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INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES
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THE STUDY OF UPFC EFFECTS ON TRANSIENT STABILITY OF MULTI MACHINE POWER SYSTEMS

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ABSTRACT

A unified power flow controller (UPFC) effects on transient stability of a multi machine power system has been introduced. Based on the combination of output results of time domain simulation (TDS) and transient energy function (TEF) analysis, the study of power system transient stability is converted to the study of transient stability of only one machine, the so called critical machine. The effects of UPFC in three basic control modes, namely, in-phase voltage control (IVC), quadrature voltage control (QVC) and shunt compensation control on the transient stability margin and for various fault clearing times has been studied. Based on acquired results, it can be seen that in-phase and quadrature voltage controls are the most effective on the improvement of transient stability margin. Also, ivc is more robust than other control modes against the increase of fault clearing time. The proposed method determines the critical machine based on the swing curves resulting from TDS, and then provides a stability margin (SM) of the critical machine with trivial computation by use of machine speeds and inertia constants. The method does not need to include a UPFC description equation in the transient energy function. The proposed method was successfully demonstrated on the 7-machine CIGRE tests system.

Key words: Critical machine, In-phase voltage control, Quadrature voltage control, Shunt compensation control, Stability margin

INTRODUCTION

Nowadays, with increased power transfer, transient and dynamic stability are of increasing importance for secure operation of power systems. The size and complexity of modern power systems has placed increased emphasis on the study of measures for improving the first swing transient stability, as the power capability of long distance transmission line is usually limited by the transient stability limit or margin. FACTS devices with a suitable control strategy have the potential to significantly improve the transient stability margin. This allows increased utilization of existing networks closer to their thermal loading capacity, and thus avoiding the need to construct new transmission lines. Amongst the available FACTS devices, the unified power flow controller (UPFC) is the most versatile and can be used to enhance system stability.

Study of UPFC effect on transient stability has been much discussed in the literature. In most cases, a study was performed on a simple single machine infinite bus or two area power systems and simulations were in time domain [1, 2, 3]. In other cases, a transient energy function or a general direct method of Lyapunov has been used [3, 4, 5, 6]. But, it should be noted that modeling of UPFC and including its controls in the system equations or transient energy functions for a multi machine power systems is a difficult task. It was shown that a combination of aspects and capabilities of two approaches, i.e. TDS and TEF, in the study of UPFC effects on transient stability is possible. The purpose of this paper is to determine the transient stability margin of a multi machine power system affected by UPFC in three basic control modes. This paper is organized as follows. In Sect. 2, a short review on the basis of transient stability analysis and UPFC structure and modeling is presented. Section 3

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describes the proposed method for studying UPFC effects on transient stability. Also, we provide some numerical test results and conclusions in Sects. 4 and 5, respectively

Transient stability analysis

Basic approaches

In a transient stability analysis of power systems, two major approaches, namely, time domain simulation (TDS) and Lyapunov direct method or transient energy function (TEF), are adopted. TDS provides the most accurate and reliable results. Its capability in modeling power systems is unlimited and inclusion of sophisticated system models and their controls in the analysis is not a difficult task. But, because of numerical integration from system dynamic equations, this method is not a fast approach. In addition, no significant information about degree of stability or instability is provided. Conversely, direct methods determine stability without explicit solution of system differential equations. Transient energy based methods are special forms of Lyapunov's second method, and a transient energy function indeed is an appropriate Lyapunov function in analysis of a power system's transient stability. This method has a good computational speed and generation capability and provides stability index or stability margin (SM); although, determination of stability margin is achieved with accuracy deterioration. Additionally, finding transient energy functions is difficult work. Therefore, many problems concerned with transient stability analysis will be solved if it is possible to combine the appropriate aspects of TEF with output results of TDS to find the stability margin by a hybrid method. In a large power system, for a given disturbance, only a few machines are severely disturbed. The dynamics of these machines, in general, dictate the stability of the entire system. It is expected that, for an unstable situation, one of the severely disturbed machines, called thecritical machine, initially loses synchronism and subsequently other severely disturbed machines may join the critical machine to form a larger group of unstable machines. Thus, checking the stability limit of only the critical machine that initiates the instability can assess the system stability. Observing the variation of machine angles generated by the TDS method can identify the critical machine. The machine that initially runs out of synchronism (or angle in the COA reference frame initially exceeds 180_) is considered to be the critical machine. Let the i th machine be the critical machine. Our objective is to find the SM of only the critical machine and investigate the effect of UPFC in various control modes on the stability margin of this machine. When the fault is cleared, the critical machine struggles to maintain stability by converting all of its KE into PE (if possible). During the energy conversion process, it is considered that the sum of potential and kinetic energies of the critical machine is constant because the injection of transient energy has already been ceased at fault clearing.

