Research Note

The Effect of an Interline Power Flow Controller (IPFC) on Damping Inter-area Oscillations in Interconnected Power Systems

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The effect of an Interline Power Flow Controller (IPFC) on damping low frequency oscillations has been implied in some papers, but has not been investigated in detail. This paper investigates the damping control function of an interline power flow controller installed in a power system. For this purpose, a single machine-infinite bus model, integrated with IPFC, is used and the linearized model is established. Using this model, the Phillips-Heffron model of the system for steady state digital simulations is derived. In this paper, the numerical results are presented using the MATLAB simulink toolbox, which shows the significant effect of IPFC on damping inter-area oscillations.

INTRODUCTION

Low frequency oscillations, with frequencies in the range of 0.2 to 2.0 Hz, are one of the results of the interconnection of large power systems. Modern power systems are stable, if electromechanical oscillations occurring in each area can be damped as soon as possible.

The Power System Stabilizer (PSS) is a simple, effective and economical method for increasing power system oscillation stability [1].

During the last three decades, a Flexible AC Transmission System (FACTS) technology has been proposed, which provides a better utilization of the existing systems.

Due to recent trends in the creation of a deregulated utility industry, power transmission requirements are undergoing major changes and present considerable challenges. Deregulation is aimed at a competitive energy market, in which the sellers (producers of electric power) and buyers (distributors) are linked together with an independent transmission network. Thus, the transmission network is challenged to deliver bulk electric power from a variety of geographically dispersed and changing locations to the contracting buyers supplying the prevailing loads [2]. Interesting FACTS capabilities, such as power flow control, the damping of power system oscillations, voltage regulation and reactive power compensation, make them a good option for the effective utilization of power systems in this environment.

One of the FACTS capabilities is damping inter-area oscillations, which will be accurately investigated for IPFC in this paper.

The interline power flow controller, which was proposed by Gyugyi et al. [3] in 1998, is a FACTS controller for series compensation, with the unique capability of power flow management between multi-lines of a substation.

By combining two or more series-connected converters working together, the IPFC extends the concepts of voltage and power flow control beyond that achievable by the one-converter FACTS controller, the Static Synchronous Series Compensator (SSSC) [4]. In the IPFC structure, a number of inverters are linked together at their DC terminals. Each inverter can provide series reactive compensation, as an SSSC, for its own line. However, the inverters can transfer real power between them via their common DC terminal. This capability allows the IPFC to provide both reactive and real compensation for some of the lines and, thereby, optimize the utilization of overall transmission systems.

Real power can be extracted from one line and injected into another. Therefore, unlike the SSSC, the

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injected voltage does not have to be in quadrature with the line current. This implies that both the voltage magnitude and the phase angle of the injected voltage can be controlled on one line. However, for proper operation of the device, the DC bus voltage must be held constant and the real power, injected to one line by the Voltage Source Converter (VSC), must be equal to the real power extracted from the other line. Hence, only one of the variables of the injected voltage of the other line can be independently controlled [5,6].

Like other FACTS elements, IPFC can be used for increasing power system stability against large and small disturbances.

In this paper, the voltage of coupling capacitance between two VSC-based converters is used as a state variable. Output power for the generator is used as an input of the PI controller, which creates a proper amplitude modulation ratio for the secondary converter.

Numerical results will show the effect of IPFC on the damping of inter-area oscillations in power systems.
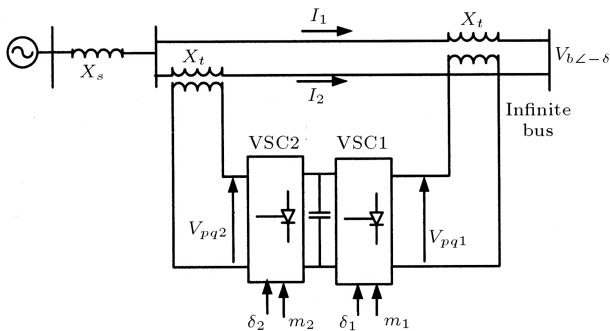
SYSTEM INVESTIGATED

A Single-Machine Infinite-Bus (SMIB) system, with IPFC installed on two lines, is considered. This configuration, which consists of two parallel transmission lines, connects the generator, G, to an infinite bus, which is illustrated in Figure 1.

