anderson [16] presented a comprehensive analysis of damping of power system electromechanical oscillations using FACTS, where the impacts of transmission line loading and load characteristics on the damping effect of these devices have been discussed. Wang and Swift [12] have discussed the damping torque contributed by FACTS devices, where several important points have been analyzed and confirmed through simulations. However, all controllers were assumed proportional and no efforts have been done towards the controller design.

On the other hand, it is necessary to measure the electromechanical mode controllability in order to assess the effectiveness of different controllers and form a clear inspiration about the coordination problem requirements [10, 13]. A comprehensive study of the coordination problem requirements among PSSs and different FACTS devices has been presented in Refs [18-21]. However, no efforts have been done towards the coordinated design of the stabilizers investigated. By controlling the magnitude of the STATCOM voltage the reactive power exchanges between the STATCOM and the transmission line [22-26]. One of the most important advantages of the STATCOM is its behaviour during the voltage collapse at the bus where it is located as it supplies almost a constant reactive power without being affected by voltage variation across it. So far, conventional power system stabilizer PSS is still used as an effective and economical facility to tackle the problem [14]. Many techniques have been reported in the literature on the topic of coordinated design of PSS [27-31].

In this paper, a comprehensive assessment of the effects of the excitation and STATCOM control when applied independently and also through coordinated application has been carried out. Also, MB-PSS is developed in this paper to get a moderate phase advance at all frequencies of interest in order to compensate for the inherent lag between the field excitation and the electrical torque induced to ensure robust oscillation damping. A combined control of STATCOM with MB-PSS is proposed also in this paper to give more increase of the
oscillation damping that improves power system stability. All these controllers are supplied to the multi-machine two-area power system.

2. STUDIED SYSTEM AND MODELING

The studied system (Kundur's four-machine two-area test system) consists of two fully symmetrical areas linked together by two 230 kV lines of 220 km length as shown in Fig. (1). Despite its small size, it mimics very closely the behavior of typical systems in actual operation [4]. Each area is equipped with two identical round rotor generators rated 20kV/900MVA. The synchronous machines have identical parameters [11], except for inertias which are H=6.5s in area 1 and H=6.175s in area 2. The parameters of the generators, turbines and excitors data are given in Appendix. Thermal plants having identical speed regulators are further assumed at all locations, in addition to fast static exciters with a gain on 200 [10]. The load is represented as constant impedances and is split between the areas in such a way that area 1 is exporting 413MW to area 2. Since the surge impedance loading of a single line is about 140 MW, the system is somewhat stressed, even in steady-state.

Fig. 1: Single line diagram of four-machine two-area test system.

2.1. Power System Model

2.1.1 Generator:

The generator is represented by the sixth-order model comprising of the electromechanical swing equation and the generator internal voltage equation [10-11]. The dynamics of rotor angle \( \delta \) and velocity \( \omega \) is described by the so called swing equations:

\[
\frac{d\Delta \omega}{dt} = \frac{1}{2H}(T_m - T_e - D\Delta \omega) \quad (1)
\]

\[
\frac{d\delta}{dt} = \omega_0 \Delta \omega \quad (2)
\]
where: \( \Delta \omega = \omega - \omega_o \) is the deviation, in rad/s of rotor angular velocity from synchronous velocity \( \omega_o = 2\pi f \), \( H \) is the p.u. inertia constant, \( T_m \) and \( T_e \) are the p.u. mechanical and electromagnetic torque, respectively, \( D \) is the damping coefficient. Figure (2) shows the electrical model of the synchronous machine in the d-q frame.

The sixth order model is frequently employed in stability and control analysis. Its stator transients (\( \psi'_d, \psi'_q \)) are considered so fast as to be negligible as far as transient stability and its associated slow rotor oscillations, are concerned.

