Fast Determination of Generation-Shedding in Transient Emergency State

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ABSTRACT

This paper is concerned with fast determination of generation-shedding in the transient emergency state of power system. A simple procedure is first developed to calculate the critical partial energy of individual machine and the associated partial energy margin. The partial energy function is then applied to the transient stability assessment of a power system subjected to a large disturbance. Following this assessment, an energy-based analytical sensitivity method is presented. The sensitivity of the partial energy margin at any instant to the change of generation level has been analytically derived in a closed form. It offers a one-shot calculation for quantitative estimation of generation that must be shed to maintain system stability. The proposed sensitivity technique and procedure are illustrated with the Taipower system with reasonably accurate results.

Keywords : generation-shedding, energy-based sensitivity

1. INTRODUCTION

Modern electric power systems have grown complexly large due to increasing interconnections, installation of large generating units, and extra high voltage tie-lines. In most cases, system disturbances such as loss of a major transmission line, load or generation component can perturb a power system from normal operating state into transient emergency state where the system may lose transient stability. There are many means which can be effectively implemented to complement system synchronizing forces during and/or after such severe system transient disturbances. In North America, generation-shedding has proved to be one of the most effective discrete supplementary control means for maintaining stability [10]. Therefore, the emphasis in this paper is placed on fast determining the amount of generation-shedding needed to ensure stability in transient emergency state.

Theoretical studies on transient stability assessment and stabilization by the direct method based on transient energy function (TEF) have been widely conducted [1-6]. Significant progress has been achieved, and practical methods to assess and control transient stability are emerging. Recent results have indicated that not all the transient energy contributes to system separation. Moreover, it is becoming increasingly obvious that system separation does not depend on the total system energy, but rather on the transient energy of individual machines tending to apart from the rest of the system [7-9]. The stability of these severely disturbed machines is what determines the transient stability of the overall system. Hence, special emphasis is focused on energy transactions of the severely disturbed machines, instead of assessing stability from a system-wide viewpoint.

In 1989, Stanton et al. [9] generalized the Vittal's individual machine energy function [7] to propose a partial energy function (PEF), a multi-dimensional generalization of the well-known equal area criterion. The PEF was used to quantify the energy transaction of an unstable generator. An inherent advantage of the PEF is the availability of a quantitative measure of the degree of stability in terms of the partial energy margin for a specific machine, which quantifies the energy causing machine unstable. The partial energy margin permits pursuing sensitivity analysis aspect. In this paper, a simple procedure for finding the critical energy of individual machine and its associated partial energy margin are presented. The calculation of energy margin plays an important role in any energy-based transient stability assessment or transient enhancement. The sensitivity analysis naturally paves the way of local transient control for system operation. In the past, some attempts have been made to derive stability limits using the sensitivity of total system transient energy margin to change in power system parameters through either repetitive simulations [10] or analytical formulations [11]. However, since the behavior of the system-wide energy function is dominated by the behavior of the partial energy of the severely disturbed machines, the latter provides a more accurate quantitative measure for transient enhancement. Therefore, this paper aims to present a completely analytical partial energy margin sensitivity on the basis of the PEF method and the related partial energy margin. It allows one to compute the generation limit of a particular generator in one-shot manner, and hence help perform local generation-shedding or other transient control for improving the transient stability. Finally, extensive analyses are conducted on the Taipower system to evaluate the effectiveness of the proposed sensitivity method for the determination of generation-shedding in transient emergency state.

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2. THE MATHEMATICAL FORMULATION

For the classical power system model of an n-generator power system, the equation of motion of the ith synchronous generator with respect to the center of inertia (COI) reference frame is described by

$$M_i \dot{\tilde{\omega}}_i = P_i - P_{ei} - \frac{M_i}{M_T} P_{COA} = f_i(\underline{\theta}) \qquad (1)$$
$$\dot{\theta}_i = \tilde{\omega}_i \qquad i = 1, 2, \ldots, n$$

