Power System Transient Stability Improvement by the Interline Power Flow Controller (IPFC)

Jun Zhang  Student Member (The University of Tokyo, zhang@syl.t.u-tokyo.ac.jp)
Akihiko Yokoyama  Member (The University of Tokyo, yokoyama@syl.t.u-tokyo.ac.jp)

Keywords: energy function, FACTS, IPFC, transient stability

As the consequence of fast growing demands on active and reactive power control and the rapid development of power electronic technology, power electronic-based equipments, under the generic name of the flexible AC transmission systems (FACTS) devices, are being developed in the field of modern power systems. Most FACTS devices have demonstrated their ability to significantly increase the transmission capabilities of the network and considerably enhance the security of the system, because they can control most parameters related to the operation of transmission systems with a quick response. Now FACTS technology is regarded as one of emerging technologies for power system security improvement. Since power system stability is an important problem for secure system operation and transient instability has been the dominant stability problem on most systems, transient stability improvement, which is one of the main applications of FACTS devices, has been attracting much interest of researchers, utilities and manufacturers.

Of all the FACTS devices, the combined compensators such as the unified power flow controller (UPFC) and the interline power flow controller (IPFC) are regarded as the most powerful and versatile ones. Both the UPFC and IPFC are based on the self-commutated, voltage-sourced switching converters (VSCs) coupled via a common DC voltage link. Unlike the UPFC, the IPFC employs at least two VSCs respectively connected in series with different lines, which can address the problem of compensating multiple transmission lines at a given substation. Figure 1(a) shows the schematic representation of a two-converter IPFC.

Compared with shunt compensators, series compensators are more effective in controlling the transmitted power, which is closely related to power system transient stability. Thus, static series compensators and combined compensators would be a better choice to improve transient stability and to damp the electromechanical oscillations. Various studies have been carried out on this topic, however, there is very few open literature on the application of IPFC to the power system transient stability improvement. Therefore, such a study is presented in this paper.

Fundamental factors in this study include proper modelling of IPFC and development of control strategies. The power injection model of IPFC is proposed in this paper as shown in Fig. 1(b). After the power injection model is obtained, control laws are derived based on energy function analysis for the application of IPFC to the single-machine infinite-bus (SMIB) system and multimachine systems respectively. Locally measurable variables are chosen to be the input signals to guarantee the reliability and reduce the complexity of the control system. Numerical simulations on an SMIB system shown in Fig. 2 and a multimachine system shown in Fig. 3 verified the effectiveness of the model and the control laws. It can be concluded that the IPFC is a very powerful FACTS device for improving power system transient stability and damping electromechanical oscillations.

---

Fig. 1. Schematic representation of a two-converter IPFC (a) and its power injection model (b)

Fig. 2. Schematic diagram of the SMIB system embedded with an IPFC

Fig. 3. IEEE 3-machine 9-bus system embedded with an IPFC
Power System Transient Stability Improvement by the Interline Power Flow Controller (IPFC)

Jun Zhang∗ Student Member
Akihiko Yokoyama† Member

This paper presents a study on the power system transient stability improvement by means of interline power flow controller (IPFC). The power injection model of IPFC in transient analysis is proposed and can be easily incorporated into existing power systems. Based on the energy function analysis, the operation of IPFC should guarantee that the time derivative of the global energy of the system is not greater than zero in order to damp the electromechanical oscillations. Accordingly, control laws of IPFC are proposed for its application to the single-machine infinite-bus (SMIB) system and the multimachine systems, respectively. Numerical simulations on the corresponding model power systems are presented to demonstrate their effectiveness in improving power system transient stability.

Keywords: energy function, FACTS, IPFC, transient stability

1. Introduction

As the consequence of fast growing demands on active and reactive power control and the rapid development of power electronic technology, power electronic-based equipments, under the generic name of the flexible AC transmission systems (FACTS) devices, are being developed in the field of modern power systems. The ability of FACTS devices to control most parameters related to the operation of transmission systems, with a quick response, has significantly increased the transmission capabilities of the network while considerably enhancing the security of the system. In Ref. (2), FACTS technology is listed as one of the new and emerging technologies to assist in power system security. As an important problem for secure system operation, power system stability has long been recognized and investigated, and transient instability has been the dominant stability problem on most systems, drawing much of the industry’s attention concerning system stability. Damping oscillations of power flows, which is one of the main applications of FACTS devices, has been attracting much interest of researchers, utilities and manufacturers.