![Electrical model of the synchronous machine (q-d frame)](image)

The following differential equations used to describe the electrical variables and the two swing equations (1), (2) to describe the mechanical motion [4]. Two of the six differential equations are used to describe the d and q axis components of the stator fluxes as follows:

\[
0 = e_d + \psi_d' + r_d i_d \\
0 = e_q - \psi_q + r_q i_q
\]

Four differential equations are required to describe rotor electrical dynamics in the four windings assumed to be lying on the rotor.

\[
\dot{E}_q = \frac{1}{T_{do}} \left[ E_d - E'_q - E'_q \frac{(x'_d - x'_d)(x_d - x_d)}{(x'_d - x_d)^2} + \psi_{kd} \frac{(x'_d - x'_d)(x_d - x_d)}{(x'_d - x_d)^2} - i_d \frac{(x'_d - x_d)(x_d - x_d)}{(x'_d - x_d)^2} \right]
\]

\[
\dot{E}_d = \frac{1}{T_{dq}} \left[ -E'_q + E'_d \frac{(x'_q - x'_q)(x_q - x_q)}{(x'_q - x_q)^2} - \psi_{kq} \frac{(x'_q - x'_q)(x_q - x_q)}{(x'_q - x_q)^2} + i_q \frac{(x'_q - x_q)(x_q - x_q)}{(x'_q - x_q)^2} \right]
\]

\[
\dot{\psi}_{kd} = \frac{1}{T_{do}} \left[ -\psi_{kd} + E'_q - (x'_d - x_1) i_d \right]
\]

\[
\dot{\psi}_{kq} = \frac{1}{T_{dq}} \left[ -\psi_{kq} - E'_d - (x'_q - x_1) i_q \right]
\]

The following algebraic equations:

\[
\psi_d = E'_q \frac{x'_d - x_1}{x'_d - x_1} + \psi_{kd} \frac{x'_d - x_d}{x'_d - x_1} - x'_d i_d
\]

\[
\psi_q = -E'_d \frac{x'_q - x_1}{x'_q - x_1} + \psi_{kq} \frac{x'_q - x_q}{x'_q - x_1} - x'_q i_q
\]

Which relate internal voltages and fluxes with output stator currents, along with the following relationship for the electromagnetic torque:
\[ T_e = \psi_d i_q - \psi_q i_d \] (11)

### 2.1.2 Exciter and PSS:

An excitation system for the synchronous machine and regulate its terminal voltage in generating mode. The excitation system is implementing a DC exciter described in [10], without the exciter's saturation function. The basic elements that form the excitation system depicted in Fig. (3) the voltage regulator and the exciter. It can be described as:

\[
\dot{E}_f = \frac{1}{T_a} \left( K_a \left( V_{ref} - v + u_{\text{PSS}} \right) - E_{id} \right) \] (12)

\[
V_f = \left( \frac{1}{K_c + s T_e} \right) E_f \] (13)

Low-pass filter time constant \( T_r \), in seconds, of the first-order system that represents the stator terminal voltage transducer. Regulator gain and time constant \( K_a \) and \( T_a \) of the first-order system representing the main regulator. Exciter gain \( K_e \) and time constant \( T_e \) of the first-order system representing the exciter. Transient gain reduction time constants \( T_b \) and \( T_c \) of the first-order system representing a lead-lag compensator. Damping filter gain and time constant \( K_f \) and \( T_f \) of the first-order system representing a derivative feedback. Regulator output limits and gain \( E_{fd-min} \) and \( E_{fd-max} \) are imposed on the output of the voltage regulator, and \( V_{ref} \) is the reference voltage. A conventional lead–lag PSS is installed in the feedback loop to generate a stabilizing signal \( U_{\text{PSS}} \):

In Fig. (3), the terminal voltage \( v \) can be expressed as:

\[
v_d = \sqrt{v_d^2 + v_q^2}
\] (14)

\[
v_q = x_q i_q \quad \text{and} \quad v_q = E_q' - x_q i_d
\] (15)

Where \( x_d \) and \( x_q \) are the d-axis, and q-axis reactance’s of the generator.
2.1.3 Governor and Turbine Model:
A typical overview of primary control in a steam unit is presented in Fig. (4), the functional blocks include the governor speed changer, speed governor, speed relay, controlled valves, and turbine systems. All the equipments with some simplification can be mathematically represented by simple block-based models. In the models, only one control valve CV between the steam generator and HP turbine is assumed [1]. Also, the models are built without intercept valves, fast valving. Boiler pressure is assumed to be constant [10].

Fig. 4: Steam unit primary control blocks.

