Global Transient Stability and Voltage Regulation for Power Systems

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Abstract—
This paper concerns the global control of power systems. It arises from the practical concern that transient stability and voltage regulation are both important properties of power system control, but they are ascribed to different model descriptions and relate to different stages of system operation (i.e. transient period and post-transient period respectively). Earlier control results deal with the two problems separately, or employ a switching strategy of two different kinds of controllers, which causes a discontinuity of system behavior. We design in this paper a global controller to co-ordinate the transient stabilizer and voltage regulator. The designed controller is smooth and robust with respect to different transient faults. Simulations on a single-machine infinite bus power system have demonstrated better performances compared with existing controllers.

Keywords— **Global nonlinear control, power systems, transient stability, voltage regulation.**

I. Introduction

A power system must be modeled as a nonlinear system for large disturbances. Although power system stability may be broadly defined according to different operating conditions, an important problem which is frequently considered is the problem of *transient stability.* It concerns the maintenance of synchronism between generators following a severe disturbance. By the excitation control in a generating unit transient stability can be greatly enhanced. Another important issue of power system control is to maintain steady acceptable voltage under normal operating and disturbed conditions, which is referred as the problem of *voltage regulation.*

The use of advanced control techniques in power systems has been one of the more promising application areas. To enhance the transient stability of power systems, in recent years a great deal of attention has been paid to the application of feedback linearization approaches ([1]), see e.g. [2], [3], [4], [5], [6], [7], [8]. Compared with use of conventional approximate linearization, which can only deal with local stability around an operating point, the controlled system can endure large disturbances and retain a steady post-fault condition. Inevitably, in order to enhance the stability, power angle has to be one of the feedback variables whereas the generator voltage is not needed. In such transient stabilizing control, a common phenomenon is that the post-fault voltage value varies considerably from the pre-fault one ([9]). From the practical point of view, voltage quality is a very important index of power supply in power system operation; so the post-fault value is expected to reach the normal value as closely as possible. In [10], [9], [11], voltage regulation was achieved by introducing voltage feedback. However, the voltage controllers are only effective around a working region, i.e., they work well when a small disturbance occurs and at the post-fault stage, but cannot survive a large disturbance.

In the design of linear controllers, attempts have been made to coordinate the various requirements for stabilization and voltage regulation within the one controller. An approach used in [12], [13] involves use of advanced robust control to effect a trade-off between voltage regulation (AVR) and small signal power system stabilization (PSS). A practical scheme called discontinuous excitation control (DEC) [14] uses switching of a transient stability control module to augment the usual PSS. In these designs the system is assumed to be linearized. The DEC however is interesting in that it uses different controller configurations for different operating conditions.

Different behavior of nonlinear power systems in different operating regions requires different control objectives and consequently different control actions must be employed under varying operating region. How to achieve a satisfactory control performance over a wide range of anticipated operating conditions is an important issue from the practical point of view and is the topic of global control. Global control is a relatively new concept which has evolved from techniques like gain scheduling and more recent multi-model control. The key idea of global control is to combine the qualitative and quantitative knowledge through some hierarchy (see [15]). One of the most practically successful approaches for utilizing the qualitative knowledge of a system to design a controller is fuzzy control. Results have been obtained in [16] where heterogeneous control provides combination of local control actions appropriate to different operating regions, and in [17], [18] where Lyapunov stability analysis was developed based on a type of fuzzy dynamic model. A common feature of these methods is that they make use of mature results for the local controller design and provide necessary coordinations.

In this paper, we design global control to maintain the transient stability and achieve satisfactory post-fault voltage level of a power system when subjected to a severe disturbance. The control signal from the global controller is the average of the signals from the local control laws, each weighted by the value of its operating region membership function. Since the membership function can be determined by direct measurable variables of power systems, it has several appealing properties compared with

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the switching control strategy proposed by [9]. For example, to achieve control action switching, the fault sequence needs to be known apriori; also as long as the switching time is fixed according to a certain fault, the system may not survive another different fault. The global control law overcomes these disadvantages by sensing the relevance of stabilisation and regulation and automatically shifting to the appropriate controller. By a smooth transition between pure control regions, our global control objective is achieved. It is important that it adopts a mature control strategy in each local region, i.e. familiar schemes can be preserved.

The rest of this paper is organized as follows. In Section II a nonlinear model of a single machine infinite bus power system is given. Then in Section III existing controllers from the literature are reviewed where various problems are discussed from the global control point of view, and simulations follow to support the claims. In Section IV the global control objective is defined, and a global control law is then explicitly designed with simulation results demonstrating its effectiveness. Finally, the paper is concluded by brief remarks in Section V.

II. Dynamical Model of Power Systems

In this paper, we focus our attention on single machine infinite bus (SMIB) power systems. Since a SMIB system qualitatively exhibits important aspects of the behavior of a multi-machine system and is relatively simple to study, it is extremely useful in describing the general concepts of power systems stability, the influence of various factors upon stability, and alternative contoller concepts.

We consider the particular SMIB power system arrangement shown in Figure 1. The actual dynamic response of a synchronous generator in a practical power system when a fault occurs is very complicated including many nonlinearities such as the magnetic saturation. However, the classical third order dynamic generator model has been commonly used for designing the excitation controller. More complete models are used in the simulations to evaluate the design in the presence of other effects.

The classical third-order dynamical model of a SMIB power system (Figure 1) can be written as follows ([19], [20], [14]):

Mechanical equations:

$$\dot{\delta} = \omega \tag{1}$$

$$\dot{\omega} = -\frac{D}{2H}\omega + \frac{\omega_0}{2H}(P_m - P_e) \tag{2}$$

Generator electrical dynamics:

$$\dot{E}_q^{'} = \frac{1}{T_{do}^{'}}(E_f - E_q) \tag{3}$$

Electrical equations:

$$E_q = \frac{x_{ds}}{x_{ds}^{'}}E_q^{'} - \frac{x_d - x_d^{'}}{x_{ds}^{'}}V_s\cos\delta \tag{4}$$

$$P_e = \frac{V_s E_q}{x_{ds}}\sin\delta \tag{5}$$

$$I_q = \frac{V_s}{x_{ds}}\sin\delta = \frac{P_e}{x_{ad}I_f} \tag{6}$$

$$Q_e = \frac{V_s}{x_{ds}}E_q\cos\delta - \frac{V_s^2}{x_{ds}} \tag{7}$$

$$E_q = x_{ad}I_f \tag{8}$$

$$E_f = k_c u_f \tag{9}$$

$$V_t = \frac{1}{x_{ds}}\left[x_s^2E_q^2 + V_s^2x_d^2 + 2x_s x_d x_{ds} P_e\cot\delta\right]^{\frac{1}{2}} \tag{10}$$

where $\delta(t)$ is the power angle of the generator (in *radian*), $\omega(t)$ is the relative speed (in *rad/s*), P_m is the mechanical input power (in *p.u.*), P_e is the active power delivered to bus (in *p.u.*), $E_q^{'}$ is the transient EMF in the quadrature axis (in *p.u.*), and V_t is the terminal voltage of the generator (in *p.u.*). The notation for other variables and parameters are standard and readers are referred to [14], [21], [9].