There are many ways to classify the FACTS devices into appropriate categories. According to the different technical approaches to their realization, the FACTS devices fall into the following two groups. The first group includes the Static Var Compensator (SVC), Thyristor-Controlled Series Capacitor (TCSC), and Thyristor-Controlled Voltage and Phase Angle Regulators (TCVR and TCPAR), etc., which use the conventional thyristor valves (switches) to control reactive impedances and tap-changing transformers. The second group employs self-commutated, voltage-sourced switching converters (VSCs). Typical representatives are the Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controller (UPFC) and Interline Power Flow Controller (IPFC), etc. The latter two are the most powerful and versatile of all the FACTS devices. According to the ways that they are connected to the power systems, these devices can be classified into three groups, namely static shunt compensators, static series compensators and the combined compensators. Static shunt compensators, which are shunt connected to the transmission lines, include SVC and STATCOM, etc., whereas static series compensators include TCSC and SSSC, etc. UPFC and IPFC are the representatives of the combined compensators, which are the combinations of components in the former two groups. Among all the FACTS devices, the IPFC, for the first time, extends the capability of independently influencing the active and reactive power flows to simultaneous series compensation of multiple transmission lines.

Compared with shunt compensators, series compensators are more effective in controlling the transmitted power, which is closely related to power system transient stability. Thus, static series compensators and combined compensators would be a better choice to improve transient stability and to damp the electromechanical oscillations. Various studies have been carried out on this topic, however, there is very few open literature on the application of IPFC to the power system transient stability improvement. Therefore, such a study is presented in this paper.

Fundamental factors in this study include proper modelling of IPFC and development of control strategies. After the power injection model of IPFC is obtained, control strategies have to be developed. One possibility is to use energy functions like Refs. (5)–(8). In this paper, an approach similar to the one presented in Ref. (8), in which the design of external-level controller of UPFC is proposed, is adopted to derive the control laws of IPFC. Locally measurable variables are chosen to be the input signals to guarantee the reliability and reduce the complexity of the control system.

∗ Department of Electrical Engineering, The University of Tokyo
7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656

© 2008 The Institute of Electrical Engineers of Japan.
The paper is organized in the following way. In section 2, the power injection model of IPFC is presented. Control laws are derived in section 3 based on energy function analysis for the application of IPFC to the SMIB system and multimachine systems respectively. Subsequently, the effectiveness of the model and the control laws are verified by numerical simulations in section 4. Finally, conclusions are outlined in section 5 to complete the paper.

2. Power Injection Model of IPFC

Without loss of generality and for the sake of simplicity, an IPFC consisting of two VSCs is shown in Fig. 1. It can be regarded as the combination of two SSSCs connected via a common dc voltage link represented by a capacitor. Based on the equivalent circuit diagram of UPFC and its phasor diagram presented in Ref. (7), Figure 2 shows the equivalent circuit diagram of IPFC where the VSCs are represented by synchronous voltage sources in series with the transformer leakage reactances \( X_{ij} \) and \( X_{ik} \). \( V_{se ij} \) and \( V_{se ik} \) are the injected controllable series voltages. Their phasor diagrams are shown in Fig. 3. Here \( V_j' \) and \( V_k' \) are voltages at the two fictitious buses between the reactances and the synchronous voltage sources. Italic bold letters in this paper denote complex voltages.

The two series injected voltages can be expressed as follows:\(^n\):

\[
V_{se in} = r_n e^{j\gamma_n} V_i, \quad \text{where} \quad n = j, k. \tag{1}
\]

Here \( r_n \) and \( \gamma_n \) are the controllable parameters of the injected series voltages, where \( r_n = \frac{V_{se in}}{V_i} \) and \( \gamma_n \) is the relative angle of \( V_{se in} \) with respect to \( V_i \). \( r_n \) varies in the range 0 to \( r_{n,\text{max}} \), and \( \gamma_n \) in the range 0 to 2\( \pi \).