UPFC representation

UPFC is capable of both supplying and absorbing real and reactive power and consists of two AC/DC converters. One of the two converters is connected in series with the transmission line through a series transformer and the other in parallel with the line through a shunt transformer, as shown in Fig. 1. The DC side of the two converters is connected through a common capacitor that provides DC voltage for the converter operation. The power balance between the series and shunt inverters is a prerequisite to maintain a constant voltage across the DC capacitor. As the series branch of the UPFC injects a voltage of variable magnitude and phase angle it can exchange real power with the transmission line and thus improve the power flow capability of the line as well as its transient stability limit. The shunt converter exchanges a current of controllable magnitude and power factor angle with the power system. It is normally controlled to balance the real power absorbed from or injected to the power system by the series converter plus the losses by regulating the DC bus voltage at a desired value.

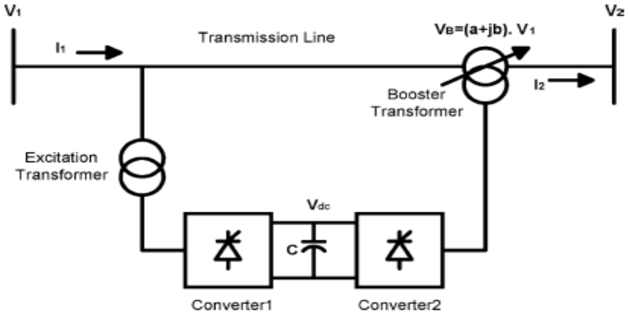


Fig. 1 UPFC schematic diagram

Various control strategies to control the series voltage magnitude and angle and the shunt current magnitude have been presented in the references [1, 2]. The series converter voltage phasor can be decomposed into in phase and Quadrature components with respect to the transmission line current. The in-phase and the Quadrature- voltage components are more readily related to the reactive and real power flows in the transmission system. During short-circuit and transient conditions, the decrease in real power can be stopped by controlling the Quadrature component of the series converter voltage and hence the improvement in transient stability. The series voltage in-phase component is either controlled by the reactive power flow deviation or voltage deviation at the injected bus where the UPFC is located. The UPFC is represented by the combination of a variable shunt susceptance, a shunt current source and a controllable series voltage source, as shown in Fig. 2. The variable shunt susceptance bs reflects the reactive compensation ability of the excitation converter. The controllable series voltage source VB represents the booster converter which inserts variable in-phase and quadrature voltage components in series with the line voltage. The shunt current source IC absorbs the same amount of real power Pc as is injected into the network by the controllable voltage source. This represents the DC power flow between the excitation converter and the booster converter. The generator output increases with increasing rotor angle even without the UPFC control action, and this action opposes the widening of the rotor angle. The transient stability can be enhanced by providing additional synchronizing power (and hence synchronizing torque), which is in phase with the rotor angle deviation as:

$$\Delta T_e = T_s \cdot \Delta\delta + T_D \cdot \Delta\omega \tag{1}$$

Thus, this way it can enhance the transient stability (first swing). In order to provide the power system this additional synchronizing power, a linear control strategy based on the deviation of the rotor angle is used and can be expressed as:

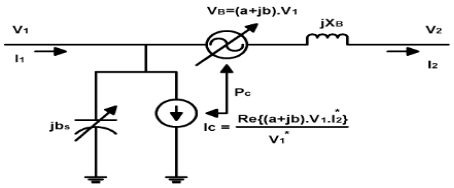


Fig. 2 UPFC circuit model

$$\Delta u = K_1 \cdot \Delta\delta \tag{2}$$

$$\Delta\delta = \delta - \delta_0 \tag{3}$$

$$\Delta u = u - u_0 \tag{4}$$

where u is the UPFC control variable defined as: u = bs for controlled shunt compensation, u = a for in-phase voltage control, u = b for Quadrature voltage control, and K1, d0 and u0 are the controller gain, initial rotor angle and reference setting, respectively

3 *Proposed method*

Consider an n -machine power system including UPFC. In the COA reference frame, the rotor dynamics of the i th machine, in the classical model of a power system, can be expressed by the following: differential equation

$$\frac{d\delta_i}{dt} = \omega_i \tag{5}$$

$$M_i \frac{d\omega_i}{dt} = P_{mi} - P_{ei} - \frac{M_i}{M_T} P_{COA} \tag{6}$$

Usual notations are used andMi =2 Hi /x0 [7]. Pmi is the mechanical power of the i th machine and is assumed to be unchanged during the period of analysis. The generator output Pei is a function of d and the UPFC control variable u. The energy function Vi of the i th machine, also called the IMEF, can be obtained by integrating Eq. 6 after multiplying both sides by ddi /dt and can be written as:

$$V_i = V_{KEi} + V_{PEi} \tag{7}$$

The IMEF has two components: kinetic energy VKEi and potential energy VPEi . The expressions for VKEi and VPEi are given in detail in [7].