The fault considered in this paper is a symmetrical three phase short circuit fault which occurs on one of the transmission lines. The transient stability control task is defined as follows.

Transient stability control problem: *Design the excitation control input u_f of (9) for power system (1)-(3), such that the closed-loop power system is transiently stable, i.e., the generator maintains synchronism when subjected to a severe transient disturbance.*

In the next section, we test the existing controller performances on different fault sequences, and then in Section IV a new global controller will be presented and tested.

III. Existing Controllers and their Problems

A. DFL Nonlinear Controller

As discussed in [1], feedback linearization is a quite appealing design method for nonlinear systems. Since it avoids the local nature of approximate linearization and transforms the system to be linear over a very wide range, it has been applied to power systems by different authors shortly after it was available – see e.g. [2], [10], [3], [4], [6], [5], [7], [9], [8]. In the following, we briefly describe the design based on so-called the direct feedback linearization (DFL) compensators [9], [8]. This allows more feasibility to preserve physical states than the geometric algorithm version in [1].

By a DFL transformation ([8]), (1)-(3) become

$$\begin{aligned}\dot{\delta} &= \omega\\ \dot{\omega} &= -\frac{D}{2H}\omega - \frac{\omega_0}{2H}\triangle P_e\\ \triangle\dot{P}_e &= -\frac{1}{T^{'}}\triangle P_e + \frac{1}{T^{'}}v_f\end{aligned} \tag{11}$$

where

$$\triangle P_e = P_e - P_{m0}, \tag{12}$$

$$T^{'} = \frac{x_{ds}^{'}}{x_{ds}}T_{d0}^{'}, \tag{13}$$

$$v_f = \frac{V_s}{x_{ds}}\sin\delta\left[k_c u_f + T_{d0}^{'}(x_d - x_d^{'})\frac{V_s}{x_{ds}}\sin\delta\ \omega\right]$$

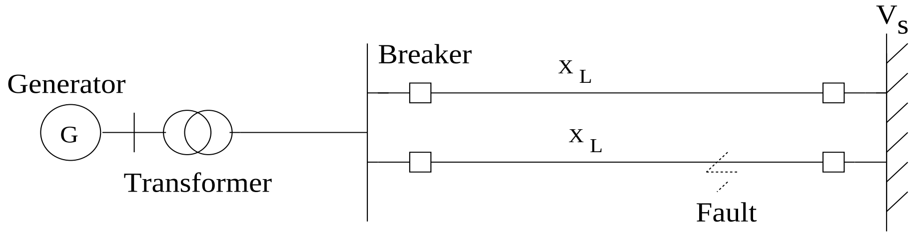

Fig. 1. A single machine infinite bus power system

$$+T^{'}\frac{V_s}{x_{ds}}E_q\cos\delta\ \omega - P_{m0}. \tag{14}$$

Note that the mechanical power control is represented as a constant power P_{m0}, i.e. the governor loop is relatively slow acting.

Now, we note (11) is a linear system with the new input v_f. Robust control techniques for linear systems [22], [23] can be employed. By solving an algebraic Riccati equation (ARE) – see [8], [21] for detail, the DFL compensating control law is obtained as

$$v_f \;=\; -k_\delta\delta - k_\omega\omega - k_P \triangle P_e \tag{15}$$

where k_δ, k_ω, k_P are the linear gains obtained from the solutions of ARE.

The real excitation control u_f can be obtained from (14) to give

$$\begin{aligned} u_f \;=\; & \frac{x_{ds}}{k_c V_s\sin\delta}\left[v_f - T^{'}\frac{V_s}{x_{ds}}E_q\cos\delta\ \omega + P_{m0}\right] \\ & -T^{'}_{d0}(x_d - x^{'}_d)\frac{V_s}{k_c x_{ds}}\sin\delta\ \omega \end{aligned} \tag{16}$$

DFL nonlinear control (16) with (15) guarantees the transient stability of power system (1)-(3) for admissible uncertain x_L and V_s (proof is given in [8]). And in the post-fault period,

$$\begin{aligned} \lim_{t\to\infty}|\triangle\delta| &= 0, \\ \lim_{t\to\infty}|\omega| &= 0, \\ \lim_{t\to\infty}|\triangle P_e| &= 0. \end{aligned} \tag{17}$$

However, since V_t is a nonlinear function of δ, P_e and the system structure, any change in the system structure will cause the voltage to reach another post-fault equilibrium point even if δ and P_e are forced to go back to their prefault steady values. So the generator terminal voltage V_t could stay at a different post-fault state which is undesirable in practice.

From the above, we can see that although the DFL nonlinear compensator is effective for stability, it cannot guarantee the voltage regulation. The simulation results shown later in Section III-D will verify that the DFL nonlinear controller enhances the transient stability of power systems but cannot by itself achieve a satisfactory post-fault voltage level.

B. Voltage Controller

Voltage regulation is an important issue particularly in the post-transient period. Its basic objective is to regulate the voltage to reach its nominal value. Voltage controllers have been given in [10] using LQ-optimal techniques and in [11] using a linear robust control technique. Both of them have the problem that they deteriorate transient stability over the whole operating region.