where

$$P_i = P_{mi} - E_i^2 G_{ii}$$
$$P_{ei} = \sum_{\substack{j=1 \\ j \neq i}}^{n} [C_{ij} \sin \theta_{ij} + D_{ij} \cos \theta_{ij}]$$
$$M_T = \sum_{i=1}^{n} M_i$$
$$P_{COA} = \sum_{i=1}^{n} (P_i - P_{ei}) = \sum_{i=1}^{n} P_i - 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} D_{ij} \cos \theta_{ij}$$
$$C_{ij} = E_i E_j B_{ij}, \qquad D_{ij} = E_i E_j G_{ij}, \qquad \theta_{ij} = \theta_i - \theta_j$$

and, using the common terminology for generator i

E_i = constant voltage behind the direct-axis transient reactance
G_{ii} = driving point conductance
P_{mi} = mechanical power input
M_i = inertia constant
$G_{ij} (B_{ij})$ = transfer conductance (susceptance) in the reduced admittance matrix
$\tilde{\omega}_i, \theta_i$ = rotor speed and angle with respect to COI reference frame, respectively

In the above, the network of power system has been reduced to the generator internal buses. For the system governed by Eq. (1), the partial energy function is given by [9]

$$V_i(\tilde{\omega}_i,\underline{\theta}) = \frac{1}{2}M_i\tilde{\omega}_i^2 - P_i(\theta_i - \theta_i^s)$$
$$- \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{\theta_i - \theta_i^s}{\theta_{ij} - \theta_{ij}^s}[C_{ij}(\cos\theta_{ij} - \cos\theta_{ij}^s) - D_{ij}(\sin\theta_{ij} - \sin\theta_{ij}^s)]$$
$$+ \frac{M_i}{M_T}[\sum_{k=1}^{n} P_k(\theta_i - \theta_i^s) - 2\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\frac{\theta_i - \theta_i^s}{\theta_{kj} - \theta_{kj}^s}D_{kj}(\sin\theta_{kj}$$
$$- \sin\theta_{kj}^s)] \tag{2}$$

The first term in the right-hand side of Eq. (2) is the kinetic energy of generator i relative to COA reference frame. The sum of the remaining terms is customarily considered as the potential energy [1-4]. Thus Eq. (2) can be compactly denoted as

$$V_i = V_{kei} + V_{pei} \tag{3}$$

Because of the path-dependence property, it is not possible to judge analytically the sign definiteness of V_i. However, it has always been conjectured that V_i is positive definite supported by simulations on actual large-scale power system [1-4]. Therefore, without further theoretical justification, the function can only be regarded as a numerical partial energy function.

3. CRITICAL PARTIAL ENERGY CALCULATION

At the instant of fault clearing, the faulted power system contains an excess energy that is injected into the system during the fault. To maintain system stability, the network must be able to absorb this energy, which is often referred to as the transient energy. Meanwhile, the partial energy V_i of each machine is also increased during the fault. It is responsible for causing a synchronous generator to swing away from the rest of the system after fault clearing. For the synchronism of a machine not to be lost, the machine must be capable of converting all the kinetic energy V_{kei} of V_i into the potential energy V_{pei}.

The ability of a power system to absorb excess energy depends on its ability to convert that kinetic energy to potential energy. For a given system configuration, there is a maximum or critical amount of transient energy, called *critical energy*, that the network can absorb and convert to other forms of energy. Similarly, extending the above concepts to the partial energy V_i, there is a corresponding limit to how much fault energy a machine can absorb. This extreme of PEF is named the *critical partial energy*, denoted by V_{cri}. It can be found by computing the value of the PEF on the *dynamic liberation point* (DLP) with zero velocity of a specific set of severely disturbed machines.

Definition : The DLP is defined as the point on the trajectory where the accelerating power drops to be zero, and beyond which the synchronizing force on the rotor promotes acceleration into instability[9].

The rotor angles of machines at the DLP will be denoted by $\underline{\theta}^d$ throughout this paper. At the DLP, the zero power mismatch exists only for the severely disturbed machines, while the other generators are in random oscillations and violate the zero power mismatch condition. Therefore, in general, the DLP does not coincide with the unstable equilibrium point (u.e.p.) in the multimachine case. The DLP and the associated critical partial energy for the PEF have been previously defined. However, an accurate procedure to estimate the DLP has been lacking.

In this section, we propose a simple procedure to find the DLP for calculating the critical partial energy of a particular disturbance under consideration. The overall procedure is depicted in the flow chart of Fig. 1. This procedure mainly comprises the following five steps:

Step 1. Compute the admittance matrices Y reduced to internal nodes for the fault-on and post-fault network configurations.