The block diagram of Fig. (5) shows an approximate model for a typical mechanical-hydraulic speed-governing system. In the figure, $T_{SR}$ and $T_{SM}$ are the speed governor and servomotor time constants, respectively. Also, $C_{v-open}$, $C_{v-close}$, $C_{open}$, and $C_{close}$ represent the valve’s rate limits and position limits, respectively. Although it is possible to extract the parameters of the governor model using dimensions and physical parameters [20], we just confine the study to the turbine model. Thus, for the governor model, only speed governor gain is taken into account using $K_G=100/D$, where D is the percentage of steady-state speed regulation or unit droop. Other parameters are considered to be typical values [14].

Fig. 5: Simple mechanical-hydraulic speed-governing model.

The steam chest and inlet piping to the first turbine cylinder and reheaters and crossover piping introduce delays between valve movement and change in steam flow. The main objective in modeling the steam system for dynamic studies is to represent these delays. Also, the configuration of turbines affects the model. There may be tandem compound or cross compound configuration. Also in each of these categories, single or double reheat stages may exist. Figure (6), three common configurations for tandem compound units are presented. The general model for the turbine system can represent all tandem compound configurations. Figure (7) $T_{SC}$, $T_{RH1}$, $T_{RH2}$, and $T_{CO}$ are steam chest, first re heater, second reheater, and crossover time constants, respectively.
Also, $F_{VHP}$, $F_{HP}$, $F_{IP}$ and $F_{LP}$, are very-high-pressure VHP, HP, IP, and LP turbines’ power fractions, respectively.

Assuming a steam vessel as in Fig. (7), using the continuity equation, the time constant of steam crossing the vessel can be written as:

$$T_v = \frac{P_0}{Q_0} V_{vessel} K_{vessel}$$  \hspace{1cm} (16)

$$K_{vessel} = \frac{\partial}{\partial P} \left( \frac{1}{V_{steam}} \right)_{T_0}$$  \hspace{1cm} (17)

where $T_v$ is the time constant of the vessel steam flow, $P_0$ is the steady-state vessel pressure, $Q_0$ and is the steady-state mass flow out of the vessel. $V_{vessel}$ is the volume of the vessel, and $K_{vessel}$ is the density change due to pressure changes in constant temperature, $V_{steam}$ is the specific volume of steam at assumed constant temperature of the vessel, and $T_0$ is the vessel temperature which is assumed to be constant. Often, the volume of the vessel for re heater, crossover, and chest cannot be determined.
exactly and has to be derived using available data. For calculating $K_{vessel}$, the tabulated thermodynamic data of steam can be used [23].

Assume $P_2$ and $P_1$ to be the boundaries of the smallest pressure interval which include the vessel pressure in steam thermodynamic specific volume table. Also, $v_2$ and $v_1$ are the specific volumes corresponding to $P_1$ and $P_2$. Then, $K_{vessel}$ can be approximately written as follows:

$$K_{vessel} = \frac{1/v_2 - 1/v_1}{P_2 - P_1}$$  \hspace{1cm} (18)

Note that in tabulated thermodynamic data, the specific volume is given at different pressures for various temperatures. The exact temperature of our vessel may not be available in the table. In such cases, a linear interpolation for gaining the specific volume is common. Using (16) and (17), time constants for steam chest, reheaters, and crossover can only be estimated. Often, the above equation parameters cannot be stated exactly or temperature steadiness is not always provided.

Another important parameter set of the turbine model are the power fractions. These fractions determine the way that each turbine contributes to total turbine system power. Assuming the rated output power as a per unit basis, we have:

$$F_{HP} + F_{IP} + F_{LP} = 1$$ \hspace{1cm} (19)

To determine each of these fractions, two useful parameters $a_1$ and $a_2$ can be defined as follows:

$$\frac{F_{LP}}{F_{HP}} = \frac{P_{LP}}{P_{HP}} = a_1, \quad \frac{F_{IP}}{F_{HP}} = \frac{P_{IP}}{P_{HP}} = a_2$$ \hspace{1cm} (20)

where PHP, PIP, and PLP are HP turbine power, IP turbine power, and LP turbine power, respectively. For calculating the turbine power, we need the steam enthalpy on each stage and mass flow which is available from the heat balance map. The power of each turbine is simply estimated via the following:

$$P_X = \sum_k Q_k (h_{ink} - h_{outk}) \quad , \quad X=HP, IP, LP$$ \hspace{1cm} (21)

where $P_X$ is the power of turbine $X$, $k$ indicates the turbine stage between draining points, $Q_k$ is the mass flow in stage $k$, $h_{ink}$ is inlet steam enthalpy of stage in $k$, and $h_{outk}$ is the outlet steam enthalpy of stage $k$. Solving (18), (20), we have:

$$F_{HP} = \frac{1}{1 + a_1 + a_2} , \quad F_{IP} = \frac{a_2}{1 + a_1 + a_2} , \quad F_{LP} = \frac{a_1}{1 + a_1 + a_2}$$ \hspace{1cm} (22)

