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Combining Multi-Band Power System Stabilizers and Hybrid Power Flow Controllers to Support Electricity Grids with High Penetration of Distributed Renewable Generation

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ABSTRACT

The paper demonstrates the application of a new power flow configuration consisting of a Hybrid Power Flow Controller (HPFC) and a Multi-Band Power System Stabilizer (MB-PSS) to enhance the performance of a multi-machine power network in the presence of solar photovoltaic (PV) and wind energy sources. The HPFC is a new type of FACTS (Flexible AC Transmission Systems) device, which has been introduced to address inter-area congestion problems by controlling the real power flow and providing voltage regulation. The MB-PSS, on the other hand, is a power system stabilizer based on different frequency modes of electromechanical oscillations, where the discontinuities caused by the faults in the grid are taken into consideration, for multiple fault clearing times. The multi-machine power network with PV and wind distributed generation and the proposed power flow configuration are simulated using Matlab/ SimPowerSystems Toolbox and analyzed under three phases to ground short-circuits faults occurring in the middle of the transmission line.

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1. INTRODUCTION

The increased penetration of highly variable renewable sources, energy storage devices, and smart loads into the power grid has created new technical challenges for grid operators who must ensure reliable and stable operation of the power network. Flexible AC Transmission Systems (FACTS) and Power Systems Stabilizers (PSS) have long been used to enhance the reliability and transmission capability of AC power grids as well as improve power quality. The Hybrid Power Flow Controller (HPFC) is a relatively new FACTS device that proved its effectiveness in providing a suitable solution for the application of FACTS devices in electric transmission systems. By keeping most of the system variables within the permissible limits at all bus bars, the HPFC can operate under any operating condition. The performance of FACTS during different fault conditions has been investigated by several researchers. A comprehensive study on FACTS and how these devices improve the stability and power flow capability is presented in [1][2][3][4][5]. The authors in [6], proposed three configurations of HPFC for the popular Western System Coordinated Council (WSCC) 3-machines 9-bus power system and investigated their effectiveness in enhancing the transient stability of the multi-machine system. Several realistic scenarios have been stimulated to demonstrate the potential benefits of the HPFC. These authors also tested different HPFC configurations on a Single-Machine Infinite Bus (SMIB) system and concluded that the HPFC is a better option for enhancing the stability of power systems [7]. In [8], the authors compared an HPFC configuration with the Unified Power Flow Controller (UPFC) on a multi-machine power system and the results showed that the HPFC exhibited better performance. Likewise, in [9], the performance of HPFC was assessed on two synchronous machines interconnected through transformers and transmission lines. The results demonstrated the capability of HPFC to control the power flow through the lines and improve the performance of the power system.

The ability of the HPFC to solve congestion problems in a real electricity grid was investigated by the authors in [10]. The authors used steady-state models of the HPFC to solve the power flow and optimal power flow (OPF) for the Ontario-Canada grid.

To improve the efficiency and robustness of the HPFC and make its control more robust, the authors in [11] proposed a Group Search Optimizer (GSO) optimization algorithm is used to determine the optimal steady-state real and reactive power flows. These authors used an interconnected hybrid power generation system to provide stable power in active and passive power networks. In another study, these authors proposed an HPFC controller for the Kundur 2-area 4-machines 12-bus system. The HPFC was evaluated under different control modes including PVV mode, PQQ mode, Impedance mode, and Voltage mode [12]. In a recent study, the HPFC was used to improve the performance of an electric distribution benchmark power system [13]. Different controllers based on fuzzy logic, radial basis function neural network, and neuro-fuzzy systems have been tested. The neuro-fuzzy controller exhibited better performance by considerably reducing voltage sag magnitudes.

All the above studies have been carried out without the presence of renewable energy sources and they focused only on the characteristics of the network (i.e. voltage, frequency, etc.).

Power System Stabilizers (PSS), on the other hand, have been used for many years as an advanced auxiliary controller to provide sufficient damping to the power system. Recent works on PSS considered the application of optimization techniques to enhance the performance and robustness of the PSS [14]. In [1andndn immune genetic algorithm is used to optimize the PSS parameters in the SMIB power system. The authors in [16] proposed the design of a PSS using Whale Optimization Algorithm (WOA) to enhance the damping in a multi-machine system. A PSS is proposed in [17] and [18] to improve the dynamic stability and provide adequate low-frequency damping for inverter-dominated future power systems. However, it is well-known that the PSS performance is effective on the characteristics of the power network locally where it is installed. Recently, a new topology of PSS termed Multi-Band-PSS (MB-PSS), which offers good compensation at all frequencies, has been proposed in [19] and applied in the Hydro-Québec power plant where it offered good performance at all frequencies. The authors in [20] developed a combined control of STATCOM and MB-PSS to improve power system stability and regulate the system voltage in Kundur's power system. The authors in [21], presented a simulation study based on a two machines power system and compared the results of MB-PSS with those of a conventional PSS. In [22], a new MB-PSS known as PSS4B is developed and tested on the electromagnetic simulation tool HYPERSIM and the results are compared with MATLAB/SimPowerSystems. All papers confirmed the robustness and performance of MB-PSS.