Step 2. Compute the value $\underline{f}^T(\underline{\theta}).(\underline{\theta}-\underline{\theta}^s)$ along the fault-on trajectory.

Detecting the point $\underline{\theta}^*$ at which the value $\underline{f}^T(\underline{\theta}).(\underline{\theta}-\underline{\theta}^s)$ reversals the sign from negative to positive.

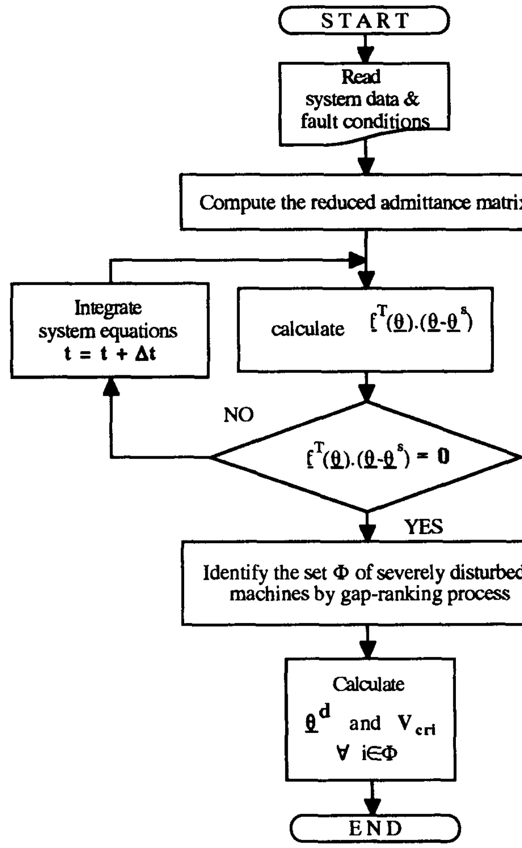

Fig. 1. Flow chart for calculating critical partial energy

Step 3. Perform a gap-ranking process according to the angles at $\underline{\theta}^*$. All rotor angles of the machines at $\underline{\theta}^*$ are ranked, taking the largest first, and all the angle gaps are then calculated. Those machines above the largest angle gap are grouped into the severely disturbed cluster Φ.

Step 4. Fix all the angles at $\underline{\theta}^*$ except for the θ_i, $i\in\Phi$, and then the $\underline{\theta}^d$ can be obtained by solving

$$P_i - P_{ei} - \frac{M_i}{M_T}P_{COA} = 0 \qquad \forall\ i \in \Phi \tag{4}$$

Step 5. The value of $V_{pei}(\underline{\theta}^d)$ is the critical partial energy of machine i in the set Φ.

In Step 2, we make use of the detecting criterion of PEBS $\underline{f}^T(\underline{\theta}).(\underline{\theta}-\underline{\theta}^s)=0$ [1] along fault-on trajectory to find a point, say $\underline{\theta}^*$, which is the closest point to the controlling u.e.p. among points on the fault-on trajectory. Since the behavior of the total system energy is mainly dominated by the behavior of the partial energy of the severely disturbed machines, the similar characteristics of the potential energy boundary surface (PEBS) method [1,2,6] of the system-wide energy function can be reasonably utilized in determining the critical partial energy. The angle $\underline{\theta}^*$ is very close to the DLP, which serves a good initial guess for solving the true DLP using Eq. (4). In a large interconnected system, the number of the machines tending to separate from the rest of the system may be more than one. In Step 3, a gap-ranking process is performed to identify the severely disturbed machines, which are characterized by their advanced rotor angle at $\underline{\theta}^*$. If the machine started with an amount of partial energy less than this critical partial energy, the machine rotor will swing back toward a new equilibrium position. In this case, the machine will be claimed first swing stable. In view of this, the partial energy margin for a specific machine i in the set Φ can be defined as the difference between V_{cri} and V_{cli} at the instant of fault clearing :