The power injection model of IPFC has been presented in Ref. (10), where the injected series voltages are expressed by the absolute voltage magnitudes and the relative voltage angles with respect to the slack bus. In order to incorporate the model into the control strategies easily, the positive direction of power injections is reversed as shown in Fig. 4. By substituting the variables of power injections in Ref. (10) with their counterparts used in this paper, power injections can be rewritten as follows:

\[
P_{inj,j} = V_i^2 \sum_{n=j,k} r_n (1/X_{in}) \sin(\gamma_n), \tag{2}
\]

\[
Q_{inj,j} = V_i^2 \sum_{n=j,k} r_n (1/X_{in}) \cos(\gamma_n), \tag{3}
\]

\[
P_{inj,m} = -r_n V_i V_n (1/X_{jm}) \sin(\theta_m + \gamma_n), \tag{4}
\]

\[
Q_{inj,m} = -r_n V_i V_n (1/X_{jm}) \cos(\theta_m + \gamma_n), \tag{5}
\]

where \( n = j, k \) and \( \theta_m = \theta_i - \theta_g \).

The power injections here can be regarded as fictitious loads. Thus the mismatch power equations at each bus should be written as follows:

\[
P_{m,m} - P_{inj,m} - P_{lm} - P_{line,m} = 0, \tag{6}
\]

\[
Q_{m,m} - Q_{inj,m} - Q_{lm} - Q_{line,m} = 0, \tag{7}
\]

where \( m = i, j, k \).

Here subscripts \( gm \) and \( line \) denote generation at bus \( m \), load at bus \( m \) and conventional transmitted power only through transmission lines leaving bus \( m \), respectively.

When losses are ignored and no independent energy source or storage is applied, the following active power balance equation exists:\(^n\):

\[
\sum_{m=i,j,k} P_{inj,m} = 0 \tag{8}
\]

3. Control Strategy of IPFC

An energy function, which has a clear physical meaning, is a very useful tool to analyze power system transient stability. In Ref. (11), the energy function for an \( n \)-machine system in the COI (center of inertia) notation is

\[
v(\theta, \omega) = E_{KE}(\dot{\theta}) + E_{PE}(\theta) \tag{9}
\]

where \( E_{KE} \) is the system kinetic energy and \( E_{PE} \) is the system potential energy, which equals 0 at the post-fault stable equilibrium point. Detailed explanation of Eq. (9) and expressions of the terms can be found in Ref. (11). In order to
damp the electromechanical oscillations, the global energy of the system should not be increased\(^\text{(5)}\), i.e., the IPFC control must make the system satisfy the following requirement:

\[
\frac{d}{dt}(\psi) \leq 0 \tag{10}
\]

The power injection model of IPFC can be easily incorporated into exiting derivation of the time derivative of energy function presented in Refs. (7) and (8). So the time derivative of the energy function of a power system embedded with an IPFC has the following form:

\[
\frac{d}{dt}(\psi) = -P_{\text{inj}i} \frac{d}{dt}(\dot{\theta}_i) - P_{\text{inj}j} \frac{d}{dt}(\dot{\theta}_j) - P_{\text{inj}k} \frac{d}{dt}(\dot{\theta}_k) - Q_{\text{inj}i} \frac{d}{dt}(\ln V_i) - Q_{\text{inj}j} \frac{d}{dt}(\ln V_j) - Q_{\text{inj}k} \frac{d}{dt}(\ln V_k) \tag{11}
\]

where

\[
\dot{\theta}_i = \theta_i - \dot{\delta}_{\text{COI}}, \quad n = i, j, k, \quad \dot{\delta}_{\text{COI}} = \frac{1}{n_g} \sum_{m=1}^{n_g} M_m \delta_m
\]

Here, \(\delta_m\) is the rotor angle of machine \(m\); \(n_g\) is the number of generators.