In general, from the littérature reviewed, it appears that most studies have focused on examining the response of the Hybrid Power Flow controlled under contingencies, disregarding the effect of the presence of Power system stabilizers.

Replacing or supplementing existing Facts is the main reason for planning HPFCs, given their performance in improving power system damping. Likewise, the multi-band stabilizer (MB-PSS) offers greater damping capability due to its different modes of oscillation. This combination is a very promising solution to enhance power system stability.

The remaining of the paper is organized as follows: Section 2 presents the basic power system configuration with the Hybrid Power Flow Controller and the Multi-Band PSS. In Section 3, a detailed description of the studied power system is presented. The simulation results and discussion are presented in Section 4 and finally, Section 5 summarizes the conclusions of the paper.

2. POWER SYSTEM CONFIGURATION

The power system configuration used in this study with the proposed combination of MB-PSS and HPFC is illustrated in Figure 1, where the two similar regions Area 1 and Area 2 are connected by a weak tie-line. Each area consists of two generators rated 900 MVA and 20 kV.

The MB-PSS and HPFC are connected to the network in separate modes, which ensures full control of the grid. The role of the MB-PSS is to improve the grid performance by keeping the generator under control during faults or a disturbance in renewable energy sources. The HPFC is installed in the transmission line to ensure the stability of the power system.

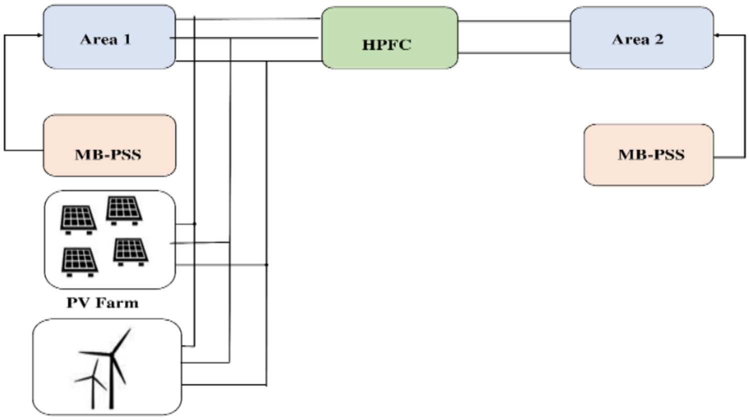

Figure 1. Power system configuration.

2.1. HPFC basic operation

The HPFC is one of the FACTS devices used for controlling real power and regulating voltage in power systems. It also can control separately the total reactive power exchanged with the sending and receiving ends of the line.

Figure 2 depicts the structure of the HPFC which is a combination of two Voltage Source Converters (VSC) connected in series and used to exchange real power and a controllable susceptance of reactive power BM connected in shunt between the two VSCs.

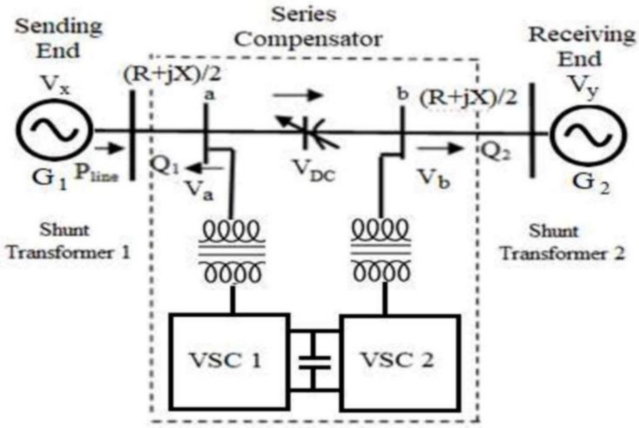

Figure 2. Configuration of the HPFC

Figure.3 shows the equivalent circuit one-line model of HPFC, including currents and voltages of regions, power flow, and lines variables.

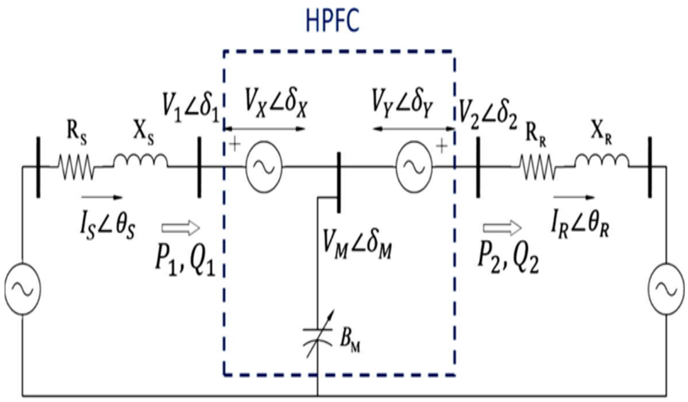

Figure 3. One-line equivalent circuit diagram of the HPFC.