Thus, the turbine model parameters can all be estimated. Note that for calculating the turbine power as a weighted sum of the turbine sections, the turbine thermodynamic process was assumed to be pure isentropic and mechanical losses are neglected. Nevertheless, these assumptions are common for turbine thermodynamic studies [27].

### 2.2 Static Synchronous Compensator (STATCOM)

The STATCOM resembles in many respects a synchronous compensator, but without the inertia. The basic electronic block of a STATCOM is the Voltage Source Converter VSC, which in general converts an input dc voltage into a three-phase output voltage at fundamental frequency, with rapidly controllable amplitude and
phase angle. In addition to this, the controller has a coupling transformer and a dc capacitor. The control system can be designed to maintain the magnitude of the bus voltage constant by controlling the magnitude and/or phase shift of the VSC output voltage. The STATCOM is based on a solid state synchronous voltage source which generates a balanced set of three sinusoidal voltages at the fundamental frequency with rapidly controllable amplitude and phase angle. The configuration of a STATCOM is shown in Fig. (8).

![Fig. 8: STATCOM connected to a transmission line.](image)

The STATCOM is represented by a first order differential equation relating the STATCOM dc capacitor voltage and current. The STATCOM consists of a stepdown transformer with a leakage reactance of $X_r$, a three phase gate turn-off GTO-based VSC and a dc capacitor. The STATCOM model used in this study is found good enough for the low frequency oscillation stability problem [26]. The VSC generates controllable ac voltage $V_o$ given by:

$$V_o = CV_{dc} \angle \psi$$

where $C = mk$, $m$ the modulation ratio defined by pulse width modulation PWM, $k$ the ratio between the ac and dc voltage depending on the converter structure, $V_{dc}$ the dc voltage, and $\psi$ is the phase defined by PWM. The magnitude and the phase of $V_o$ can be controlled through $m$ and $\psi$ respectively.

By adjusting the STATCOM ac voltage $V_B$ or $V_o$, the active and reactive power exchange between the STATCOM and the power system can be controlled through the difference between $V_o$ and the STATCOM-bus voltage $V_m$. The dc voltage $V_{dc}$ is governed by:

$$\dot{V}_{dc} = \frac{I_{dc}}{c_{dc}} = \frac{C}{c_{dc}} (I_{sd}\cos\psi + I_{sq}\sin\psi)$$

(24)

Where $c_{dc}$ is the dc capacitor value and $I_{dc}$ is the capacitor current while $i_{sd}$ and $i_{sq}$ are the d- and q-components of the STATCOM current $I_s$, respectively. The d- and q-axis components of the $I_s$ can be expressed as:

$$I_d = \frac{c_1E_q - c_2CV_{dc}\sin\psi - v_h\cos\delta}{c_1X_d + c_3}, \quad \text{and} \quad I_q = \frac{c_2CV_{dc}\cos\psi + v_h\sin\delta}{c_1X_q + c_3}$$

(25)

Where $c_1$, $c_2$, and $c_3$ are constants.
Figure (9) illustrates the block diagram of STATCOM ac and dc voltage PI controller. The proportional and integral gains are $K_{pac}$, $K_{iac}$ and $K_{pdc}$, $K_{idc}$ for ac and dc voltages, respectively [26-28].

![Block diagram of STATCOM AC and DC voltage PI controller]