For example, as proposed in [11], differentiating equation (10) gives

$$\triangle\dot{V}_t \;=\; f_1(t)\omega + \frac{f_2(t)}{T^{'}_{d0}}\triangle P_e + \frac{f_2(t)}{T^{'}_{d0}}v_f \tag{18}$$

where $f_1(t)$ and $f_2(t)$ are highly nonlinear functions of δ, P_e and V_t – see [11] for details. Since $f_1(t)$ and $f_2(t)$ are dependent on the operating conditions, their bounds can be found within a certain operating region. So a new linearized system which is represented by the vector $[\triangle V_t, \omega, \triangle P_e]$ can be developed. Robust linear control techniques can be applied to obtain

$$v_f \;=\; -k_V\triangle V_t - k_\omega\omega - k_P\triangle P_e \tag{19}$$

where k_V, k_ω, k_P are linear gains dependent on the bounds of $f_1(t), f_2(t)$. The real excitation input u_f is chosen as defined in (16).

Since the voltage is introduced as a feedback variable in (19), the post-fault voltage is prevented from excessive variation. It is unnecessary to keep the power angle regulated once transient stability is assured.

However, since the design of the voltage controller involves estimating nonlinearity bounds within a certain operating region, it is only effective locally. In another words, when serious disturbances occur which cause the system to operate in a wider range outside the estimated one, the designed system may not perform well.

In conclusion, the voltage controller achieves voltage regulation, but it is only valid locally. This point will be verified in the simulations in Section III-D.

C. Coordinated Control by Switching

By now it can be seen that the DFL nonlinear controller and voltage controller achieve different control objectives in different regions of the states. In [21], [9], a nonlinear coordinated control scheme was proposed where a switching strategy is used between the different control actions to guarantee transient stability enhancement and voltage regulation.

A typical switching scheme is as follows:

Step 1: When the fault occurs at $t = t_0$, the DFL nonlinear controller u_f with (15) is employed to maintain the transient stability of power systems;

Step 2: At $t = t_s$, the control law switches to the voltage controller u_f with (19) to maintain the desired post-fault voltage level.

The switching time t_s should be reasonably chosen within the post-transient period, which requires that the fault sequence must be known as apriori. Further, the exact switching time has to be determined by trial and error in simulation. Thus, as the switching time is physically fixed according to one particular fault sequence, it may not be suitable for a different fault sequence, which may then destabilize the power system. Also, the switching time fixed in the first post-transient period cannot achieve voltage regulation over the whole working region allowing for later faults.

In summary, the obstacles preventing the switching strategy from practical success are as follows:
- The switching time is fixed;
- Not robust with respect to different faults.

How to design a universal control law which is robust with respect to uncertain faults is a challenging problem. Before stating our global controller, we show in the next subsection simulation results of the controllers which were discussed above.

D. Simulations of Local Controllers

The parameters of the SMIB power system which is shown in Figure 1 are as follows:

$$\begin{aligned} &x_d = 1.863, \quad x_d^{'} = 0.257, \quad x_T = 0.127, \\ &T_{do}^{'} = 6.9, \quad x_L = 0.4853, \quad H = 4, \quad D = 5, \\ &K_c = 1, \quad x_{ad} = 1.712, \quad \omega_0 = 314.159. \end{aligned} \tag{20}$$

The physical limit of the excitation voltage is taken as

$$-3 \leq \quad k_c u_f \quad \leq 6 \tag{21}$$

The operating point of the power system used in the simulations is:

$$\delta_0 = 72^{\circ}, \quad P_{m0} = 0.9p.u., \quad V_{t0} = 1.0p.u. \tag{22}$$

The fault is a symmetrical three phase short circuit fault with its sequences described as:

Case 1. Permanent fault

Stage 1: The system is in a prefault steady state;
Stage 2: A fault occurs at $t = t_0$;
Stage 3: The fault is removed by opening the breakers of the faulted line at $t = t_1$;
Stage 4: The system is in a post-fault state.

Case 2. Permanent fault + increase of the mechanical input power

Stage 1: The system is in a prefault steady state;
Stage 2: A fault occurs at $t = t_0$;
Stage 3: The fault is removed by opening the breakers of the faulted line at $t = t_1$;
Stage 4: The mechanical input power of the generator has a 30% step increase at $t = t_2$;
Stage 5: The system is in a post-fault state.

Case 3. Temporary fault + permanent fault

Stage 1: The system is in a prefault steady state;
Stage 2: A fault occurs at $t = t_0$;
Stage 3: The fault is removed by opening the breakers of the faulted line at $t = t_1$;
Stage 4: The transmission lines are restored at $t = t_3$;
Stage 5: Another fault occurs at $t = t_4$;
Stage 6: The fault is removed by opening the breakers of the faulted line at $t = t_5$;
Stage 7: The system is in a post-fault state.

We choose in the simulation $t_0 = 0.1s, t_1 = 0.25s, t_2 = 1s, t_3 = 1.4s, t_4 = 2.1s, t_5 = 2.25s$.

The fault location is indexed by a positive constant λ which is the fraction of the line to the left of the fault. The fault locations for the three cases of fault sequences are:
Case 1: $\lambda = 0.035$;
Case 2: $\lambda = 0.204$;
Case 3: $\lambda = 0.04$.

The controllers employed in the simulations are [11]:

$$\begin{aligned} &\text{Transient controller :} \\ &v_f = 22.36\ \delta + 12.81\ \omega - 82.45 \bigtriangleup P_e \qquad (23) \\ &\text{Voltage controller :} \\ &v_f = -40.14 \bigtriangleup V_t + 10.11\ \omega - 30.81 \bigtriangleup P_e \qquad (24) \end{aligned}$$

The power system responses with the different controllers subjected to different faults are shown in Figures 2-6. Figure 2 exhibits the closed-loop power system responses for three kinds of controllers in fault sequence Case 1. Figure 3 shows the responses for the transient nonlinear controller and voltage controller in Case 2, whereas the switching controller responses are shown in Figure 4 for different switching time. In fault sequence Case 3, the responses for the three controllers are shown in Figures 5 and 6.

From the simulation results it can be observed that the transient nonlinear controller stabilizes the disturbed systems but the post-fault voltage differs from the prefault value by 10%-20%, which is not acceptable in practice. The voltage controller can only stabilize the system and maintain good post-fault voltage level in Case 1, but cannot survive more severe faults as in Case 2 and 3. For the switching controllers, the switching time is seen to be important since an inappropriate one causes the loss of synchronism of generators. This point is clearly shown in Figures 4 and 6 where the switching controller with switching time $t_s = 1s$ stabilizes the system in Case 2, but destabilizes it in Case 3.