If the two areas are directly interconnected, the power transfer between the sending and receiving ends V_S and V_R will then be calculated as:

$$P_0=3\frac{|V_S||V_R|}{X_S+X_R}\sin(\delta) \quad (1)$$

Where $V_S = R_S + jX_S$ and $V_R = R_R + jX_R$
R_S is Series resistance representing HPFC Converter 1
X_S is Series reactance representing HPFC Converter 1
R_R is Series resistance representing HPFC Converter 2
X_R is Series reactance representing HPFC Converter 2
and δ represents the angle between the two voltages V_R and V_S.

$$\delta=\delta_S-\delta_R \quad (2)$$

Where δ_S *and* δ_R are respectively the angle of the voltage V_S of HPFC Converter 1 and the voltage V_R of HPFC converter 2

Including the shunt susceptance B_M between the two regions gives the following steady-state phasor equations [15] :

$$jX_S I_S + \frac{1}{jB_M}(I_S - I_R) = V_S - V_X \quad (3)$$

$$-\frac{1}{jB_M}(I_S - I_R) + j(X_R - X_S)I_R = -V_R + V_Y \quad (4)$$

I_S: Current phasor remaining into HPFC Terminal 1
I_R: Current phasor remaining out of HPFC Terminal 2
V_X: Series voltage phasor representing HPFC Converter 1
V_Y: Series voltage phasor representing HPFC Converter 2
The constraint of real power balance is expressed as:

$$\mathcal{R}e[V_X I_S^*] = \mathcal{R}e[V_Y I_R^*] \quad (5)$$

Where $\mathcal{R}e$ denotes the real part of the complex power.

Four control modes for the HPFC are distinguished, starting with the PVV mode, where the active power P_2 and voltage amplitudes V_1 and V_2 at the HPFC terminals are controlled separately, according to the equations (6), (7), (8), (9) [16]. If the limits of one of the variables I_S, I_R, V_X, or V_Y are exceeded, the HPFC switches to PQQ mode, where the P_2, Q_1, and Q_2 are defined, depending on the operating constraints of the device.

$$P_1 = R_e\{(V_X + V_M)I_S^*\} \quad (6)$$

$$P_2 = R_e\{(V_Y + V_M)I_R^*\} \quad (7)$$

$$Q_1 = I_m\{(V_X + V_M)I_S^*\} \quad (8)$$

$$Q_2 = I_m\{(V_Y + V_M)I_R^*\} \quad (9)$$

Where
P_1: Active power remaining in HPFC Terminal 1
P_2: Active power remaining out of HPFC Terminal 2
Q_1: Reactive power remaining in HPFC Terminal 1
Q_2: Reactive power remaining out of HPFC Terminal 2
V_M: Shunt device voltage phasor
Im denotes the imaginary part of the complex power.

When the device is set to V control, the voltage amplitude at the V_M shunt bus is regulated to a specified value using the variable shunt susceptance B_M as indicated in equation (10), and finally, it switches to Z mode, which corresponds at the minimum regulating capability of the HPFC.

$$V_M = \frac{I_S - I_R}{jB_M} \quad (10)$$

2.2. Multi-band power system stabilizer topology

Power System Stabilizers (PSS) produce an electrical torque factor in phase with the rotor speed deviation, by varying field excitation, to dampen rotor oscillations [23].

The input of the PSS can be the generator rotor speed (Δω), the electrical power variation (ΔP), the frequency variation (Δf) any or other signals. The output of the PSS is the signal V_stab to be injected into the exciter system.

The MB-PSS is a compound of three separate bands committed to the low, intermediate, and high-frequency modes of oscillations. Each band is made of a differential band-pass filter, again, and a limiter [24] as shown in Figure 4.

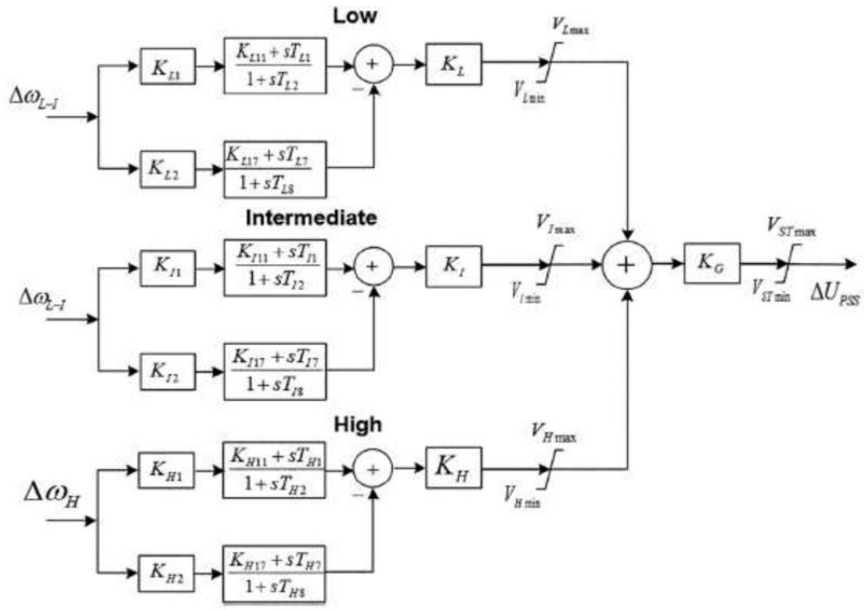

Figure 4. Structure of the MB-PSS.