Now assume that the power system is subject to a three-phase fault clearing in tcl . When tcl >tcr at least one of the machines, namely the critical machine, runs out of synchronism (tcr is the critical clearing time). In this situation the post-fault angle of the critical machine increases monotonously and it doesn’t have a peak value. Figure 3 shows typical variations of potential, kinetic and total energy of the machine for such a case. Figure 3 depicts tcl =0.23 s, whereas the actual value of critical clearing time of fault is between 0.20–0.21 s. It can be observed in Fig. 3 that both potential and kinetic energies of the machine increase during the fault period. When the fault is cleared at tcl , the KE of the machine converts into PE in the early part of the postfault period, i.e. the KE decreases while the PE increases. The energy conversion process satisfies the following criteria

$$V_{KEi}(t_{cl} + \Delta t) < V_{KEi}(t_{cl}) \tag{8}$$

$$V_{PEi}(t_{cl} + \Delta t) > V_{PEi}(t_{cl}) \tag{9}$$

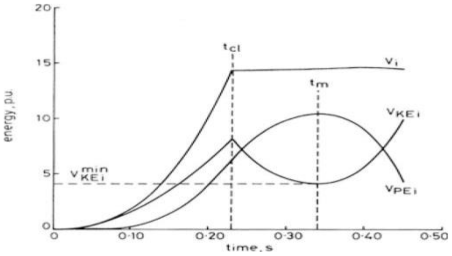


Fig. 3 Typical variation of potential, kinetic and total energy of a machine for a three-phase fault

Here Dt is an incremental time. It can be observed in Fig. 3 that the post-fault KE of the machine initially decreases and reaches a minimum value of VKEimin at time tm , and that the total energy of the machine Vi in the post-fault period is almost constant. The minimum kinetic energy VKEi min is the excess kinetic energy that cannot be absorbed or converted into PE. The first swing stability or existence of a peak angle demands the zero speed or kinetic energy of the machine in the post fault period. In this case, the SM of the machine can be considered as the negated excess or unabsorbed KE:

$$SM = -V_{KEi}^{\min} \tag{10}$$

The negative value of the stability margin indicates that the system is unstable.

According to [7], the energy function of the i th machine can be written as follows:

$$\begin{aligned} V_i = \; & \tfrac{1}{2}\sum_{i=1}^{n} M_i \cdot \omega_i^2 - P_i(\delta_i - \delta_i^{SEP}) - \\ & \sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\left[C_{ij}\left(\cos\delta_{ij} - \cos\delta_{ij}^{SEP}\right)\right] + \\ & \int_{\delta_i^{SEP}+\delta_j^{SEP}}^{\delta_i+\delta_j} D_{ij}\cos\delta_{ij}(\delta_i + \delta_j) \end{aligned} \tag{11}$$

The first term on the right hand side of Eq. 11 is kinetic energy of the machine, i.e.:

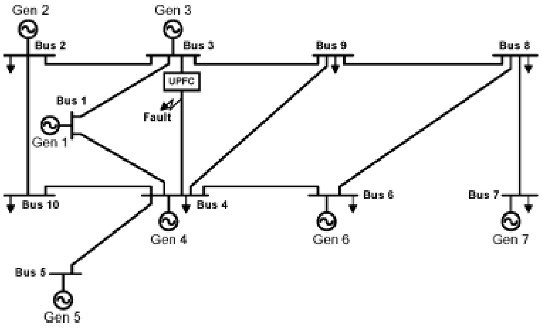
$$V_{KEi} = \sum_{i=1}^{n}\frac{1}{2}M_i\omega_i^2 \tag{12}$$

Since inclusion and insertion of the model and descriptive equations of UPFC into the transient energy function is a difficult task, it is proposed to first perform a time domain simulation and specify the critical machine in the system which is in fact the first machine that runs out of synchronism. It is then appropriate to determine machine speeds xi for any control strategies in the post-fault condition. Finally, according to Eq. 12, kinetic energy KE of the machine for various states and control modes is computed. The minimum value of KE with a negative sign is equal to the transient stability margin of the critical machine. It means that this value of kinetic energy for the post-fault condition can be evaluated merely by the values of Mi and xi , while effects of UPFC on transient stability in various control modes can be investigated by kinetic energy profiles, particularly according to its minimum value. As the fault location is close to the UPFC, the voltage at the excitation transformer will be low during the fault, thus reducing the effectiveness of shunt compensation. In addition, the high magnitude of the fault current which passes through the booster transformer will make it necessary to reduce the inserted series voltage to keep the converter VA within the limit. Therefore, the effect of UPFC is very limited during the fault and thus it is assumed that its controller is active only after the fault is cleared. This assumption simplifies the analysis.