The simulation results are consistent with the analysis stated early in this Section. As stated in [9], surviving a severe transient disturbance and maintaining normal voltage values simultaneously are of key importance in power system control. The strategy by simply switching between different control actions is not reliable due to the non-existing of a universal switching time. In the next Section, we will propose a new global control strategy which achieves tran-

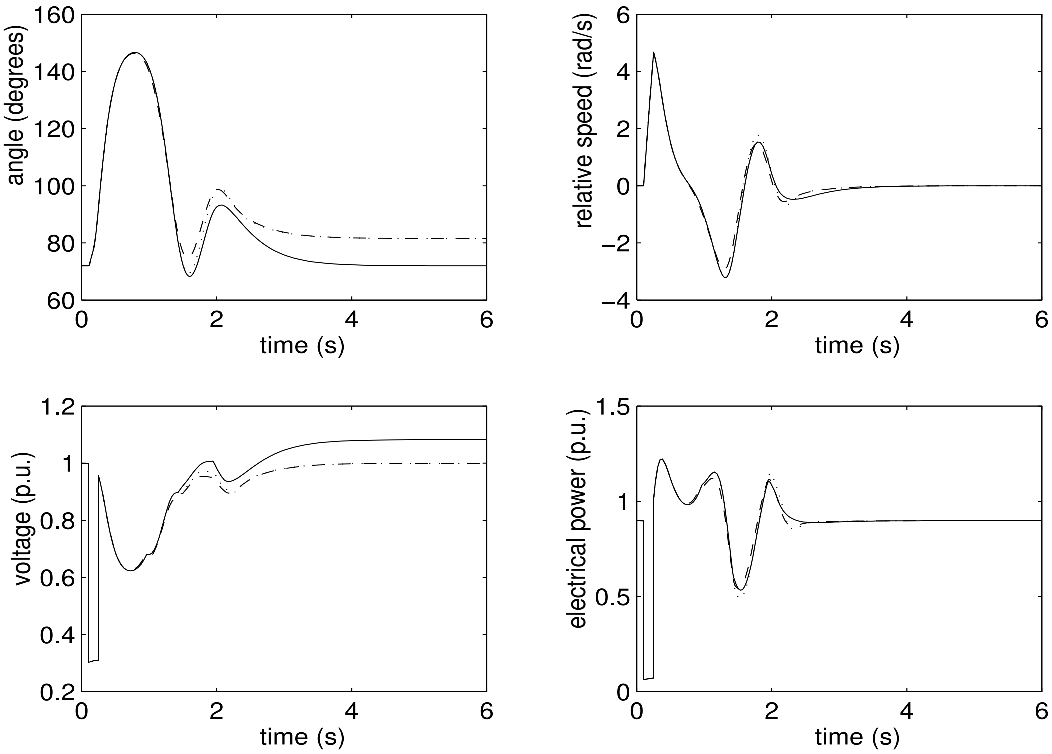

Fig. 2. Power system responses for *Case 1*: '—' DFL nonlinear controller; '- -' voltage controller; '·' switching controller ($t_s = 1s$).

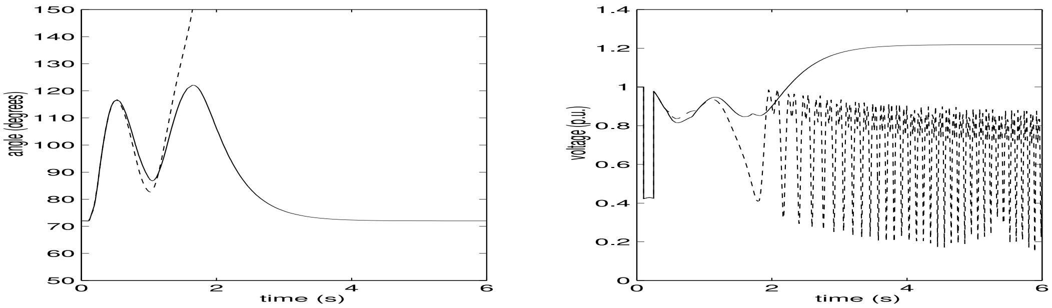

Fig. 3. Power system responses for *Case 2*: '—' DFL nonlinear controller; '- -' voltage controller.

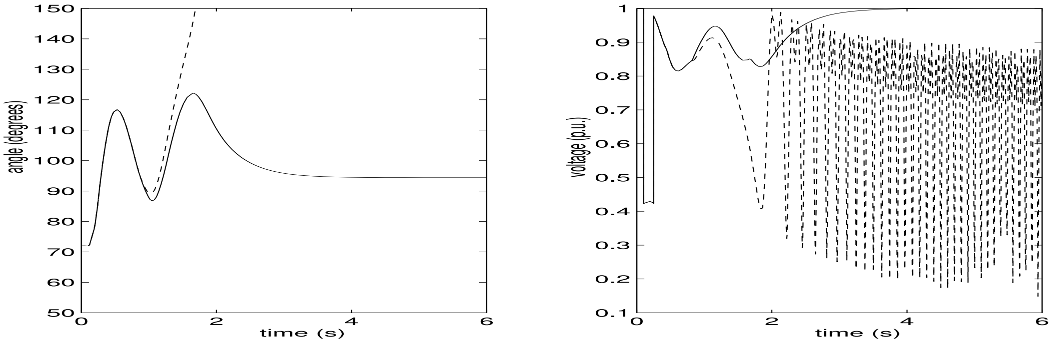

Fig. 4. Power system responses for *Case 2*, switching controller: '—' $t_s = 1s$; '- -' $t_s = 0.8s$.

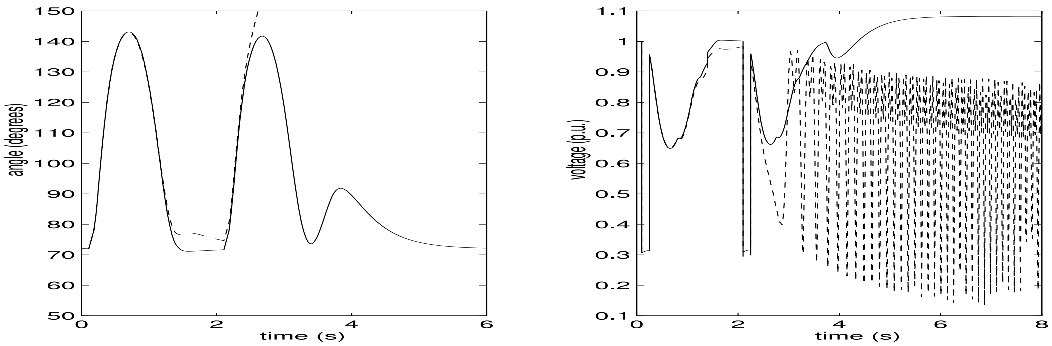

Fig. 5. Power system responses for *Case 3*: '—' DFL nonlinear controller; '--' voltage controller.