$$
\begin{aligned}
\Delta V_i &= V_{cri} - V_{cli} \\
&= -\frac{1}{2}M_i\tilde{\omega}_i^{c2} - P_i(\theta_i^d - \theta_i^c) \\
&\quad - \sum_{\substack{j=1\\ j\neq i}}^{n} \beta_{ij}\,[C_{ij}(\cos\theta_{ij}^d - \cos\theta_{ij}^c) - D_{ij}(\sin\theta_{ij}^d - \sin\theta_{ij}^c)] \\
&\quad + \frac{M_i}{M_T}[\sum_{k=1}^{n} P_k\,(\theta_i^d - \theta_i^c) - 2\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\beta_{ijk}\,D_{kj}(\sin\theta_{kj}^d \\
&\qquad - \sin\theta_{kj}^c)]
\end{aligned}
\tag{5}
$$

where

$\tilde{\omega}_i^c, \theta_i^c$ = rotor speed and angle at fault clearing with respect to COI reference frame, respectively

$$\beta_{ij} = \frac{\theta_i^d - \theta_i^c}{\theta_{ij}^d - \theta_{ij}^c}$$

$$\beta_{ijk} = \frac{\theta_i^d - \theta_i^c}{\theta_{kj}^d - \theta_{kj}^c}$$

Note that in Eqs. (4) and (5), all the parameters pertain to the post-fault configuration.

4. SENSITIVITY ANALYSIS

In simple notation, the partial energy margin ΔV_i in Eq. (5) can be expressed as a multivariable function

$$\Delta V_i = \eta_i(\tilde{\omega}_i^c, \underline{\theta}^c, \underline{\theta}^d, \underline{E}, \underline{P}_m) \tag{6}$$

To check whether there is a notable change in the relevant DLP with respect to the base case, where the system is unstable without generation-shedding, extensive analyses incorporating various kinds of temporary generation-shedding were performed. No appreciable difference is noticed regarding to the DLPs, and therefore the DLP is assumed unchanged after temporary generation-shedding in our studies for simplicity. The sensitivity of the partial energy margin with respect to the change of generation power ΔP_{ml} is given as

$$
\begin{aligned}
S_{ip_{ml}} &= \lim_{\Delta P_{ml}\to 0} \frac{\Delta\eta_i(\tilde{\omega}_i^c, \underline{\theta}^c, \underline{E}, \underline{P}_m)}{\Delta P_{ml}} \\
&= \frac{\partial\eta_i(\tilde{\omega}_i^c, \underline{\theta}^c, \underline{E}, \underline{P}_m)}{\partial P_{ml}}
\end{aligned}
\tag{7}
$$

Applying the chain rule of differentiation, above equation can be explicitly expressed as

$$
\begin{aligned}
S_{ip_{ml}} &= -M_i\tilde{\omega}_i^c\frac{\partial\tilde{\omega}_i^c}{\partial P_{ml}} - P_i(-\frac{\partial\theta_i^c}{\partial P_{ml}}) - (\theta_i^d - \theta_i^c)(\frac{\partial P_{mi}}{\partial P_{ml}} - 2E_iG_{ii} \\
&\quad \frac{\partial E_i}{\partial P_{ml}}) - \sum_{\substack{j=1\\ j\neq i}}^{n}\beta_{ij}\,[(\cos\theta_{ij}^d - \cos\theta_{ij}^c)\frac{\partial C_{ij}}{\partial P_{ml}} - (\sin\theta_{ij}^d - \\
&\quad \sin\theta_{ij}^c)\frac{\partial D_{ij}}{\partial P_{ml}}] - \sum_{\substack{j=1\\ j\neq i}}^{n}\beta_{ij}\,[(C_{ij}\sin\theta_{ij}^c + D_{ij}\cos\theta_{ij}^c)(\frac{\partial\theta_i^c}{\partial P_{ml}} \\
&\quad - \frac{\partial\theta_j^c}{\partial P_{ml}})] - \sum_{\substack{j=1\\ j\neq i}}^{n}[C_{ij}(\cos\theta_{ij}^d - \cos\theta_{ij}^c) - D_{ij}(\sin\theta_{ij}^d - \\
&\quad \sin\theta_{ij}^c)][\gamma_{ij}(\frac{\partial\theta_i^c}{\partial P_{ml}} - \frac{\partial\theta_j^c}{\partial P_{ml}})] + \frac{M_i}{M_T}\sum_{k=1}^{n}[P_k(-\frac{\partial\theta_i^c}{\partial P_{ml}})] \\
&\quad + \frac{M_i}{M_T}(\theta_i^d - \theta_i^c)\sum_{k=1}^{n}(\frac{\partial P_{mk}}{\partial P_{ml}} - 2E_KG_{kk}\frac{\partial E_k}{\partial P_{ml}}) \\
&\quad - \frac{2M_i}{M_T}\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}[\beta_{ijk}\,(\sin\theta_{kj}^d - \sin\theta_{kj}^c)\frac{\partial D_{kj}}{\partial P_{ml}}] \\
&\quad - \frac{2M_i}{M_T}\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}[\beta_{ijk}\,D_{kj}(-\cos\theta_{kj}^c)(\frac{\partial\theta_k^c}{\partial P_{ml}} - \frac{\partial\theta_j^c}{\partial P_{ml}})] \\
&\quad - \frac{2M_i}{M_T}\sum_{k=1}^{n-1}\sum_{j=k+1}^{n}\{D_{kj}(\sin\theta_{kj}^d - \sin\theta_{kj}^c)[\gamma_{ijk}^a\frac{\partial\theta_i^c}{\partial P_{ml}} \\
&\qquad + \gamma_{ijk}^b(\frac{\partial\theta_k^c}{\partial P_{ml}} - \frac{\partial\theta_j^c}{\partial P_{ml}})]\}
\end{aligned}
\tag{8}
$$