Since the influences of the terms with reactive power injections are negligible\(^\text{(5)}\), Eq. (11) can be written as follows:

\[
\frac{d}{dt}(\psi) = -P_{\text{inj}i} \frac{d}{dt}(\dot{\theta}_i) - P_{\text{inj}j} \frac{d}{dt}(\dot{\theta}_j) - P_{\text{inj}k} \frac{d}{dt}(\dot{\theta}_k) \tag{12}
\]

Because of Eq. (8), we have

\[
\frac{d}{dt}(\psi) = -P_{\text{inj}i} \frac{d}{dt}(\dot{\theta}_i) - P_{\text{inj}j} \frac{d}{dt}(\dot{\theta}_j) - P_{\text{inj}k} \frac{d}{dt}(\dot{\theta}_k) \tag{13}
\]

Thus \(\dot{\delta}_{\text{COI}}\) no longer appears in the expression of the time derivative of energy function, which now is only determined by the IPFC active power injections and the time derivatives of the corresponding bus voltage angles. All the information needed here is locally measurable. The control laws of IPFC can be derived based on Eq. (13), as explained in the following two subsections.

As the classical model of the synchronous generators is adopted in this paper, the swing equations are:

\[
\frac{d\delta_i}{dt} = \omega_i - \omega_N = \Delta\omega_i \tag{14}
\]

\[
\frac{d\Delta\omega_i}{dt} = \frac{1}{M_i}(P_{mi} - P_{ei}) \tag{15}
\]

where

\[
\delta_i: \text{rotor angle of generator } i \\
\omega_i: \text{rotor angular velocity of generator } i \\
\omega_N: \text{the synchronous speed} \\
M_i: \text{inertia constant of generator } i \\
P_{mi}: \text{mechanical power input of generator } i \\
P_{ei}: \text{electric power output of generator } i
\]

The mechanical power input of each generator is assumed to be constant during the entire period of simulation. Obviously, here calculation of \(P_{ei}\) is one of the fundamental problems of this study.

### 3.1 IPFC Control Law in SMIB System

The SMIB system is a very useful example system to study the transient stability improvement by IPFC control. As shown in Fig. 5, a two-converter IPFC is embedded in the SMIB system. The VSCs are in series with two identical transmission lines represented by their reactance \(X_L\). Here \(X_L\) represents the transformer reactance.

As shown in Fig. 6, the generator can be represented by the transient reactance \(X'_j\) and the voltage \(E_q^{(g)}\) behind it, the magnitude of which remains constant at its predisturbance value during the transient process. In Fig. 6, the VSCs of the IPFC are represented by two series synchronous voltage sources. The leakage reactances of the two series transformers are equal, both of which can be represented by \(X_L\). Thus, with the power injection model of IPFC proposed in the last section, we can model the SMIB system embedded with one IPFC into a circuit model with fictitious loads shown in Fig. 7, where \(X_1 = X'_j + X_T\) and \(X_2 = X_S + X_L\). \(X_2/2\) is the equivalent reactance of the two parallel electric components represented by reactance \(X_T\).

Since the voltage at the infinite bus remains constant all the time, i.e., \(d\theta_i/dt = d\theta_j/dt = 0\), the time derivative of energy function can be further simplified as follows:

![Fig. 5. Schematic single line diagram of the SMIB system embedded with an IPFC](image)

![Fig. 6. Equivalent circuit of the SMIB system embedded with the IPFC](image)
where 

\[
\frac{d}{dt}(\theta_i) = -\frac{P_{mij}}{X_i} \sin(\gamma_n) \cdot \sum_{n=1,2} r_n \sin(\gamma_n) \cdot \sum_{n=1,2} r_n \cos(\gamma_n) \cdot \sin(\theta_i + \gamma_n) - \frac{P_{mij} + P_{line}}{X_i} \sin(\theta_i - \gamma_n) \cdot \sum_{n=1,2} \gamma_n \cos(\theta_i + \gamma_n) \quad \text{(17)}
\]

Here \( K \) is an appropriate positive coefficient.

Substituting the reactances in Eqs. (2)–(5) with the corresponding reactances shown in Fig. 7, we have:

\[
P_{mij} = \frac{V_i^2}{X_i} \sum_{n=1,2} r_n \sin(\gamma_n) \quad \text{(18)}
\]

\[
Q_{mij} = \frac{V_i^2}{X_i} \sum_{n=1,2} r_n \cos(\gamma_n) \quad \text{(19)}
\]

\[
P_{mjk} = -\frac{V_i V_h}{X_2} \sum_{n=1,2} r_n \sin(\theta_i + \gamma_n) \quad \text{(20)}
\]

\[
Q_{mjk} = -\frac{V_i V_h}{X_2} \sum_{n=1,2} r_n \cos(\theta_i + \gamma_n) \quad \text{(21)}
\]

The generator's electric power output \( P_e \) can be expressed as follows:

\[
P_e = E' V_i \sin(\delta - \theta_i) \quad \text{(22)}
\]

Thus, the problem left is to determine the value of \( V_i \) and \( \theta_i \).