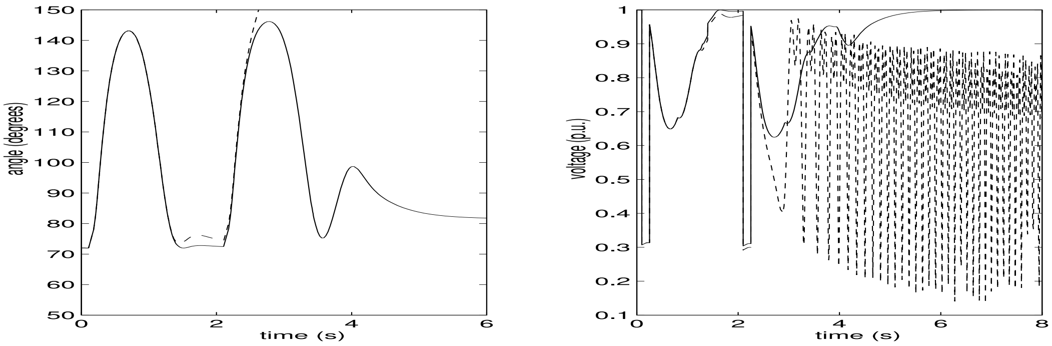

Fig. 6. Power system responses for *Case 3*, switching controller: '—' $t_s = 1.3s$; '--' $t_s = 1s$.

sient stability enhancement and voltage regulation simultaneously and robustly.

IV. Global Control of Power Systems

As stated in the Introduction, our global control objective is to achieve good control performance over a wide range for the anticipated operating region. Specifically, we have the following control task.

Global control problem: *Design a smooth nonlinear feedback control law for the excitation system (1)-(3), such that the closed-loop power system is transiently stable when subjected to a severe disturbance, and restores the steady prefault voltage value after the disturbance.*

Desired properties of the global controller include robustness with respect to different faults whose sequences are not known apriori.

A. Operating Region Membership Function

From the analysis of the previous section, we find that if we introduce the power angle δ in a feedback controller, transient stability of the system can be greatly improved. In practice, we want to achieve both transient stability enhancement and good post-fault performance of the system. In this context, good post-fault performance means that after the transient period we wish to control the excitation unit to regulate the generator terminal voltage V_t. According to the qualitatively distinct operating conditions and the corresponding control objectives over each region, local controllers are designed and coordinated through some strategy. We firstly need to define the operating regions and membership functions.

We use the following trapezoid-shaped like membership functions which are able to indicate different operating stages.

$$\begin{aligned} \mu_V(z) &= (1 - \frac{1}{1+\exp(-120(z-0.08))}) \\ &\quad \cdot (\frac{1}{1+\exp(-120(z+0.08))}) \\ \mu_\delta(z) &= 1 - \mu_V \end{aligned} \tag{25}$$

where

$$z = \sqrt{\alpha_1 \omega^2 + \alpha_2 (\triangle V_t)^2} \tag{26}$$

and α_1, α_2 are positive design constants providing appropriate scaling which can be chosen according to different sensitivity requirement of power frequency and voltage.

Membership function (25) is plotted in Figure 7. It can be seen that $\mu_\delta(z)$ gets its dominant value when z is far away from the origin, which corresponds to the transient period; on the other hand, $\mu_V(z)$ does so when z is close to the origin, which indicates the post-transient period. Since the membership function values are determined by the directly measurable variables, ω and $\triangle V$, the fault sequence need not to be known beforehand.

Therefore, the whole operating region is partitioned into the following two subspaces by the membership functions, where S_1 indicates the transient period and S_2 indicates the post-transient period.

$$\begin{aligned} S_1 &= \{(\omega, \triangle V) | \mu_V \le \mu_\delta\} \\ S_2 &= \{(\omega, \triangle V) | \mu_V > \mu_\delta\} \end{aligned} \tag{27}$$

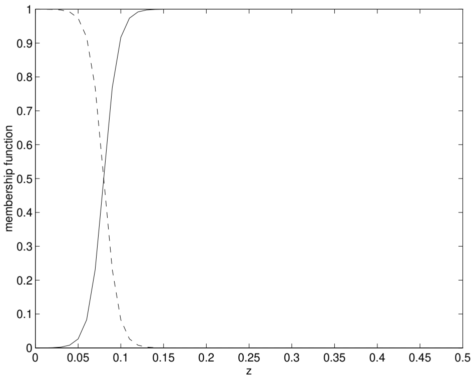

Fig. 7. Membership functions: '–' μ_δ, '- -' μ_V.

The characteristic function of each subspace S_l $(l = 1, 2)$ is defined by:

$$\tau_l = \begin{cases} 1 & z \in S_l \\ 0 & \text{otherwise} \end{cases} \tag{28}$$

Note that $\tau_1 + \tau_2 = 1$.

It should be pointed out that ω and $\triangle V_t$ are chosen as the index variables in (26) since they sufficiently represent the operating status for the problem of transient stability and voltage regulation. If the problem under consideration is voltage stability, reactive power could be included in the index. Similarly, the proposed method can be extended to other power system control issues. The chosen membership functions have a trapezoid-like shape which is well known in fuzzy control to separate operating conditions. From our simulation experience, the system performance is not sensitive to different parameters α_1 and α_2.

B. Global Control Law

After the state space is partitioned, it is desirable that in the transient period, which corresponds to subspace S_1, the DFL nonlinear controller takes effect; while in the post-transient period, which corresponds to subspace S_2, the voltage controller does. The global control law is the average of the individual control laws, weighted by the operating region membership functions, i.e., the input v_f takes the form:

$$v_f = \mu_\delta v_{f1} + \mu_V v_{f2} \tag{29}$$

where v_{f1} is the DFL nonlinear controller (15) and v_{f2} is the voltage controller (19). The real excitation control u_f can be implemented by (16).