PSS is not taken into account in the power system. Operating conditions and parameters are represented in Appendix C.

DYNAMIC MODEL OF THE SYSTEM WITH IPFC

The Phillips-Heffron linear model of a single-machine infinite-bus system with IPFC is derived from the non-linear differential equations. Neglecting the resistance of all the components of the system, such as generators, transformers, transmission lines and series converter transformers, a nonlinear dynamic model of the system

Figure 1. Schematic of the investigated system.

is derived as follows:

$$\dot{\delta} = \omega_0(\omega - 1), \tag{1}$$

$$\dot{\omega} = (P_m - P_e - P_D)/M, \tag{2}$$

$$\dot{E}_q' = (-E_q + E_{fd})/T_{do}', \tag{3}$$

$$\dot{E}_{fd} = [-E_{fd} + K_A(V_{\text{ref}} - V_S)]/T_A, \tag{4}$$

where:

$$P_e = V_{sd}(I_{1d} + I_{2d}) + V_{sq}(I_{1q} + I_{2q}), \tag{5}$$

$$P_e = P_1 + P_2, \tag{6}$$

$$E_q = E_q' + (X_d - X_d')(I_{1d} + I_{2d}), \tag{7}$$

$$V_S = V_{sd} + jV_{sq} = X_q I_q + j[E_q' - X_d'(I_{1d} + I_{2d})], \tag{8}$$

where:

P_1: the transferred power of the primary line,
P_2: the transferred power of the secondary line,
P_e: the total transferred power of the lines,
V_s: the terminal voltage of the generator,
I_{id}: the direct axes current of line i,
I_{iq}: the quadrature axes current of line i,
X_d: the direct axes reactance of the generator and
X_q: the quadrature axes reactance of the generator.

If the general Pulse Width Modulation (PWM) is used for VSCs, the voltage equations of the IPFC converters in the dq coordinates will be as follows [1]:

$$\begin{bmatrix} V_{P1} \\ V_{q1} \end{bmatrix} = \begin{bmatrix} 0 & -X_t \\ X_t & 0 \end{bmatrix} \begin{bmatrix} I_{1d} \\ I_{1q} \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} m_1 \cos \delta_1 \\ m_2 \cos \delta_2 \end{bmatrix}, \tag{9}$$

$$\begin{bmatrix} V_{P2} \\ V_{q2} \end{bmatrix} = \begin{bmatrix} 0 & -X_t \\ X_t & 0 \end{bmatrix} \begin{bmatrix} I_{2d} \\ I_{2q} \end{bmatrix} + \frac{V_{dc}}{2} \begin{bmatrix} m_1 \sin \delta_1 \\ m_2 \sin \delta_2 \end{bmatrix}, \tag{10}$$

where:

$$\overline{V_{pqK}} = V_{pK} + jV_{qK} = V_{pqK}e^{j\delta_K}, \tag{11}$$

$$\frac{dV_{dc}}{dt} = \frac{3m_1}{4C}[I_{1d} \cos \delta_1 + I_{1q} \sin \delta_1]$$
$$+ \frac{3m_2}{4C}[I_{2d} \cos \delta_2 + I_{2q} \sin \delta_2]. \tag{12}$$

It should be noted that using other techniques, such as space-vector modulation or optimized pulse patterns, results in the same equations as Equations 10 and 11.

From Figure 1, it can be obtained that:

$$V_S = jX_S I_S + V_{pq2} + jX_L I_2 + V_b. \tag{13}$$

This equation in the $d - q$ coordinates is as follows:

$$V_{Sd} + jV_{Sq} = jX_S[(I_{1d} + I_{2d}) + j(I_{1q} + I_{2q})]$$

$$+ jX_L(I_{2d} + jI_{2q}) + V_{P2} + jV_{q2}$$

$$+ V_b \sin\delta + jV_b \cos\delta. \tag{14}$$

On the other hand, according to Figure 2, it can be written that:

$$V_{Sd} = X_q(I_{1q} + I_{2q}), \tag{15}$$

$$V_{Sq} = E'_q - (X_d - X'_d)(I_{1d} + I_{2d}). \tag{16}$$

From Equations 6 to 12, the following can be obtained:

$$\begin{bmatrix} X_{ds} & X_{d\Sigma'} \\ X_{TL} & -X_{TL} \end{bmatrix} \begin{bmatrix} I_{1d} \\ I_{2d} \end{bmatrix} = \begin{bmatrix} E'_q - \frac{V_{dc}}{2}m_2 \sin\delta_2 - V_b \cos\delta \\ \frac{V_{dc}}{2}(m_2 \sin\delta_2 - m_1 \sin\delta_1) \end{bmatrix}, \tag{17}$$

$$\begin{bmatrix} X_{qs} & X_{q\Sigma} \\ -X_{TL} & X_{TL} \end{bmatrix} \begin{bmatrix} I_{1q} \\ I_{2q} \end{bmatrix} = \begin{bmatrix} \frac{V_{dc}}{2}m_2 \cos\delta_2 + V_b \sin\delta \\ \frac{V_{dc}}{2}(m_2 \cos\delta_2 - m_1 \cos\delta_1) \end{bmatrix}, \tag{18}$$
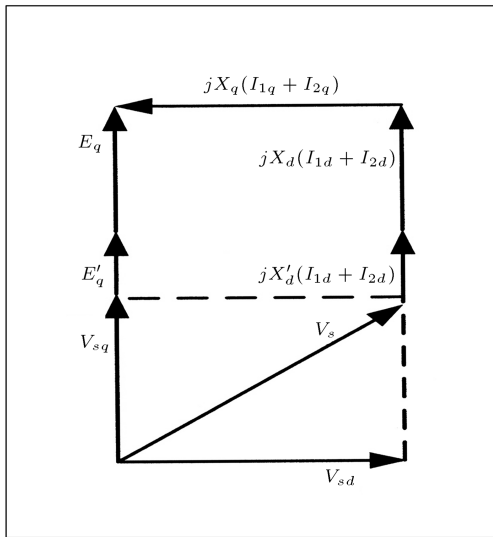
where:

$$X_{qs} = X_q + X_s, \tag{19}$$

$$X_{TL} = X_t + X_L, \tag{20}$$

$$X_{ds} = X'_d + X_s, \tag{21}$$

$$X_{q\Sigma} = X_{qs} + X_{TL}, \tag{22}$$

$$X_{d\Sigma'} = X_{ds} + X_{TL}, \tag{23}$$

and X_L is the series reactance of each transmission line.

Figure 2. Phaseor diagram of investigated system.

LINEAR DYNAMIC MODEL

Power system oscillation stability and control can be studied using a linearized model of the power systems.

A linear dynamic model of the system, illustrated in Figure 1, is obtained by linearizing the nonlinear model of the system, presented previously around an operating condition. The linearized model is as follows:

$$\Delta\dot{V}_{dc} = K_7\Delta\delta + K8\Delta E'_q + K_9\Delta V_{dc} + K_{cm}\Delta m_2, \tag{24}$$

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{E}'_q \\ \Delta\dot{E}_{fd} \end{bmatrix} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ \frac{-K_1}{M} & \frac{-D}{M} & \frac{-K_2}{M} & 0 \\ \frac{-K_4}{T'_{do}} & 0 & \frac{-K_3}{T'_{do}} & \frac{1}{T'_{do}} \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & \frac{1}{T_A} \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta E'_q \\ \Delta E_{fd} \end{bmatrix}$$

$$+ \begin{bmatrix} 0 & 0 \\ \frac{-K_{pv}}{M} & \frac{-K_{pm}}{M} \\ \frac{-K_{qv}}{T'_{do}} & \frac{-K_{qm}}{T'_{do}} \\ \frac{-K_{vv}}{T_A} & \frac{-K_{vm}}{T_A} \end{bmatrix} \begin{bmatrix} \Delta V_{dc} \\ \Delta m_2 \end{bmatrix}, \tag{25}$$

where:

ΔV_{dc}:   the deviation of the coupling capacitance voltage between converters and

Δm_2:   the deviation of the amplitude modulation ratio of converter 2.