Where $T_{L1} \ldots T_{L8}, T_{I1} \ldots T_{I8}, T_{H1} \ldots T_{H8}$ are lead-lag time constants and K_L, K_I, and K_H are gains at central frequencies for low, intermediate, and high bands and K_G is the global gain.

The conventional PSS (CPSS) usually consists of an amplifier block, a high-pass filter block 'filter washout', a phase compensation block, and a limiter as shown in Figure 5.

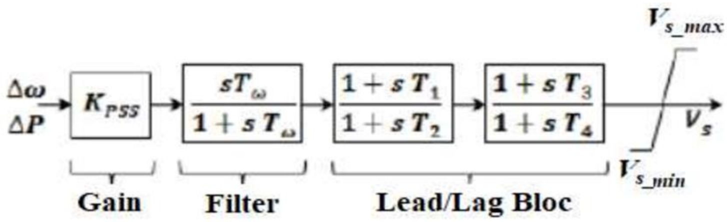

Figure 5. Structure of the CPSS.

Each limb of the MB-PSS is viewed as a CPSS which can be described by the following transfer function:

$$\frac{V_S}{\Delta\omega} = \frac{V_S}{\Delta P} = K_{PSS} \frac{sT_W}{1+sT_W} \frac{1+sT_1}{1+sT_2} \frac{1+sT_3}{1+sT_4} \quad (11)$$

Where:

V_S Output of CPSS.

$\Delta\omega$ or ΔP Input of CPSS.

K_{PSS} Gain of the conventional PSS Gain of the conventional PSS.

T_W Time constant of the first-order high-pass filter (sec).

T_1, T_2 Time constants of the first lead-lag transfer function (sec).

T_3, T_4 Time constants of the second lead-lag transfer function (sec).

3. SIMULATION MODEL OF THE STUDIED SYSTEM

To assess the performance of our proposed compensator combining HPFC and MB-PSS in large interconnected power systems, the Kundur 4-machines, 11-bus system [25] is taken as a case study. As shown in Figure 6, it consists of two similar areas connected through two 220 km long transmission lines, rated 100 MVA and 230 kV base. The generators are rated 900 MVA and 20 kV and the system frequency is 60 Hz. Area 1 exports 413 MW to Area 2 and all generators are required to produce about 700 MW each. At time t = 1 sec, a three-phase fault occurs at the midpoint of the line and lasts 100 millisec.

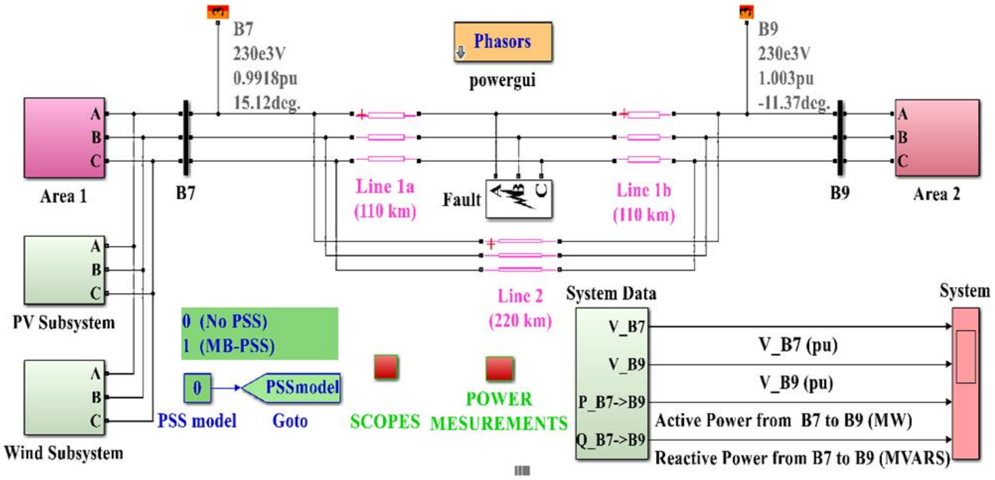

Figure 6. Two-area Kundur power system.

A Hybrid Renewable Energy System (HRES) consisting of solar photovoltaic (PV) and wind power plant is connected to Area 1 of the power system. The solar PV farm generates 40 MW at a solar irradiance oscillating between 0 and 400 Watt/m², and the wind farm generates 30 MW at a wind of different speeds ranging from 08 m/s to 11m/s from t=3 sec, as specified in figure 7.