The global control (29) has the following interpretation: in the transient period system states are far away from the equilibrium, the primary control is to regulate them to enter a neighborhood of the equilibrium without large oscillations; then in the post-transient period around the equilibrium the voltage needs to be tuned to reach the pre-fault level. The membership functions play the role of appropriate weighting and smooth interpolation of the two controllers. One of the appealing abilities of the method is that the operating status is automatically distinguished by the membership functions which are functions of directly measurable variables. The form of control law (29) is such that a smooth transfer between the local controllers is automatically achieved.

The global heterogeneous control of power systems is illustrated in Figure 8, where block #1 and #2 represents local controllers, and membership functions play the role of appropriate coordination.

C. Discussion of Global Control Law

The global control design procedure involves the following three steps:

- Qualitatively distinct operating regions are indicated by membership functions of directly measurable variables, and the region partitionings admit overlap;
- The control law in each region is specified to be the usual type of controller developed from model-based nonlinear control techniques: in the transient period, the controller is designed to dampen out the power angle oscillations quickly, while in post-transient period the voltage is regulated to return to the original equilibrium;
- The global control law is the weighted sum of local controllers, which achieves smooth transitions between the transient period and post-transient period.

The proposed global control law (29) features the following properties:

- Control action is determined by online measurement of power frequency and voltage, which makes it unnecessary to know the fault sequence beforehand;
- The controller is globally effective in the presence of different uncertain faults;
- The controller inherits the properties of local controllers, i.e., it is robust with respect to parameter uncertainties.

It should be pointed out that the design replies on a fixed system frequency, which may not be valid in a situation where the system frequency is abnormal. However, from our simulation experience, the global controller has certain robustness with respect to system frequency.

Simulation results follow to demonstrate the effectiveness of the heterogeneous control law.

D. Simulations of the Global Controller

In this subsection, we exhibit the closed-loop power system performances in the presence of different fault sequences and locations. The power system parameters and fault cases are the same as in Section III-D. The global control law employed is (29) with v_{f1} and v_{f2} from (23) and (24) respectively.

Figures 9-11 show the system performance when subjected to different faults as defined in Section III-D. In fault sequence *Case 1*, Figure 9 exhibits good transient performance and restoration of normal post-transient voltage. In fault sequence *Case 2*, Figure 10 shows similar performances; this contrasts with that in Figures 3 and 4 where unsatisfactory performances are observed for the voltage and switching controllers. In fault sequence *Case 3*, Figure 11 contrasts with Figures 5 and 6 in that both transient stability and normal post-fault voltage values are achieved.

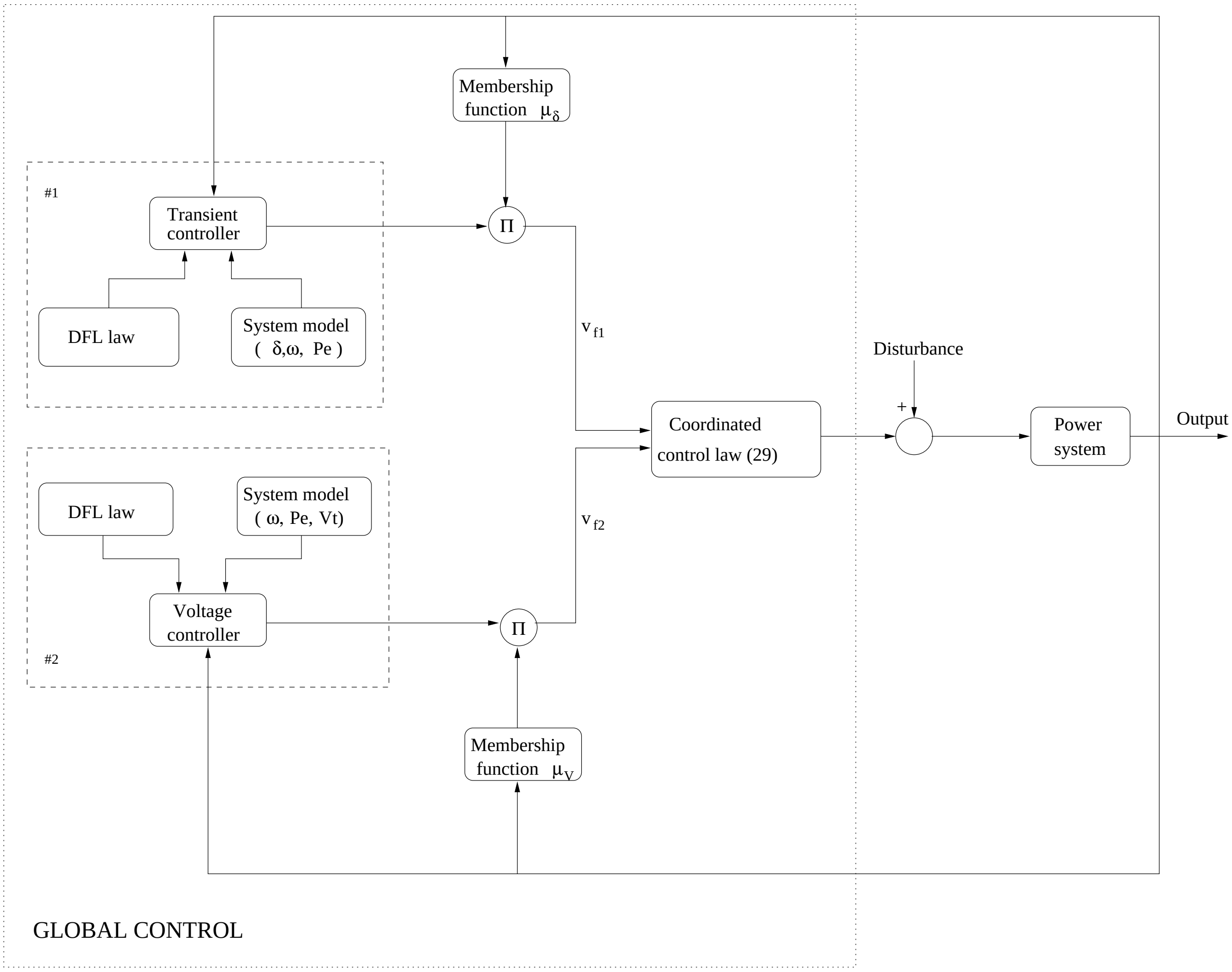

Fig. 8. Global control of power systems.