Consider the mismatch power equations at bus \( i \). The mismatch active power equation (6) can be rewritten as:

\[
P_{mij} + P_{line,i} = 0 \quad \text{(23)}
\]

where

\[
P_{line,i} = \frac{E' V_i}{X_i} \sin(\theta_i - \delta) + \frac{V_i V_h}{X_2} \sin(\theta_i) \quad \text{(24)}
\]

The mismatch reactive power equation (7) can be rewritten as follows:

\[
Q_{mij} + Q_{line,i} = 0 \quad \text{(25)}
\]

where

\[
Q_{line,i} = \frac{V_i^2}{X_1} - \frac{V_i E_i^\prime \cos(\theta_i - \delta)}{X_1} + \frac{V_i^2 - V_i V_h \cos(\theta_i)}{X_2} \quad \text{(26)}
\]

In this case, the active power balance equation of IPFC can be rewritten as:

\[
P_{in,i} + P_{in,j} = 0 \quad \text{(27)}
\]

Eqs. (17), (23), (25) and (27) compose a set of nonlinear equations. With the expression of the active power injection at bus \( i \) in mind, we set \( r_1 \) and \( r_2 \) to their maximum values in order to fully explore the damping capability of the two VSCs. Thus by solving the set of nonlinear equations mentioned above, \( V_i \) and \( \theta_i \) can be obtained and so can the generator's electric power output \( P_e \) be calculated. Then the desired time solution for \( \delta \) can be obtained by numerical integration.

### 3.2 IPFC Control Law in Multimachine Systems

In the multimachine systems, unlike the SMIB system, voltage angle at every bus is constantly varying, so no time derivative of any bus voltage angle is equal to zero. Accordingly, the time derivative of energy function expressed by Eq. (13) can not be simplified in the same way as the SMIB system case. Intuition may lead to the following solution to satisfy the damping requirement that \( dv/dt \) is not greater than zero:

\[
P_{mij} = K_1 \frac{d}{dt}(\theta_i) \quad \text{(28)}
\]

\[
P_{mik} = K_2 \frac{d}{dt}(\theta_i) \quad \text{(29)}
\]

\[
\sum_{n=1}^{n=1,2} P_{n} = \sum_{n=1}^{n=1,2} K_{n} \frac{d}{dt}(\theta_i) = 0 \quad \text{(29)}
\]

where \( K_1, K_2, K_3 \) are proper positive coefficients.

However, due to the active power invariance of IPFC, i.e.,

\[
\sum_{n=1}^{n=1,2} P_{n} = \sum_{n=1}^{n=1,2} K_{n} \frac{d}{dt}(\theta_i) = 0 \quad \text{(29)}
\]

finding these three coefficients may not be an easy task. Simplification of Eq. (13) is necessary.

One possible way to simplify the expression of the time derivative of energy function is to let one active power injection be equal to zero. Thus, the remainder two active power injections have the same absolute value, which is vital to the simplification process. The details are explained in the following.

Without loss of generality, we suppose the leakage reactances of the two series transformers are equal, i.e. \( X_{ij} = X_{ik} = X \). If we let \( r_j \) be equal to \( r_k \) and \( \gamma_j \) be equal to minus \( \gamma_k \), we have:

\[
P_{mij} = V_i^2 (1/X) \sum_{n=1,2} r_n \sin(\gamma_n) = 0 \quad \text{(30)}
\]

and Eq. (8) can be rewritten as:

\[
P_{mij} + P_{mik} = 0 \quad \text{(31)}
\]

Now, the expression of the time derivative of energy function can be simplified as follows:

\[
\frac{d}{dt}(\dot{v}) = -P_{mij} \frac{d}{dt}(\theta_i) - P_{mik} \frac{d}{dt}(\theta_k)
\]

\[
= -P_{mij} \frac{d}{dt}(\theta_i - \theta_k) \quad \text{(32)}
\]

The technique used in the previous subsection can be applied...
here. If we determine $P_{m,j}$ by the following equation, the time derivative of energy function will always be not greater than zero.

$$P_{m,j} = K \frac{d}{dt}(\theta_j - \theta_k) \quad \quad \quad \quad \quad \quad \quad \quad (33)$$

where $K$ is an appropriate positive coefficient.