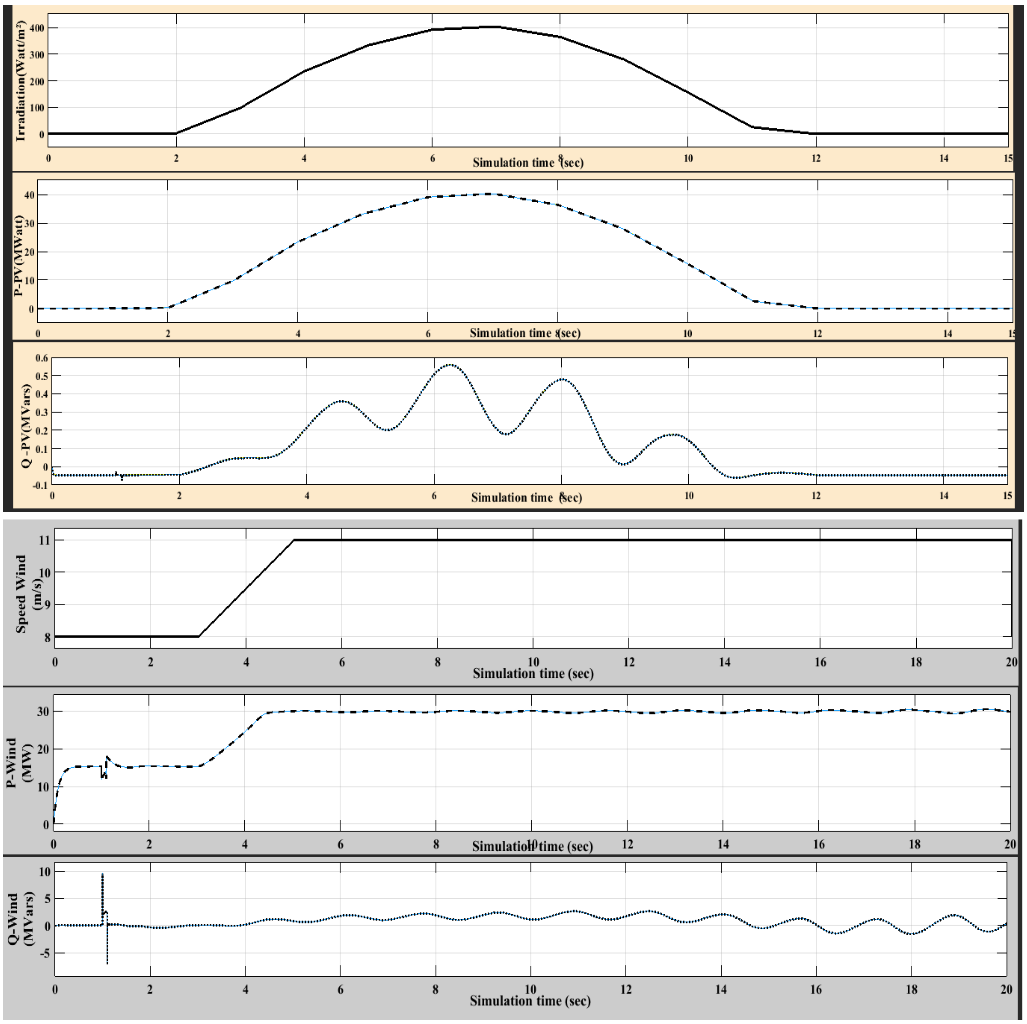

Figure 7. PV and Wind properties in Kundur System without control or compensation.

The typical HPFC, connected at the middle of the transmission line, utilizes the phasor models of two Static Synchronous Series Compensator (SSSC) related in series, and in shunt with a Static Var Compensator (SVC). The overall system with all components is modeled by using MATLAB and SimPowerSystems Toolbox as shown in Figure 8.

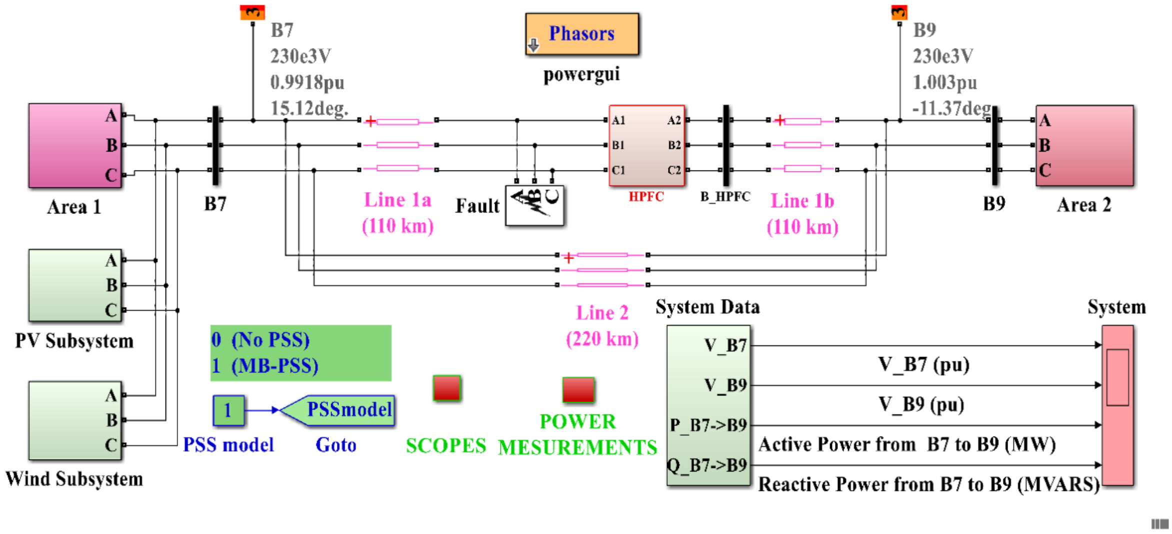

Figure 8. MATLAB/Simulink-based model of the Kundur power system equipped HPFC and MB-PSS.