where

$$\gamma_{ij} = \frac{\theta_j^d - \theta_j^c}{(\theta_{ij}^d - \theta_{ij}^c)^2}$$

$$\gamma_{ijk}^a = \frac{1}{\theta_{jk}^d - \theta_{jk}^c}$$

$$\gamma_{ijk}^b = \frac{\theta_i^d - \theta_i^c}{(\theta_{jk}^d - \theta_{jk}^c)^2}$$

$$\frac{\partial C_{ij}}{\partial P_{ml}} = E_jB_{ij}\frac{\partial E_i}{\partial P_{ml}} + E_iB_{ij}\frac{\partial E_j}{\partial P_{ml}}$$

$$\frac{\partial D_{ij}}{\partial P_{ml}} = E_jG_{ij}\frac{\partial E_i}{\partial P_{ml}} + E_iG_{ij}\frac{\partial E_j}{\partial P_{ml}}$$

Before calculating the sensitivity of partial energy margin by Eq. (8), several partial derivatives need to be determined, including

$$\frac{\partial\tilde{\omega}_i^c}{\partial P_{ml}},\ \frac{\partial\theta_i^c}{\partial P_{ml}},\ \frac{\partial E_i}{\partial P_{ml}},\ \frac{\partial P_{mi}}{\partial P_{ml}} \qquad i = 1, 2, \ldots, n$$

The analytical determination of these partial derivatives has been previously derived in reference [11] by the authors. Results for these derivations are not included due to lack of space. Substituting these results into Eq. (8) and after some sophisticated algebraic manipulation, the sensitivity of the partial energy margin with respect to the changes of generation power, in general a severely disturbed machine i, is derived in a closed form

$$
\begin{aligned}
S_{ip_{mi}} &= -M_i\tilde{\omega}_i^c\frac{\partial\tilde{\omega}_i^c}{\partial P_{mi}} + (P_i - \frac{M_i}{M_T}P_T)\frac{\partial\theta_i^c}{\partial P_{mi}} \\
&\quad - (1 - \frac{M_i}{M_T})(\theta_i^d - \theta_i^c)(1 - 2E_iG_{ii}\frac{\partial E_i}{\partial P_{mi}}) \\
&\quad - \frac{\partial E_i}{\partial P_{mi}}\sum_{\substack{j=1\\ j\neq i}}^{n}\beta_{ij}\,E_j[B_{ij}(\cos\theta_{ij}^d - \cos\theta_{ij}^c) \\
&\quad - (1 - \frac{2M_i}{M_T})G_{ij}(\sin\theta_{ij}^d - \sin\theta_{ij}^c)] \\
&\quad - \frac{\partial\theta_i^c}{\partial P_{mi}}\sum_{\substack{j=1\\ j\neq i}}^{n}\beta_{ij}\,[C_{ij}\sin\theta_{ij}^c + (1 - \frac{2M_i}{M_T})D_{ij}\cos\theta_{ij}^c] \\
&\quad - \frac{\partial\theta_i^c}{\partial P_{mi}}\sum_{\substack{j=1\\ j\neq i}}^{n}\gamma_{ij}[C_{ij}(\cos\theta_{ij}^d - \cos\theta_{ij}^c) - (1 - \frac{2M_i}{M_T})
\end{aligned}
$$