2.3 Multi-Band Power System Stabilizer (MB-PSS)

A PSS can be viewed as an additional block of a generator excitation control or AVR, added to improve the overall power system dynamic performance, especially for the control of electromechanical oscillations. Thus, the PSS uses auxiliary stabilizing signals such as shaft speed, terminal frequency and/or power to change the input signal to the AVR. This is a very effective method of enhancing small-signal stability performance on a power system network. The main characteristics of the MB-PSS model are shown in Fig. 10(a). As for conventional PSS, the MB-PSS comprises three main functions, the transducers, the lead-lag compensation and the limiters. Two speed deviation transducers are required to feed the three band structure used as lead-lag compensation. Four adjustable limiters are provided, one for each band and one for the total PSS output. The low band is taking care of very slow oscillating phenomena such as common modes found on isolated system. Hydro-Quebec system is a good example with its 0.05 Hz global mode. The intermediate band is used for inter-area modes usually found in the range of 0.2 to 1.0 Hz. The high band is dealing with local modes, either plant or intermachines, with a typical frequency range of 0.8 to 4.0 Hz. The speed deviation transducers are both derived from machine terminal voltages and currents. The first one, so called $\Delta\omega_L$, is associated with the first two bands. Its measurement is accurate in the 0 to 2.0 Hz range. $\Delta\omega_H$, the second transducer, is designed for the high band with a frequency range of 0.8 to 5.0 Hz. The MB-PSS also provides two tunable notch filters to reject the high frequency torsional modes found on turbo-generators. These are tuned for the first two torsional modes of a given machine. With a simple and efficient setting method such as the one presented here, it is possible to set the PSS with only two high level parameters per band. Doing so, the whole lead-lag compensation circuit is specified with six parameters. They are the three filter central frequencies $FL$, $FI$, $FH$ and gains $KL$, $KI$, $KH$, Being plain band-pass filters, only the first block in each branch is involved. Time constants and gains are derived from simple equations for the high band case.
Central time constants $T_{H2}$, and $T_{H7}$ are directly derived from the filter central frequency $FH$ while the symmetrical time constants, $T_{H1}$, and $T_{H6}$ are computed using constant ratio $R$. Equation (29) is used to derive branch gains $K_{H1}$ and $K_{H2}$ to obtain a unit gain for the differential filter. The band gain is therefore equal to $K_H$. This technique allows us to represent the MB-PSS in a simplified model as shown in Fig. 10(b).

The performance of the MB-PSS will now be assessed using stability simulations on the actual Hydro-Quebec power system. To do so, an analytical approach, previously described in [28]. The aim of this type of analysis is to identify the electromechanical behavior of the system by developing a MIMO (Multiple Inputs Multiple Outputs)
type of conventional linear model \((A,B,C,D)\) fulfilling the following state equations [25, 30]:

\[
x_{k+1} = Ax_k + Bu_k \tag{30}
\]
\[
y_k = Cx_k + Du_k \tag{31}
\]

In large power systems, participation factors corresponding to the speed deviation of generating units can be used for initial screening of generators on which to add PSS. However, a high participation factor is a necessary but not sufficient condition for a PSS at the given generator to effectively damp oscillation. Following the initial screening a more rigorous evaluation using residues and frequency response should be carried out to determine the most suitable locations for the stabilizers.

3.1 PSS Tuning

The MB-PSS settings were easily selected by varying the center frequency and gain of each band so as to achieve a nearly flat phase response between 0.1Hz and 5Hz. The \(d\omega\)-PSS settings with two changes [11]: a gain increase from 20 to 30 and the addition of a 15-ms transducer time constant. The frequency responses of these PSSs as shows Bode Plot of the PSS in Fig. (11). This figure confirms that the MP-BSS phase is effectively flat around 20-40 degrees in the frequency range of interest. The \(d\omega\)-PSS has an overall poor phase shape, especially around 1-2 Hz, which makes it unable to cope with faster local or intermachine modes in multi-unit power plants. By contrast, the \(d\omega\)-PSS has a good combination of strong gain and phase advance above 0.3 Hz, although it is unpractical at low frequency where it shows a 180 deg phase advance, which actually has a destabilizing effect despite the rather small low-frequency gain. Finally, even though the low-frequency shaping of the \(d\omega\)-PSS is satisfactory in overall, its DC rejection (washout) is not efficient enough, providing five time less attenuation than the MB-PSS.

![Bode Plot of the PSS tuning](image)

Fig. 11: Frequency responses of these PSSs as Bode Plot of the PSS tuning

3. RESULTS AND DISCUSSIONS

3.1 System without STATCOM or MB-PSS

The 4-machine 2-area test system was subjected to a three phase fault at the mid-point of the one transmission lines and cleared after 200 ms. In this case; the system didn't
have any stabilizer such as PSS or FACTS devices. Therefore, the system stability was affected by this three-phase fault and led the system to be unstable. The responses of the test system are shown in Fig. (12). The performance of the rotor angle $\delta$, speed deviation $\Delta \omega$, the terminal voltage $V_t$, the field excitation voltage $E_{fd}$, acceleration power $P_a$ and tie line power $P_{tie}$ in the two area system are shown below.