The power system can be expressed in the following general form consisting of a set of first-order differential equations

$$\dot{x} = f(x, y) \quad \quad \quad \quad \quad \quad \quad \quad (34)$$

and a set of algebraic equations

$$0 = g(x, y) \quad \quad \quad \quad \quad \quad \quad \quad (35)$$

where $x$ represents the state vector of the system, and $y$ includes system bus voltages and IPFC parameters. In this case, Eq. (34) comprises Eqs. (14) and (15), and Eq. (35) includes mismatch power equations at all buses except the internal machine buses, active power invariance of IPFC expressed by Eq. (31), and Eq. (33). Solving the above overall system equations, we can get the dynamic response of the multimachine system. Actually the above description also applies to the previous subsection. In the case of the SMIB system, the set of algebraic Eq. (35) has a much simpler form, which is only composed of Eqs. (17), (23), (25) and (27) as discussed in the previous subsection.

4. Numerical Simulations

4.1 The SMIB System Case  In the simulations of this subsection, the dynamic behaviour of the SMIB system embedded with an IPFC shown in Fig. 5 is studied. The system is modelled in the way proposed in section 3 and all the parameters are given in the appendix. The performance of the control law is examined.

The system is subject to a double line-to-ground self-clearing fault which occurs at 0.19 s and clears at 0.45 s with no change in the system configuration. The location of the fault is shown in Fig. 8. The rotor angle response of the SMIB system without IPFC is shown in Fig. 9. In case the IPFC is embedded, since the high magnitude of the fault current passing through the series transformer would make it necessary to reduce the inserted series voltage to keep the converter VA within the limit $10 \text{ p.u.}$, the effect of the IPFC is very limited during the fault and, accordingly, in the simulations the IPFC is active only after the fault clears.

As shown in Fig. 9, without the presence of IPFC, the generator loses synchronism rapidly, because the actual clearing time is much longer than the critical clearing time. The damping effect of the IPFC is demonstrated in Fig. 10, where $r_{1,\text{max}} = r_{2,\text{max}} = 0.34$ and $K = 0.21$. Here, once $r_{1,\text{max}}$ and $r_{2,\text{max}}$ are given, trials are necessary for the precise determination of an appropriate $K$ after its rough range is determined by Eqs. (17) and (18). The control law proves to be very effective. Figure 11 shows the variation of $\gamma_1$ and $\gamma_2$ of the
two VSCs’ injected voltages. It is reasonable that $\gamma_1$ and $\gamma_2$ converge to different values, otherwise the two VSCs will be exactly the same and both of them will either generate or absorb active power, which violates the active power invariance of IPFC, i.e. Eq. (8). By the time around 5 s, the oscillation has almost been fully damped, so $d\theta_i/dt \approx 0$ and $P_{\text{in},i} = K(d\theta_i/dt) \approx 0$ too. As shown in Fig. 11, at the end $\gamma_2 \approx \gamma_1 + 180^\circ$. This is to guarantee the above law, as can be seen in Eq. (18). Fig. 12 shows the active power transferred between the two VSCs. The positive direction is taken to be from VSC2 to VSC1. $K$ is a very important parameter reflecting the damping capability. If $r_1$ and $r_2$ are respectively set to the same values in different cases, the larger $K$ is, the faster the electromechanical oscillation is damped, as shown in Fig. 13, where $r_{1,\text{max}} = r_{2,\text{max}} = 0.4$. Large enough $r_1$ and $r_2$ are necessary for any properly given $K$. Once $K$ is determined, variation of $r_1$ and $r_2$ has little impact on the rotor angle response.