4. SIMULATION RESULTS AND DISCUSSION

The test power system is simulated under the following four scenarios:

Scenario 1: Without compensation and control.

Scenario 2: With renewable energy and without compensation and control.

Scenario 3: With renewable energy and with HPFC.

Scenario 4: With renewable energy and with the proposed compensation (MB-PSS-HPFC).

4.1. Power system without the proposed combination MB-PSS-HPFC

First, the results obtained are compared to assess the impact of HPFC on the transient stability of the power system in the presence of hybrid renewable energy sources (HRES). Useful variables are the voltages on the two sides of the line between Area 1 and Area 2 (bus B7 and bus B9), and the tie-line active and reactive powers from Area 1 to Area 2, as plotted in Figure 9.a) and Figure 9.b) respectively.

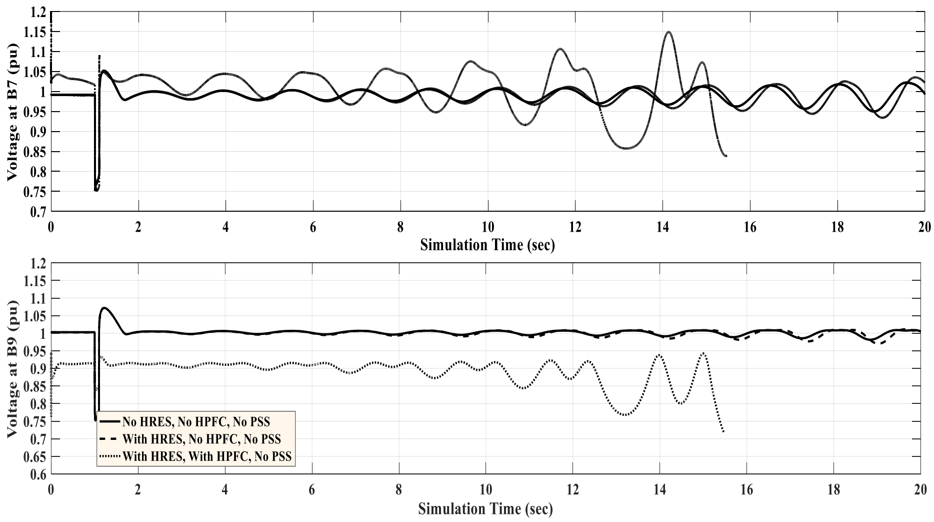

Figure 9. a). Voltages at sides B7 and B9 of Kundur areas.