![Graphs showing system dynamics](image)

(a) Rotor angle $\delta_{14}$, in deg. (b) Speed Deviation $\omega_{1}$, pu.

(c) Voltage Terminal $V_{t1}$, pu. (d) Exciter Voltage $E_{fd1}$, pu.

(e) Acceleration Power $P_{a1}$, pu. (f) Power Tie Line $P_{tie}$, MW

![Graphs showing system dynamics](image)

Fig. 12: Four-machine two-area test system with 3-Φ fault and without MB-PSS or STATCOM

3.2 System with STATCOM device and without MB-PSS

If the STATCOM controller is added to the above test system (4-machine 2-area system) and subjected to the same 3-Φ fault, then the system response maintain to be stable and the oscillations nearly damped. Figure (13) shows the performance of the rotor angle $\delta$, speed deviation $\Delta \omega$, the terminal voltage $V_t$, the field excitation voltage $E_{fd}$, acceleration power $P_a$ and tie line power $P_{tie}$ in the two area system are shown below.
$E_{fd}$, acceleration power $P_a$ and tie line power $P_{tie}$ when the disturbance of 3-Φ fault has occurred in the two-area system with STATCOM controllers of +/-500MVA converter rating fixed at each end of the two areas.

If the MB-PSS is used with the exciter of each machine in the test system (4-machine 2-area system), and the system is subjected to the same 3-Φ fault, then the system response maintain to be stable and the oscillations are damped. Figure (14) shows the performance of the rotor angle $\delta$, speed deviation $d\omega$, the terminal voltage $V_t$, the field voltage $E_{fd}$, acceleration power $P_a$ and tie line power $P_{tie}$.

Fig. 13: Four-machine two-area test system with STATCOM controller under 3-Φ fault

3.3 System with MB-PSS and without STATCOM

If the MB-PSS is used with the exciter of each machine in the test system (4-machine 2-area system), and the system is subjected to the same 3-Φ fault, then the system response maintain to be stable and the oscillations are damped. Figure (14) shows the performance of the rotor angle $\delta$, speed deviation $d\omega$, the terminal voltage $V_t$, the field voltage $E_{fd}$, acceleration power $P_a$ and tie line power $P_{tie}$.
excitation voltage $E_{fd}$, acceleration power $P_a$ and tie line power $P_{tie}$ when the disturbance of 3-Φ fault has occurred in the two-area system which have excitation control by MB-PSS [13].

![Graphs](image1.png)

(a) Rotor angle $\delta_{14}$, in deg.      (b) Speed Deviation $d\omega_1$, pu.

![Graphs](image2.png)

(c) Voltage Terminal $V_{t1}$, pu.                 (d) Exciter Voltage $E_{fd1}$, pu.

![Graphs](image3.png)

(e) Acceleration Power $P_{a1}$, pu.                (f) Power Tie Line $P_{tie}$, MW

Fig. 14: Four-machine two-area test system with multi-band power system stabilizer (MB-PSS) under 3-Φ fault

3.4 System with Combined Control of STATCOM Controller and with Excitation Control of (MB-PSS)

When the combination of the STATCOM and the MB-PSS were added to the two-area system, this leads to a significant increase of the oscillation damping and leads to
the improvement of the power system stability. Comparing with the previous results, the combination between STATCOM and MB-PSS gives more stable performance of the system parameters. Figure (15) shows the performance of the disturbance of 3-Φ fault occurred in the two-area system which have combined control of MB-PSS and STATCOM.

![Graphs showing system parameters](image)

(a) Rotor angle $\delta_{14}$, in deg.  
(b) Speed Deviation $d\omega_1$, pu.  
(c) Voltage Terminal $V_{t1}$, pu.  
(d) Exciter Voltage $E_{fd1}$, pu.  
(e) Acceleration Power $P_{a1}$, pu.  
(f) Power Tie Line $P_{tie}$, MW

Fig. 15: Four-machine two-area test system with combined STATCOM controller and MB-PSS under 3-Φ fault

3.5 Comparison between the Three Cases (STATCOM, MB-PSS, and Combined)

When the combination between the STATCOM and the MB-PSS is added to the two-area system, this is result in a significant increase in damping oscillation which leads
to improve the power system stability. Comparison between the three cases (STATCOM, MB-PSS, and Combined) is shown in Fig. (16). The combination STATCOM and MB-PSS gave more stable performance of the system parameters.