Using Equations 24 and 25, the Phillips-Heffron model of the system can be obtained. Figure 3 shows this model including IPFC. This model has 16 constants, which are presented in Table 1 and are functions of the system parameters and the initial operating condition.

Table 1. Phillips-Heffren model constants for system with IPFC.

K_i	Value	K_i	Value
K_1	0.3837	K_5	0.0237
K_2	-0.1717	K_6	1.0659
K_{pv}	0.1092	K_{vv}	-0.0009
K_{pm}	1.1562	K_{vm}	-0.0025
K_3	3.6667	K_7	0.0139
K_4	-0.7350	K_8	-0.6890
K_{qv}	0.0509	K_9	0.0023
K_{qm}	0.1249	K_{cm}	-0.0397
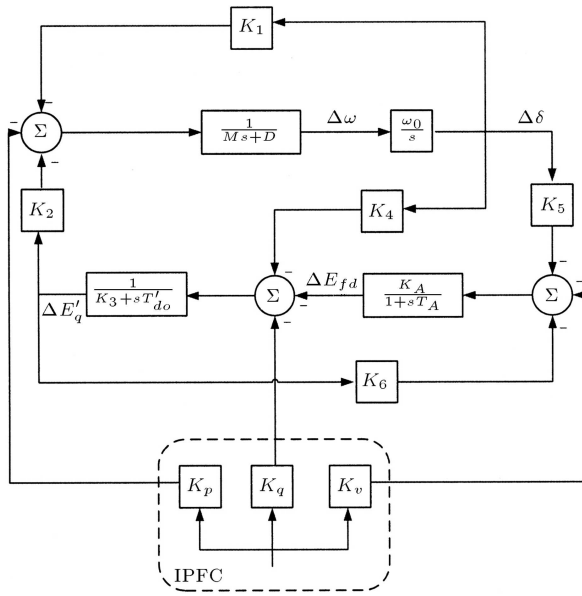
Figure 3. Phillips-Heffron model of a single-machine infinite-bus system with IPFC controller to create a proper amplitude modulation ratio for the second converter $P_{e(\mathrm{ref})}$ is the output power of the generator in the operating condition [7].
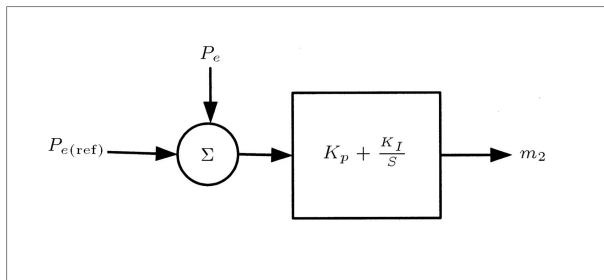
POWER SYSTEM OSCILLATION DAMPING CONTROLLER

A damping controller as illustrated in Figure 4 is provided to improve the damping of power system oscillations. This damping controller consists of three cascade-connected blocks. The first block compares the output power of the generator with reference power $(P_{e(\mathrm{ref})})$. Then, the error is applied to a PI.

DIGITAL SIMULATIONS

In order to understand the effect of IPFC on damping low frequency oscillations, digital simulations using the MATLAB simulink toolbox are undertaken in two cases: With and without IPFC.

When there is no IPFC in the system, the Phillips-Heffron model constants are as presented in Table 2 [8].

Figures 5 to 12 show the numerical results. Fig-

Figure 4. Structure of power system oscillation damping controller.