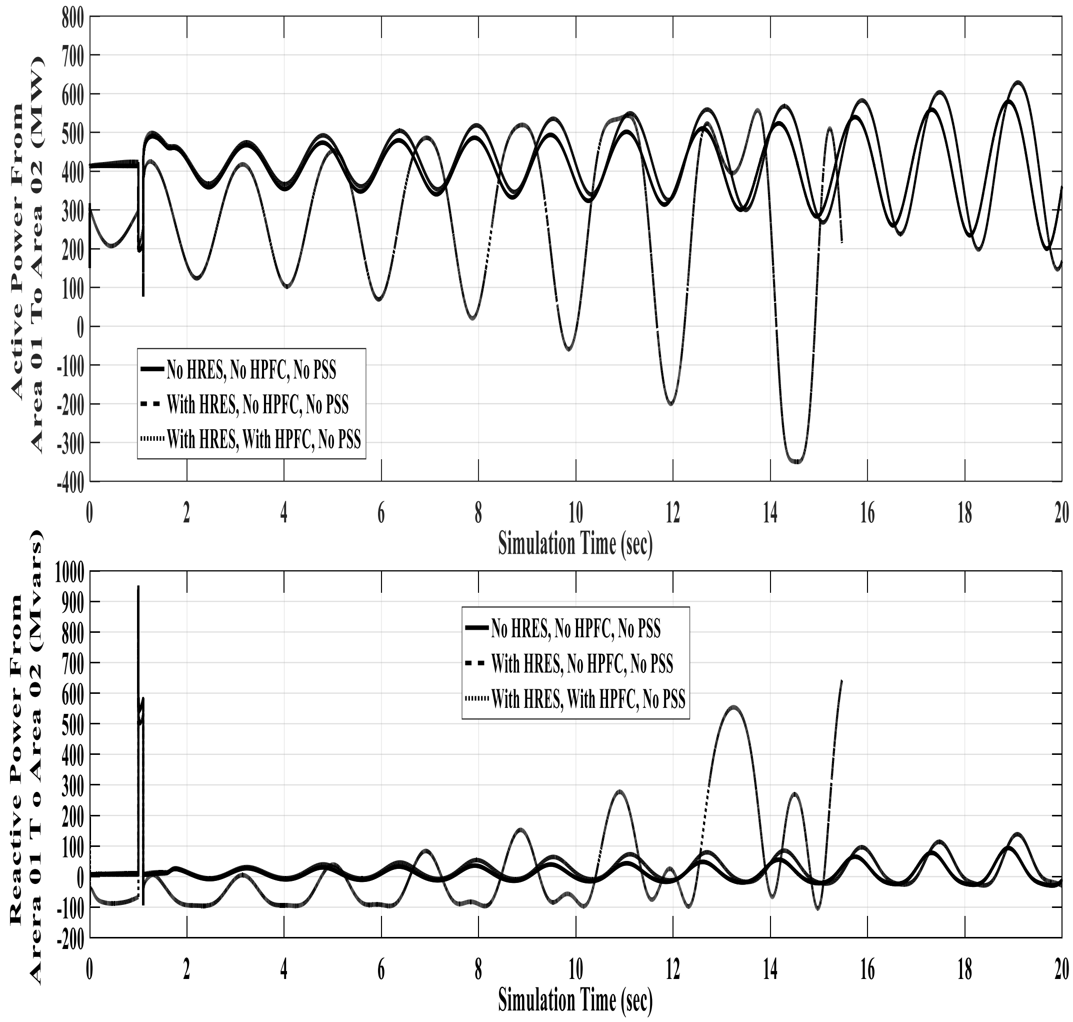

Figure 9. b). Active and Reactive Power From Area 01 to Area 02 in Kundur Power System.
Figure 9. Useful variables Kundur power System without MB_PSS.

It can be observed from Figure 9 that with the PV and wind sources and the Hybrid Power Flow Controller HPFC connected to the power system, this leads to instability in addition to a loss of synchronism of the generators in the absence of the Multi-Band power system stabilizer (MB_PSS).

The harmonics of oscillations are more significant towards the end of the simulation when the system is not equipped with MB_PSS. The tie-line active power transmitted between the two areas exceeds the nominal power of 400 MW and reaches the maximum value of 600 MW. Likewise, the level of harmonics of the voltages at the terminals of buses B7 and B9 remains within the adequate voltage variation range [0.93_1.05] and the system losses the synchronism in presence of HPFC.

4.2. Power system with the proposed combination MB-PSS-HPFC

As explained above, the performance of the HPFC can be evaluated just with the network parameters (transit power, voltage bus profile, etc.). Based on the obtained results in presence of only renewable energy sources and the HPFC device and because the system loses synchronism and becomes unstable before the end of the simulation, it is necessary to find a solution to guarantee its transient stability.

The solution is the proposed combination of MB-PSS-HPFC presented in the paper. By adding a PSS to each generator in the system, to increase the damping of low-frequency oscillations, to remove the negative effects of voltage regulators, and to ensure the system's stability, the MB-PSS is used. The active power flow from bus B7 to bus B9 and the voltages at bus B7 and bus B9 is shown in Figure10. The same three-phase to ground short-circuit fault is applied to the system.

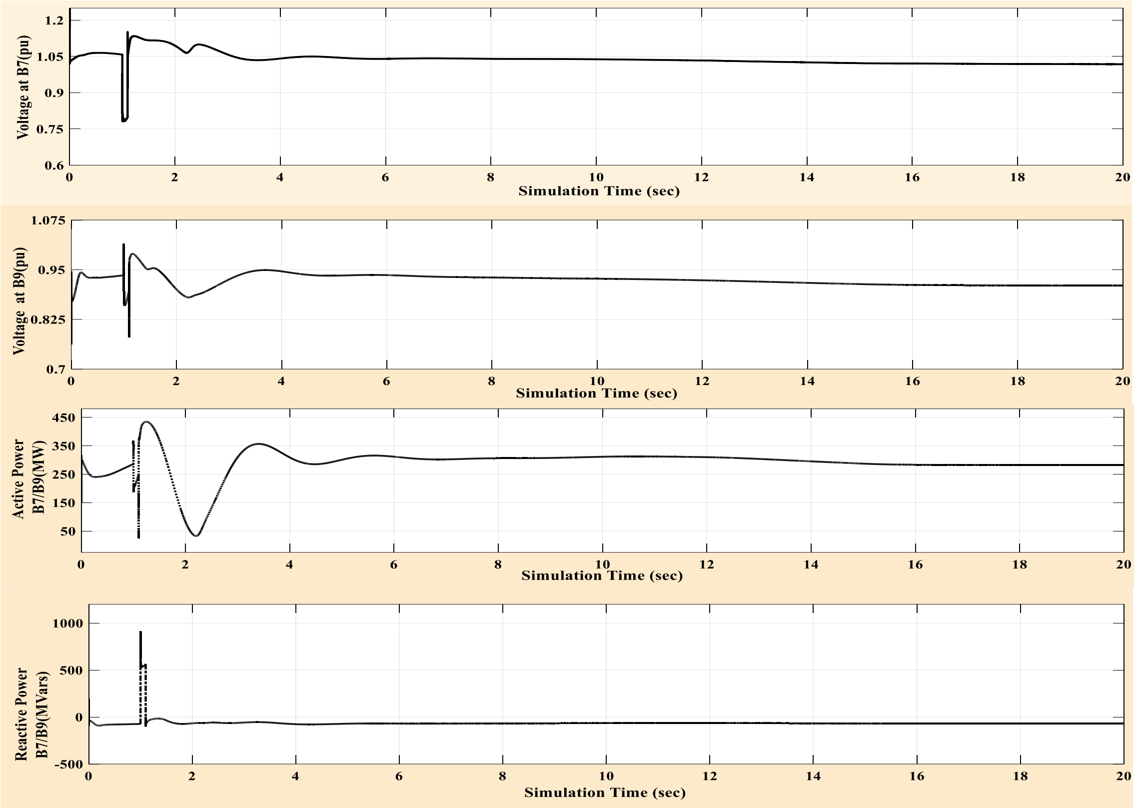

Figure 10. Useful variables Kundur power System with HRES_HPFC_MB_PSS

It can be observed from Figure 10 that after adding the MB-PSS to all the generators, the system regains its stability in a short time (about 5 seconds). Voltages are always inadequate variation range and transmitted active power from area 01 to area 02 stabilized at about 283 MW with no transmitted reactive power.