4.2 The Multimachine System Case In the simulations of this subsection, the dynamic behaviour of the multimachine system embedded with an IPFC is studied. The control law proposed in section 3 is tested and its effect on the first swing stability of the power system is examined. The IEEE 3-machine 9-bus system is chosen to be the model power system. All loads are represented by constant equivalent impedances to ground during simulations. Bus 4 is selected to be the common bus connected to the two VSCs, which are embedded in lines 4 and 5 respectively as shown in Fig. 14. A three-phase fault occurs on line 6 near bus 7 at 0.0 s, and is cleared by the simultaneous opening of breakers at both ends of the line. Without the presence of the IPFC, the critical clearing time is determined to be between 0.162
and 0.163 s by numerical simulation. If the fault is cleared at 0.18 s, the rotor angle differences between the generators increase without limit as shown in Fig. 15. With IPFC control, the system can be stabilized as shown in Figs. 16 and 17. Like the previous subsection, the IPFC is also active only after the fault is cleared. Similarly, here $K$ reflects the damping capability. In Figs. 16 and 17, different values of $K$ are tested and their performances are compared. It can also be concluded that the larger $K$ is, the faster the system is stabilized.

There is active power exchange between the two VSCs too. The active power transferred from VSC2 to VSC1 is shown in Fig. 18 when $K = 11$. The variations of the relative angles $\gamma_1$ and $\gamma_2$ of the two VSCs in this case are shown in Fig. 19, which have the same absolute value but the opposite sign all the time. This result is in line with the setting made in subsection 3.2 that $\gamma_1$ is always equal to minus $\gamma_2$. The two series injected voltages have the same magnitude, say, $V_{se}$, which is plotted in Fig. 20. Figures 21 and 22 show the
dynamic response of the system at a different fault clearing time \(T_{\text{clear}}\) for comparison. Still here \(K = 11\).

5. Conclusion

The effect of the IPFC control on improving power system transient stability has been investigated. The power injection model of IPFC for transient analysis has been proposed, which can significantly simplify the process of incorporating the IPFC into existing power system models and energy function analysis. With this model, control laws are proposed for IPFC application to the SMIB system and multimachine systems respectively based on energy function analysis. This control strategy uses locally measurable variables, which can be easily obtained. Thus, the complexity of the control system is reduced and its reliability is improved. Numerical simulations demonstrate the effectiveness of the proposed control laws. And it is shown that the faster the global energy of the system can be decreased, the better the damping effect is. It can be concluded that the IPFC is a very powerful FACTS device for improving power system transient stability and damping electromechanical oscillations. In the future work, control systems, in which the simultaneous solution of the nonlinear equations is not necessary, will be developed.

Acknowledgment

The first author would like to thank Dr. Hua Xie from Beijing Jiaotong University for stimulating discussions.

(Manuscript received March 26, 2007, revised July 31, 2007)

References


Appendix

Parameters of the SMIB system embedded with an IPFC shown in Fig. 8

- infinite bus voltage magnitude \(V_b\): 1.0 p.u.
- transmission line reactance \(X_l\): 0.732 p.u.
- Transformer reactance \(X_T\): 0.138 p.u.
- transient reactance \(X'_T\): 0.295 p.u.
- inertia constant \(M\): 0.026 s/rad
- pre-fault \(E'_q\): 1.408 p.u.
- pre-fault rotor angle \(\delta\): 0.603 rad
- pre-fault generator’s electric power output \(P_e\): 1.0 p.u.
- IPFC series transformer leakage reactance \(X_S\): 0.05 p.u.

The above SMIB data are obtained by slightly modifying the SMIB system in Ref. (15), and the above \(X_S\) is in line with the one of UPFC in Ref. (9).

Jun Zhang (Student Member) was born in Xi’an, Shaanxi Province in the People’s Republic of China, on June 27, 1980. He received the B.Eng. degree in electrical engineering and automation and the M.Eng. degree in electrical engineering in 2002 and 2005, respectively, both from Tsinghua University, Beijing, P. R. China. He is currently a Ph.D. candidate at the University of Tokyo, Tokyo, Japan, with the Japanese Government’s MEXT scholarship. His research interests include flexible AC transmission systems and optimal power flow control. He is a student member of IEEE and IEEJ.

Akihiko Yokoyama (Member) was born in Osaka, Japan, on October 9, 1956. He received B.S., M.S., and Dr.Eng. from the University of Tokyo, Tokyo, Japan in 1979, 1981 and 1984, respectively. He has been with Department of Electrical Engineering, the University of Tokyo since 1984 and currently a professor in charge of Power System Engineering. He is a member of IEEE, IEEE and CIGRE.