Table 2. Phillips-Heffren model constants for system without IPFC.

| i	K_i
1	3.2944
2	0.8533
3	1.2308
4	0.0640
5	-0.0150
6	0.9220

ures 5 to 8 illustrate power system oscillations when there is no IPFC in the system. These figures are related to the two values for the damping coefficient. Figures 5 and 6 show the rotor angle deviations and rotor speed deviations, respectively, for a damping coefficient equal to zero and, in Figures 7 and 8, those for a damping coefficient equal to 2. In the
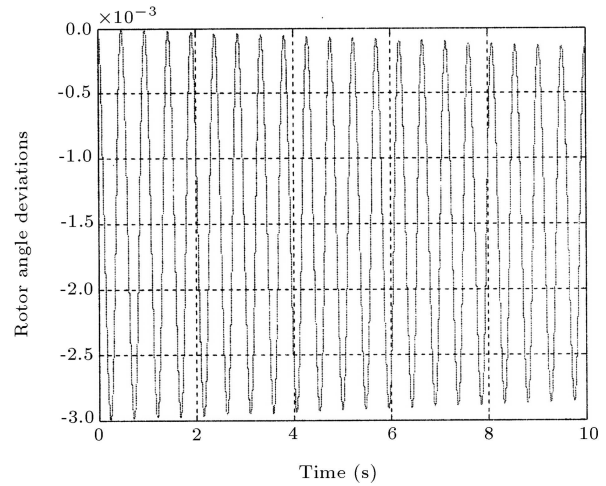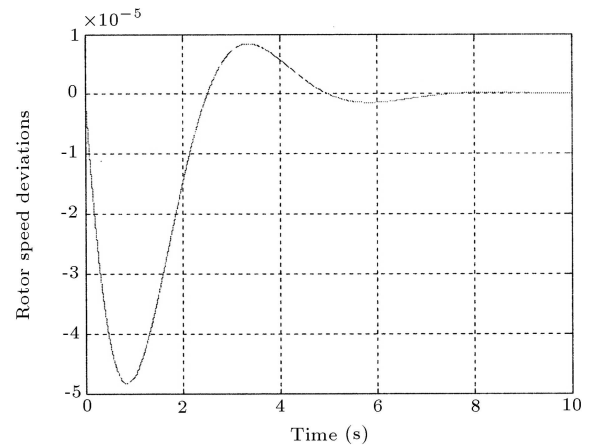