The curves of active powers between the two areas for several Fault Clearing Times are presented in Figure 11, accompanied, in Table 01, by a recapitulation of values of the response characteristics for the premeditated Fault Clearing Time, where the stability is delayed with increasing the FCT.

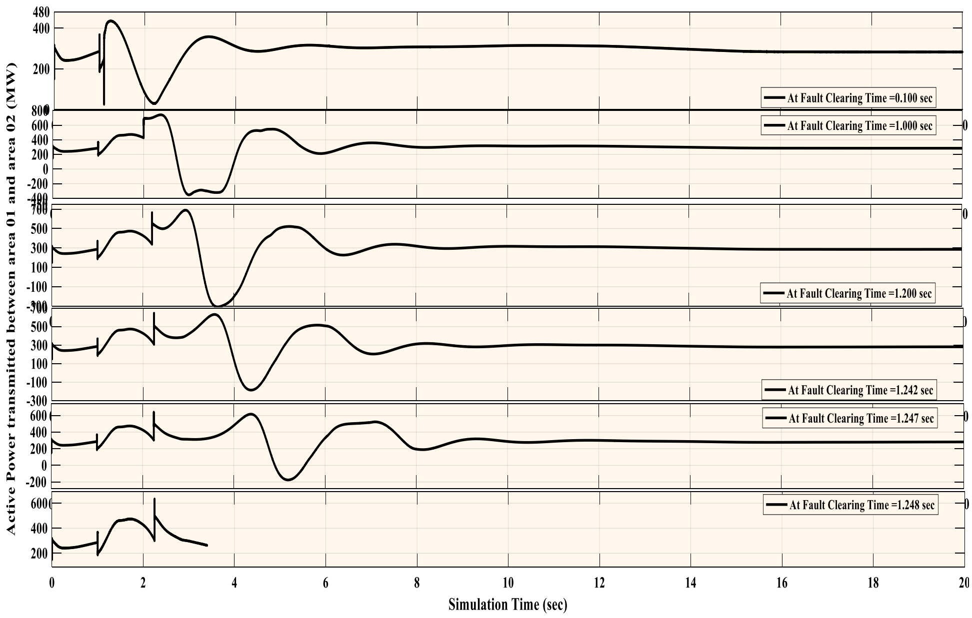

Figure 11. Active Powers for different Fault Clearing Time values in Kundur power System with HRES_HPFC_MB_PSS

Table 1. Recapitulation of values of response characteristics with HRES_HPFC_MB-PSS

Fault Clearing Time (FCT)	Rise Time (ms)	Max Value (MW)	Overshoot (%)	Peak To Peak (MW)
0.100	253.33	435.30	29.49	409.30
1.000	257.48	**742.90**	44.43	1096.00
1.200	515.57	689.60	40.10	998.10
1.242	142.36	642.20	127.64	826.10
1.247	161.11	639.10	98.35	814.80
1.248 (Critical Fault Clearing Time CFCT)	Loss Of Synchronism at 3.363 sec			

As seen in Table 1, the active power achieved the maximum value of 742.90 MW at time t=2.37 seconds, when the fault clearing time is taken as 1.000 seconds. The system lost the synchronism at t= 3.363 seconds when the fault clearing time is taken at t=1.248 seconds.

In [26], different HPFC configurations have been implemented on a Multi-Machine system, for different values of FCT for the system. Results show that in presence of HPFC in the system, the maximum value of overshoot and the value of rise time is low, for lower values of fault clearing time.

The investigation confirms that HPFCs help in quickly stabilizing the system, and thus, reducing the value of settling-time.

5. CONCLUSION

The paper proposed and investigated extensively a new compensator topology combining a Multi-Band Power System Stabilizer (MB-PSS) and Hybrid Power Flow Controller (HPFC) to improve the performance and transient stability of the large electrical system in the presence of renewable energy sources. This study was based on the two areas Kundur 4 machines, 11-bus network connected to a solar photovoltaic and wind farms, considering three-phase fault under different fault clearing times. The overall model of the system is simulated under various fault conditions using MATLAB and SimPowerSystems Toolbox. The main advantage of the proposed design is a delay of critical fault clearing time (CFTC) and enhancement of the stability of the power system. The results of the simulation also proved that the proposed design is secure since the required voltage ranges are correctly respected, and the results obtained are very satisfactory.

It can be therefore interesting to combine several electrical system controllers, to secure the electrical network, which is often subject to breakdowns and malfunctions.

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