Figure 12 shows the angle and voltage responses with respect to different fault locations. From the simulations, we can see the global controller achieves the proposed control task and is robust with respect to different faults.

V. Conclusions

In this paper, we presented a design for global control of a single machine on an infinite bus power system. Power systems present a rich source of nonlinear control problems of practical importance. We define our global control objective as achieving satisfactory control performance over a wide range of anticipated operating conditions; specifically, transiently stabilizing the power system when subjected to a severe disturbance and retaining good voltage level after the disturbance.

The power control is introduced from the excitation loop where a nonlinear feedback law can be employed. Looking through the existing controllers from the literature, for each local control objective, i.e. transient stability enhancement and voltage regulation, there are mature controllers developed from feedback linearization and robust control techniques. Since they are designed according to a unique criterion in certain operating regions, they are not globally effective. Specifically, a transient stability controller cannot achieve satisfactory voltage values after the transient period, and the voltage controller cannot stabilize the system when subjected to large disturbance. In practice, surviving transient disturbances and maintaining normal voltage values are the basic requirements. This has been pointed out in [21] where a coordinated control was proposed by switching between different control actions. Due to the difficulty of choosing a universal switching time, this coordinated controller is not robust. Simulation results of all the above mentioned controllers have been given in Section III-D to support these claims.

We successfully designed a global control law for the power system. Membership functions, which are real-valued functions of measurable variables, are chosen to indicate different stages of the operating conditions. The global control law is the sum of local controllers weighted by their membership functions. Since in practice various kinds of fault occur whose sequences and locations are not known a prior, the global controller is superior due to its robustness with respect to uncertain faults. Simulation results shown in Section IV-D demonstrate the transient stability enhancement and voltage regulation in the presence

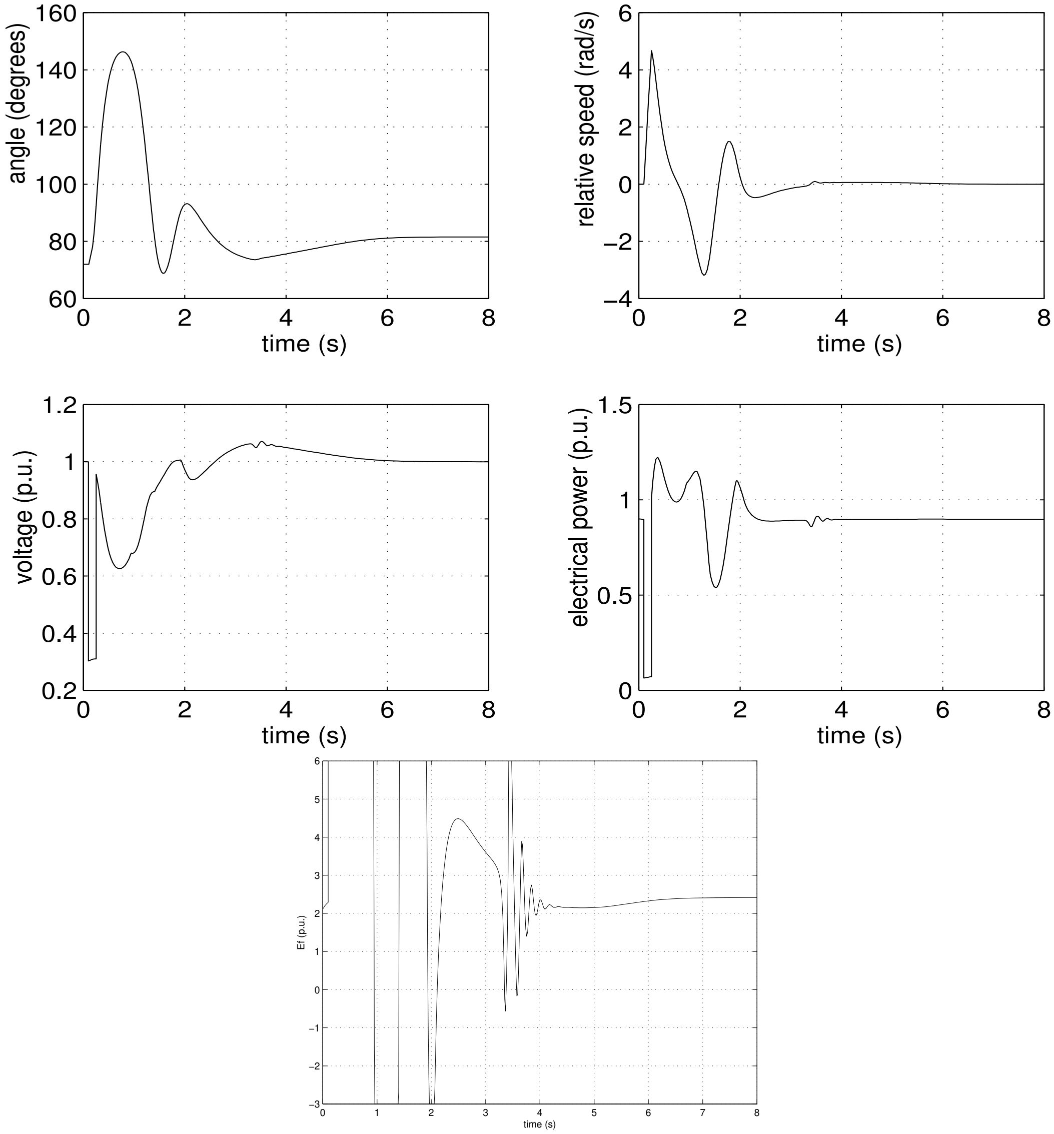

Fig. 9. Power system responses for *Case 1*: global control law.

of different fault sequences and locations.

Future work needs to be undertaken to extend the application of the proposed method to large systems and other control requirements. Discontinuous excitation control [14] uses switching of controllers to achieve multiple control objectives. The techniques proposed here could refine such schemes for multi-machine systems.