$$D_{ij}(\sin\theta^d_{ij} - \sin\theta^c_{ij})] \quad (9)$$

where $P_T = \sum_{i=1}^{n} P_i$

Particularly interesting in Eq. (9) is that the sensitivity takes on a completely analytical algebraic form in terms of the system parameters. This equation is then readily possible to evaluate $S_{iP_{mi}}$ and ΔP_{mi}, which is necessary to obtain a small change $\Delta\eta_i$ of η_i. These in turn allow one to compute power generation limits and generation-shedding in transient emergency state. To help explain this, the overall procedure is depicted in Fig. 2. In Fig. 2, the generation shed is timed to start at a short time after fault occurring, say Δt_b. The time Δt_b is assumed 5 cycles in our studies to complete the control procedure, including fault detection, telecommunication time, computation time for estimating the amount of generation shed [10]. The amount of generation needed to be shed is fast calculated by the analytical sensitivity method to make the partial energy margin $\Delta V_i \geq 0$. This generation-shedding is held constant during the first foreswing, and is removed at the very inception of backswing.

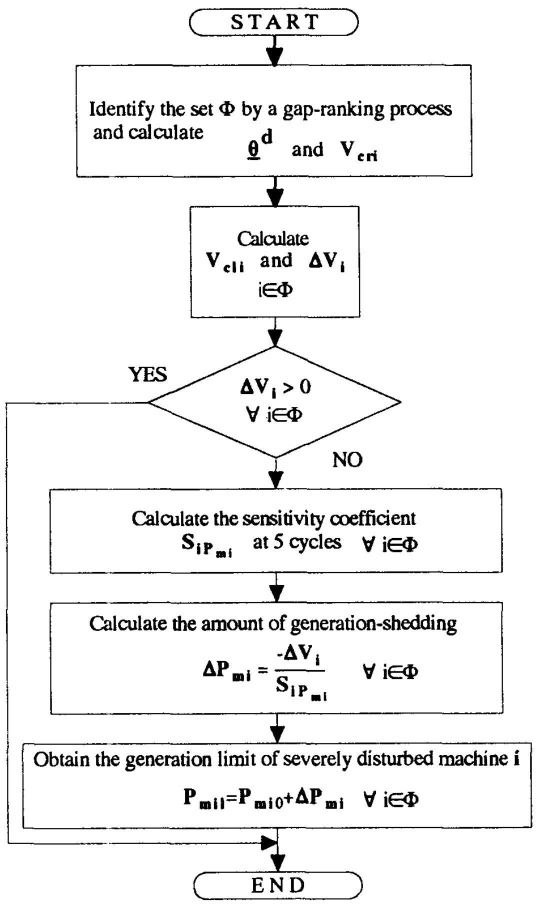

Fig. 2. Flow chart for computing the amount of generation-shedding

5. SIMULATION RESULTS AND DISCUSSION

5.1 Simulation conditions

The proposed procedure and the derived sensitivity method were tested on the Taipower system, a realistic medium-sized system in Taiwan. This system is of longitudinal structure and comprises 34 generators, 191 buses, and 234 lines. A comprehensive series of analyses are performed on the Taipower system with different faulted conditions. The system is disturbed by a three-phase short-circuit (3ΦSC) fault. It occurred at either generator buses (labelled GB), which is cleared without line switching, or load buses (labelled LB) x of a transmission line x*-y, which is cleared by opening the line at both terminals. Results obtained by the proposed procedure are compared with those obtained by using the conventional step-by-step integration method (labelled SBS).