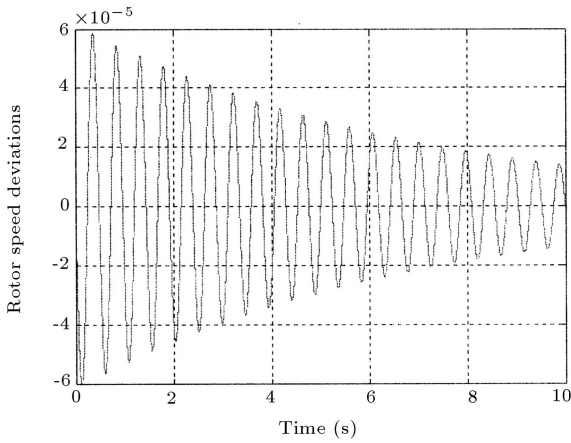**Figure 5.** Rotor angle deviation for $D = 0$ without IPFC.
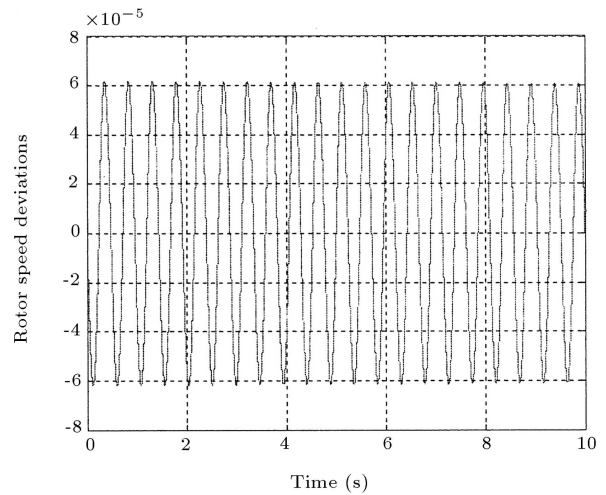
Figure 6. Rotor speed deviation for $D = 0$ without IPFC.
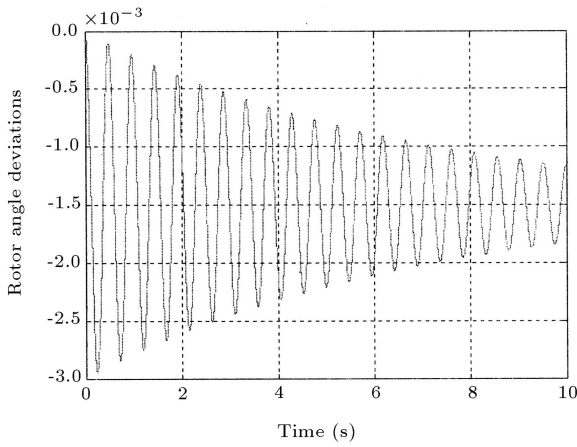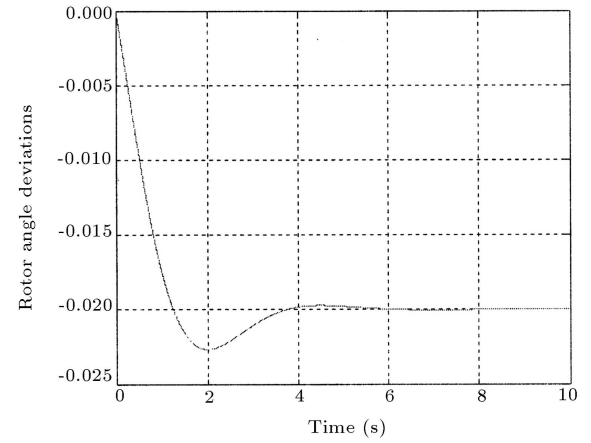
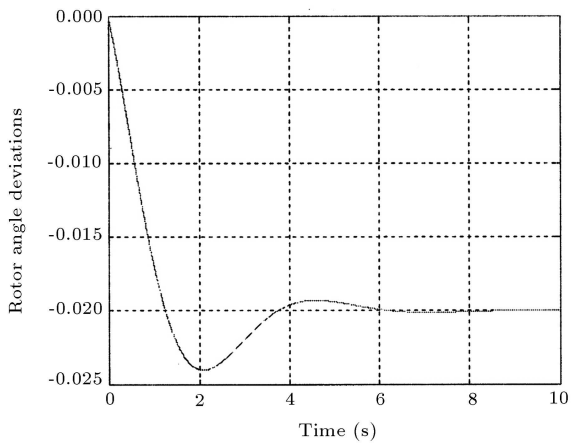**Figure 7.** Rotor angle deviation for $D = 2$ without IPFC.

Figure 8. Rotor speed deviation for $D = 2$ without IPFC.

Figure 9. Rotor angle deviation for $D = 0$ with IPFC.

Figure 10. Rotor speed deviation for $D = 0$ with IPFC.

Figure 11. Rotor angle deviation for $D = 2$ with IPFC.

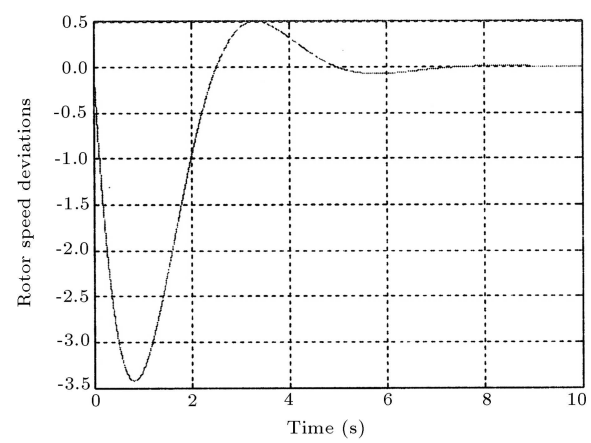**Figure 12.** Rotor speed deviation for $D = 2$ with IPFC.

same way, Figures 9 to 12 illustrate power system oscillations when IPFC is taken into account. Figures 9 and 10 show the rotor angle deviations and rotor speed deviations, respectively, for a damping coefficient equal to zero and Figures 11 and 12 show those for a damping coefficient equal to 2.

From these results, it can be seen that IPFC has significant effects on damping inter-area oscillations. These effects decrease the amplitude and frequency of power system oscillations. Moreover, oscillations will be damped faster.