![Rotor Angle, delta 1-4](image1)

(a) Rotor angle $\delta_{14}$, in deg.

![Speed Deviation $d\omega_1$, pu.](image2)

(b) Speed Deviation $d\omega_1$, pu.

Fig. 16: Four-machine two-area test system with combined STATCOM controller and MB-PSS under 3-$\Phi$ fault

4. CONCLUSIONS

In this study, the power system stability enhancement via STATCOM device and MB-PSS are presented and discussed. The coordination between the STATCOM controller and the MB-PSS is taken into consideration to improve the system transient stability as well as the system voltage regulation. The electromechanical mode is more controllable through based stabilizers. The proposed stabilizers have been tested on a Kundur's four-machine two-area power system with three-phase fault disturbance and
loading conditions. The nonlinear simulation results show the effectiveness and robustness of the proposed STATCOM controller and power system stabilizer to enhance the system stability.

REFERENCES


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**Appendices**

1- MB-PSS Simplified Settings Mode [11]:

\[ K=1, \quad F_{th}=0.2\text{Hz}, \quad K_{t}=20, \quad F_{tl}=0.9\text{Hz}, \quad K_{t}=25, \quad F_{tl}=12\text{Hz}, \quad K_{t}=145, \quad V_{l,\text{max}}=0.075\text{pu}, \quad V_{l,\text{max}}=0.15\text{pu}, \quad V_{l,\text{max}}=0.15\text{pu}, \quad V_{l,\text{max}}=0.15\text{pu} \]

2- STATCOM parameters [26]: 230 KV, ±500 MVAR

\[ R=0.0073\text{pu}, L=0.22\text{pu}, V_{dc}=40\text{KV}, C_{dc}=\pm 375\mu F, \quad V_{ref}=1.0\text{pu}, \quad V_{dc}=0.15\text{pu}, \quad V_{dc}=0.15\text{pu}, \quad V_{dc}=0.15\text{pu} \]

3- Synchronous Generator [4, 14]:

\[ X_{d}=1.8\text{pu}, X_{q}=0.3\text{pu}, X_{q}=0.25\text{pu}, X_{d}=1.7\text{pu}, X_{q}=0.55\text{pu}, X_{q}=0.25\text{pu}, X_{d}=0.2\text{pu}, R_{e}=0.0025\text{pu}, T_{d,\text{c}}=8\text{sec}, T_{q,\text{c}}=0.03\text{sec}, T_{q,\text{c}}=0.4\text{sec}, T_{q,\text{c}}=0.05\text{sec}, H_{\text{c}}=6.5\text{sec}, p=4 \]

4- Excitation System [4, 10]:

\[ T_{e}=0.02\text{sec}, \quad K_{e}=300, \quad T_{e}=0.001, \quad K_{e}=1, \quad T_{e}=0, \quad T_{e}=0, \quad K_{e}=0.001, \quad T_{e}=0.1\text{sec}, \quad E_{\text{min}}=-11.5, \quad E_{\text{max}}=11.5 \]

5- Steam Turbine and Governor [10, 11]:

\[ K_{p}=1, \quad R_{e}=0.05, \quad D_{e}=0, \quad T_{e}=0.001, \quad T_{q,\text{c}}=0.15, \quad V_{g,\text{max}}=-0.1, \quad V_{g,\text{max}}=0.1\text{pu/s}, \quad g_{\text{min}}=0, \quad g_{\text{max}}=4.496, \quad \text{and} \quad T_{q}=0, \quad T_{q}=10, \quad T_{q}=3.3, \quad T_{q}=0.5, \quad T_{q}=0.5, \quad T_{q}=0, \quad T_{q}=0, \quad H_{c}=0.24897, \quad H_{c}=0, \quad H_{c}=0, \quad H_{c}=0.4734, \quad K_{d}=0.2, \quad K_{d}=0.2, \quad K_{d}=0, \quad D_{e}=0, \quad D_{e}=0, \quad D_{e}=0, \quad D_{e}=0, \quad \text{torque/pu speed deviation}. \]
Biographies

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