5.2 Accuracy assessments

Table I summarizes the results obtained by the one-shot sensitivity method for the unstable cases. In such cases, generation is shed from the severely disturbed machines to make the system stable. The clearing time for each fault case was set 0.05 seconds lagging the critical clearing time so as to get unstable case. With the setting of clearing times, the partial energy margins (ΔV_i) of severely disturbed machines calculated in Table I are all negative, which indicates that these machines are unstable. In the 7th column of Table I shows the estimated amounts of generation-shedding ΔP_{mi}. The associated generation limits P_{mil} are also included in the 8th column. Corresponding to the amount of generation-shedding, the critical clearing time, T_{cct}, are calculated by using the SBS method as the benchmark. The accuracy is then assessed by comparing the clearing times T_{cl} with the critical clearing times T_{cct}. The differences $T_{cl}-T_{cct}$ are listed in the 10th column. It merits attention that the proposed method yields fairly accurate results of generation-shedding for these faults. Moreover, for almost all cases the method yields conservative results of the amount of generation-shedding. It indicates that the proposed sensitivity method predicts the generation-shedding requirements with a reasonable margin on the safe side of operation.

Table II deals specifically with the cases where the fault occurred at LB, which is cleared by tripping a transmission line and hence the post-fault configuration is different from the original one. The values of partial energy margin, sensitivity, generation-shedding, generation limit, and machine's number of each severely disturbed machine in the multimachine unstable situation are listed. From physical reasoning, sensitivity coefficients $S_{iP_{mi}}$ should be negative for the machines in severely disturbed situation. Numerical results in Tables I and II verify this conjecture. Moreover, the results in Table II show that the more severe the disturbance to the machines, the larger the sensitivities. It is reasonable because the severely disturbed machine provides greater effects on the partial energy margin. From Tables I and II, it is should be noted that the sensitivity coefficients $S_{iP_{mi}}$ are quit accurate for both GB's and LB's.

Fig. 3(a) and Fig. 3(b) show the representative rotor angles (partial list) regarding the faulted cases 3*-7 with and without generation-shedding, respectively. The clearing time is set 0.36 seconds. In such a fault case, there are totally 10 severely disturbed machines, which can be easily identified by their advanced rotor angles at $\underline{\theta}^*$ as cited in Section 3. As evidenced in Fig. 3(b), the unstable generators are regained stable operation after shedding the amount of generation calculated by the proposed method.

In Table III, another series of analyses concerning with the exploration of the dependance between the accuracy and the clearing time are carried out. A typical case with a fault occurred at GB 160* is considered. Its initial critical clearing time and power generation are 0.29 seconds and 900MW, respectively. The values of sensitivity and generation power limits at various clearing times are listed. The results show that the closer the clearing time to the critical clearing time, the more accurate the results. This is evident due to the nonlinear feature of the transient stability margin against clearing time. The relationship between the transient stability margin and clearing time is sketched in Fig. 4. Note that the curve is near linear in the vicinity of CCT. It again verifies the effectiveness of using only the linear sensitivity coefficients.

6. CONCLUSIONS

A fast one-shot sensitivity method has been proposed for determining the required amount of generation-shedding in transient emergency state. Its primary attraction lies in that the method succeeds in providing purely analytical forms for expressing sensitivity coefficients. A simple procedure has also been developed to find the relevant DLP for calculating the critical partial energy. Preliminary results of the study performed on the Taipower system with different fault conditions are found to be reasonably accurate. All these contributions can greatly help operators make corrective control in transient emergency state of power system.

Table I. Sensitivity accuracy assessment and generation power limits for fault occurred at generator buses