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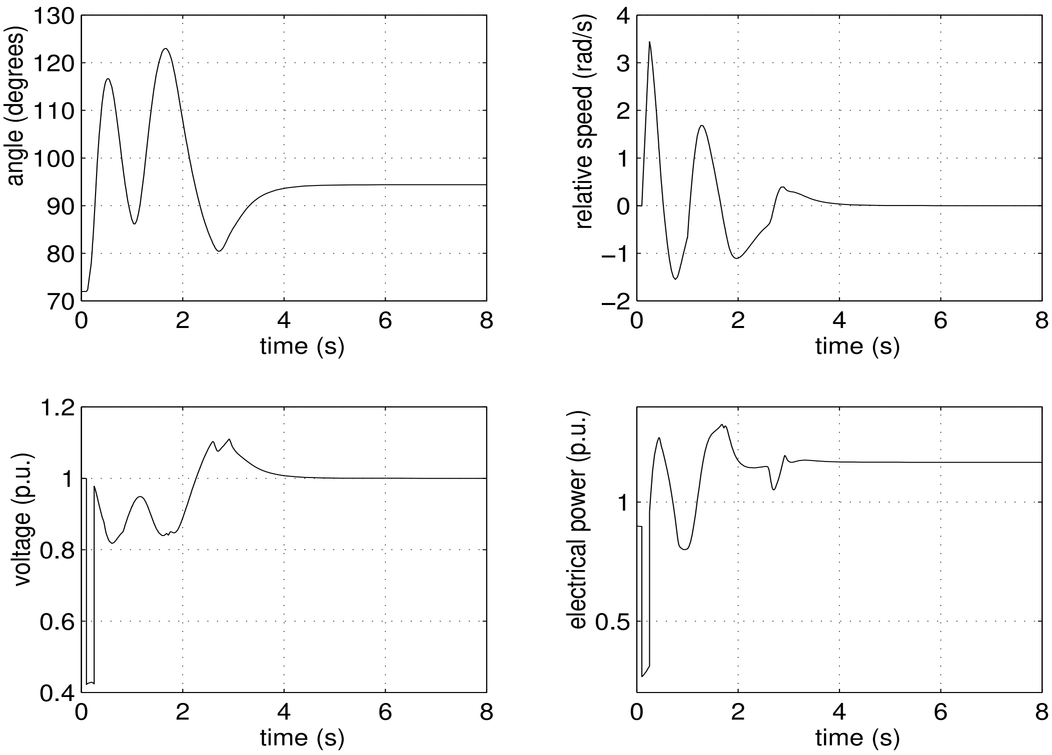

Fig. 10. Power system responses for *Case 2*: global control law.

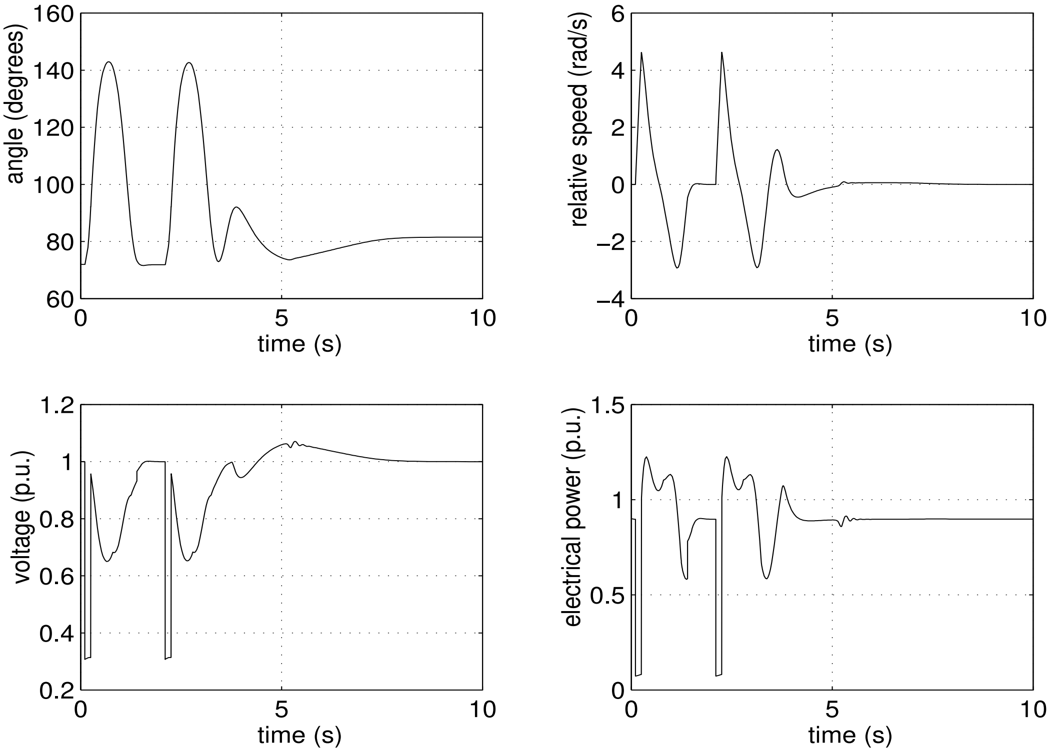

Fig. 11. Power system responses for *Case 3*: global control law.

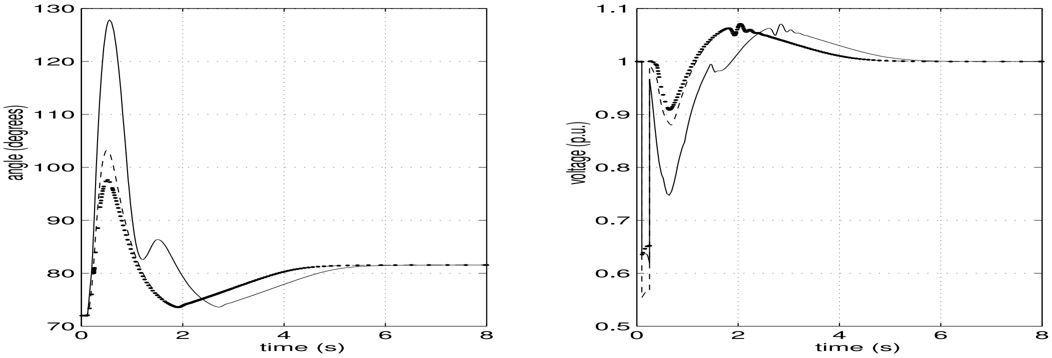

Fig. 12. Power system responses for different fault locations in Case 1: '-' $\lambda = 0.1$; '- -' $\lambda = 0.5$; '·' $\lambda = 0.8$.

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