4. Simulation results

The proposed method of determining the stability margin affected by UPFC, in addition to analyzing and combining the output results of the TDS with the TEF method, was studied on the 7-machine CIGRE test system in various UPFC control schemes. The CIGRE system, shown in Fig. 4, consists of seven machines, ten uses and 13 lines. The single line diagram and data of the system are given in [7]. The dynamic model and parameters of UPFC was adopted from [4]. A three phase fault on the line between buses 3 and 4, nearer to bus 3, occurs. The fault is cleared by opening the line after tcl . It is assumed that UPFC is installed at bus 3. We have represented effects of quadrature voltage control, in-phase voltage control and shunt compensation control methods on kinetic energy and transient stability margin of the critical machine at different fault clearing times. For the uncontrolled case, critical clearing time was computed as 0.388 s. Based on TDS, machine 3 was determined as the critical machine because it was the first machine its rotor angle exceeded 180˚. The transient stability margin of the critical machine for various fault clearing times is shown in Fig. 5. It is seen that by utilizing UPFC, critical fault clearing time is prolonged considerably. This increase is even greater for quadrature voltage control and in-phase voltage control methods. In the other words, with UPFC insertion into the network for a specific fault clearing time, the stability margin of the critical machine will improve significantly. Figure 6 shows the kinetic energy variation of the critical machine without installation of UPFC in the post-fault condition and for different fault clearing times; in this figure both stable and unstable situations have been illustrated. The increasing minimum kinetic energy instant for greater fault clearing times is obvious; this implies a Decrease of stability margin or, rather, an increase of instability. Figure 7 shows variation of kinetic energy at tcl =0.41 s for uncontrolled and controlled cases. The value of minimum kinetic energy, namely VKEmin, decreases by UPFC insertion at post-fault condition in three basic control schemes. For tcl =0.41 s, the value of VKEmin in QVC, IVC and shunt compensation controlled mode will be negative. It means that the system is stable and the transient stability margin is positive. Quadrature voltage control will result in the smallest value of VKEmin and hence the greatest stability margin, i.e. _ VKEmin, while IVC shows good performance, and although shunt compensation benefits less than the others its effect is not negligible

Fig. 4 CIGRE test system



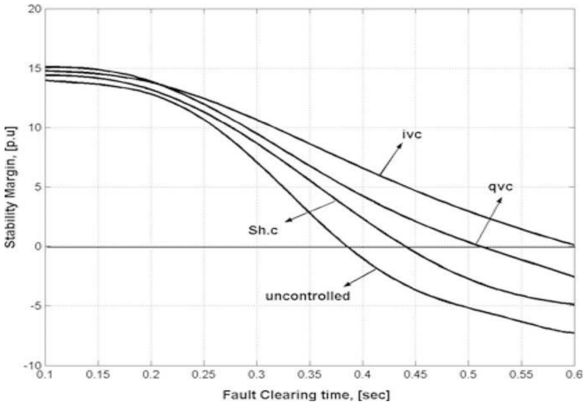


Fig. 5 Transient stability margin for various fault clearing times

CONCLUSIONS

Time domain simulation in the study of UPFC effects on the power system transient stability is the most commonly used method. But this approach requires a laborious trial and error computation and does not provide any information about the degree of stability or instability. On the other hand, use of the transient energy function (TEF) and insertion of the UPFC model and its equations with various control schemes is difficult work. In this paper the effect of three UPFC basic control strategies, namely IVC, QVC and shunt compensation, on improvement of the transient stability margin of a multi machine power system has been studied. The 7-machine CIGRE test system was selected as a case study. The results show that the values of kinetic energy in the post-fault condition are considerably lower in the QVC and IVC modes. Hence they have the greatest effect on enhancing the transient stability margin.Results also show that with increasing fault clearing time, IVC displays better characteristics than QVC on the TSM. In the other words, it is more robust than the other methods. The results can be used to select and apply an optimally coordinated control strategy for UPFC when a power system is expected to see severe disturbances.

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