The results indicate, not only the superior capability of the IPFC in power applications, but also suggest a powerful capacity for transient stability

improvement and power oscillation damping.

CONCLUSIONS

Using a Power System Stabilizer (PSS) is a simple, effective and economical method for increasing power system oscillation stability. Although the damping duty of FACTS controllers is not often their primary function, their potential for damping low frequency oscillations has attracted interests.

The Interline Power Flow Controller (IPFC) is a FACTS controller for series compensation, with the unique capability of power flow management between multi-lines of a substation.

IPFC is a multitask controller, which plays an effective role in damping inter-area oscillations. In this paper, this function of IPFC has been investigated and numerical results have emphasized its significant effect. In fact, even if there were no damping coefficients in the power systems, the IPFC would dampen low frequency oscillations, in addition to its other capabilities.

The purpose of this paper is to illustrate damping oscillations by IPFC.

A single machine-infinite bus model, integrated with IPFC, is used and the linearized model is established. Using this model, the Phillips-Heffron model of the system for steady state digital simulations is derived. The results obtained from digital simulations by the MATLAB simulink toolbox, indicate that IPFC has significant effects on the damping of inter-area oscillations.

These effects decrease the amplitude and frequency of power system oscillations. Therefore, oscillations will be damped faster.

The results indicate the superior capability of the IPFC in power applications and suggest a powerful capacity for transient stability improvement and power oscillation damping.

Only one of the variables of the injected voltage of the other line can be independently controlled. The voltage of coupling capacitance between two VSC-based converters is used as a state variable and the output power of the generators is a proper feedback for constructing an amplitude modulation ratio for the second converter.

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APPENDIX A

MATLAB simulink block diagram for simulation without IPFC (Figure A1).

APPENDIX B

MATLAB simulink block diagram for simulation with IPFC (Figure B1).

APPENDIX C

Operating conditions and parameters are as follows:

Generator:

$$M = 2H = 6 \text{ s}, \qquad D = 2, \qquad T'_{do} = 5.044 \text{ s},$$

$$X_d = 0.1 \text{ pu}, \qquad X'_d = 0.025 \text{ pu}, \qquad X_q = 0.06 \text{ pu}.$$

Excitation system:

$$K_A = 0.5, \qquad T_A = 0.005 \text{ s}.$$

Converter transformers:

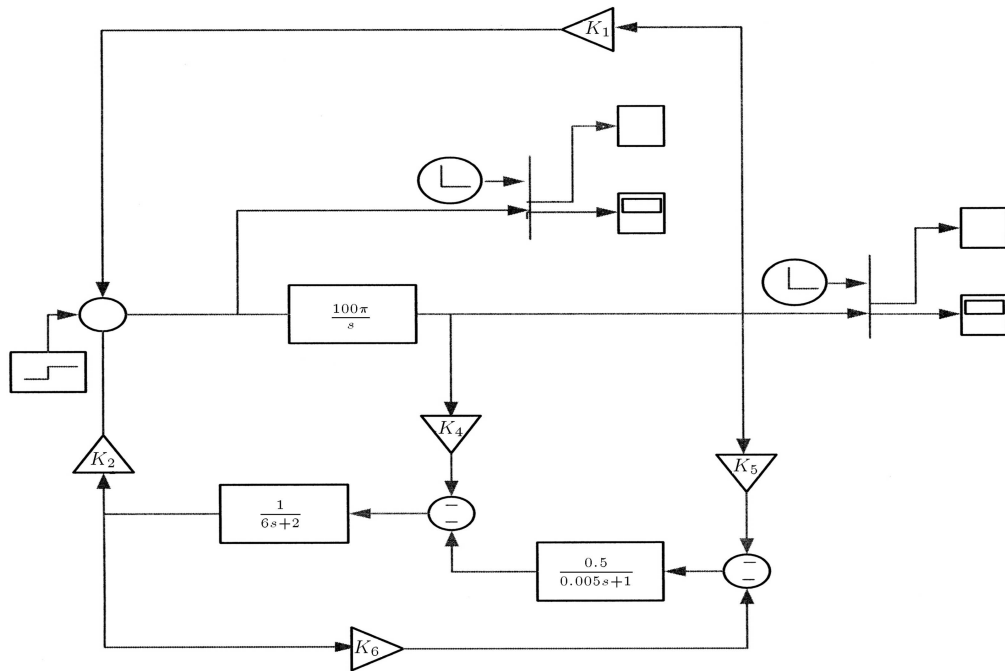$$X_t = 0.1 \text{ pu}.$$

Converter parameters:

$$m_1 = 0.15, \quad \delta_1 = 15°, \quad m_2 = 0.10, \quad \delta_2 = 22°.$$

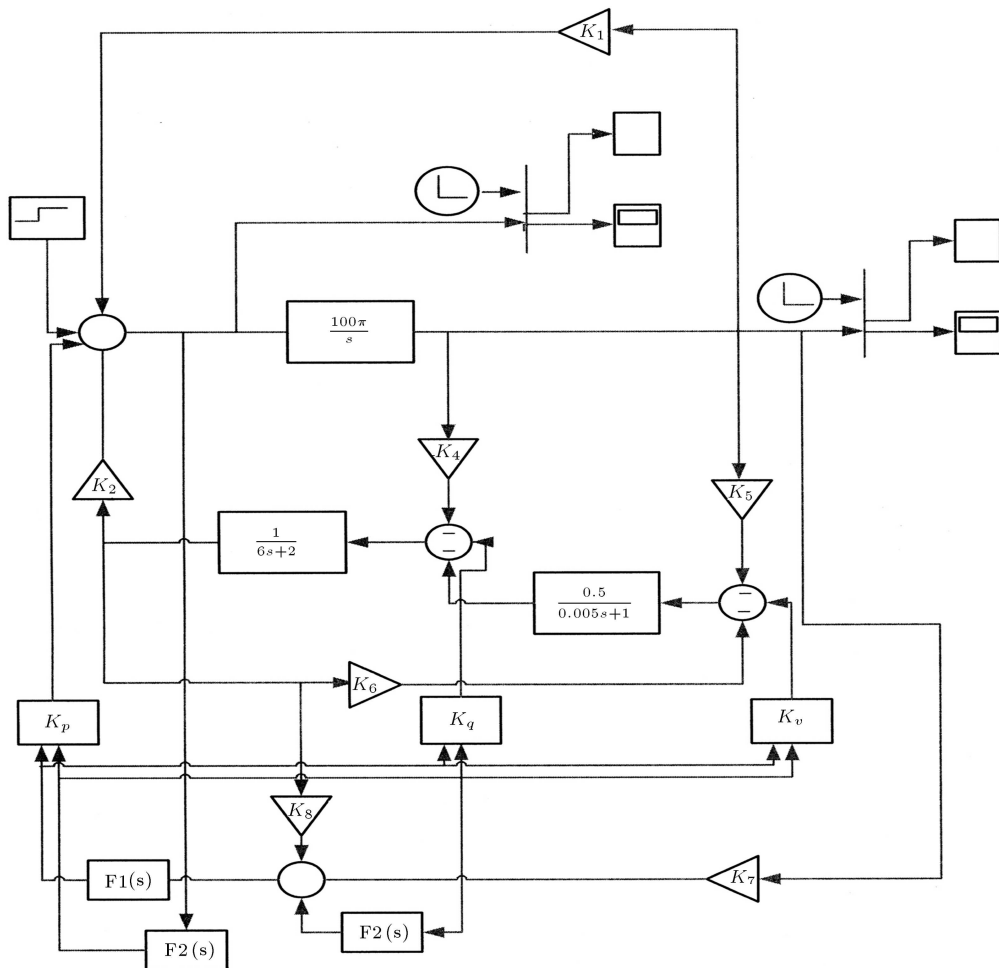Transmission line transformers:

$$X_L = 0.2 \text{ pu}, \qquad X_S = 0.2 \text{ pu}.$$

DC link parameters:

$$V_{dc} = 0.50 \text{ pu}, \qquad C = 1.0 \text{ pu}.$$

Figure A1. MATLAB simulink block diagram for simulation without IPFC

Figure B1. MATLAB simulink block diagram for simulation with IPFC