* - Faulted Bus NO.	Type	T_{cl} (sec)	Critical Machine	ΔV_i	$S_i P_{mi}$	ΔP_{mi} (MW)	P_{mil} (MW)	T_{cct} [SBS] (sec)	$T_{cl}-T_{cct}$ (sec)
159*	GB	0.27	G2	-6.064	-3.910	155.10	414.9	0.26	+0.01
160*	GB	0.34	G3	-6.974	-4.201	164.46	735.5	0.34	0
161*	GB	0.34	G4	-8.335	-3.867	215.56	700.4	0.35	-0.01
162*	GB	0.29	G5	-1.769	-5.069	34.9	34.1	0.29	0
163*	GB	0.29	G6	-2.057	-4.676	44.00	85.0	0.29	0
164*	GB	0.34	G7	-2.418	-5.805	41.65	138.4	0.34	0
165*	GB	0.34	G8	-2.992	-6.030	49.61	204.4	0.34	0
166*	GB	0.42	G9	-3.812	-7.216	52.83	230.2	0.42	0
167*	GB	0.36	G10	-4.778	-5.794	82.47	311.5	0.35	+0.01
168*	GB	0.37	G11	-5.463	-5.543	98.55	288.5	0.38	-0.01
169*	GB	0.37	G12	-5.593	-5.520	101.33	288.8	0.38	-0.01
170*	GB	0.58	G13	-0.684	-12.093	5.65	32.4	0.58	0
171*	GB	0.95	G14	-0.793	-16.917	4.69	55.3	0.96	-0.01
172*	GB	0.53	G15	-1.156	-11.268	10.26	56.7	0.53	0
173*	GB	0.29	G16	-1.267	-5.076	24.96	55.1	0.29	0
174*	GB	0.70	G17	-0.865	-15.006	5.76	42.2	0.71	-0.01
175*	GB	0.25	G18	-0.960	-4.547	21.12	21.9	0.26	-0.01
176*	GB	0.26	G19	-1.959	-4.962	39.48	60.5	0.26	0
177*	GB	0.99	G20	-1.499	-13.767	10.89	137.1	1.01	-0.02
178*	GB	0.45	G21	-3.373	-9.064	37.21	132.8	0.45	0
179*	GB	0.34	G22	-4.592	-6.766	67.87	187.1	0.34	0
180*	GB	0.46	G23	-3.236	-9.354	34.60	129.4	0.45	+0.01
181*	GB	0.19	G24	-0.784	-2.506	31.28	52.7	0.19	0
182*	GB	0.57	G25	-4.778	-7.819	61.11	366.9	0.58	-0.01
183*	GB	0.34	G26	-3.206	-5.964	53.76	200.2	0.34	0
184*	GB	0.34	G27	-4.298	-6.023	71.36	195.6	0.34	0
185*	GB	0.36	G28	-3.831	-5.522	69.37	264.6	0.35	+0.01
186*	GB	0.37	G29	-2.629	-5.725	45.93	264.1	0.37	0
187*	GB	0.34	G30	-4.102	-5.207	78.78	325.2	0.34	0
188*	GB	0.31	G31	-4.905	-4.437	110.60	349.5	0.32	-0.01
189*	GB	0.36	G32	-10.208	-4.883	209.06	600.9	0.37	-0.01
190*	GB	0.40	G33	-1.144	-8.320	13.75	56.3	0.40	0
191*	GB	0.30	G34	-1.973	-5.184	38.06	81.9	0.29	+0.01

Table II. Sensitivity accuracy assessment and generation power limits for fault occurred at load buses

* - Faulted Bus NO.	Type	T_{cl} (sec)	Critical Machine (in order)	ΔV_i	$S_i P_{mi}$	ΔP_{mi} (MW)	P_{mil} (MW)	T_{cct} [SBS] (sec)	$T_{cl}-T_{cct}$ (sec)
3* - 7	LB	0.36	G2	-2.248	-2.376	94.61	475.4	0.38	-0.02
			G4	-2.794	-1.518	184.05	732.0		
			G3	-2.583	-1.437	179.78	720.2		
			G6	-0.154	-1.050	14.66	114.3		
			G10	-0.680	-0.996	68.25	325.7		
			G12	-0.661	-0.966	68.36	321.6		
			G11	-0.649	-0.944	68.84	318.2		
			G1	-0.640	-0.933	68.64	315.6		
			G5	-0.074	-0.857	8.69	60.3		
			G7	-0.271	-0.617	43.90	136.1		
22* - 23	LB	0.39	G31	-3.890	-3.889	100.04	360.0	0.41	-0.02
			G32	-4.921	-3.599	136.73	733.3		
30* - 26	LB	0.40	G2	-1.019	-1.881	54.19	515.8	0.42	-0.02
			G6	-0.157	-1.536	10.20	118.8		
			G4	-1.690	-1.108	152.59	763.4		
			G3	-1.667	-1.072	155.54	744.5		
			G10	-0.573	-1.163	49.27	344.7		
			G12	-0.572	-1.146	49.90	340.1		
			G11	-0.576	-1.110	51.90	335.1		
			G1	-0.572	-1.103	51.82	332.4		
			G5	-0.067	-1.006	6.68	62.3		
			G7	-0.330	-1.045	31.56	148.4		
54* - 17	LB	0.40	G31	-3.154	-3.564	88.49	371.5	0.41	-0.01
			G32	-3.105	-3.591	86.47	783.5		

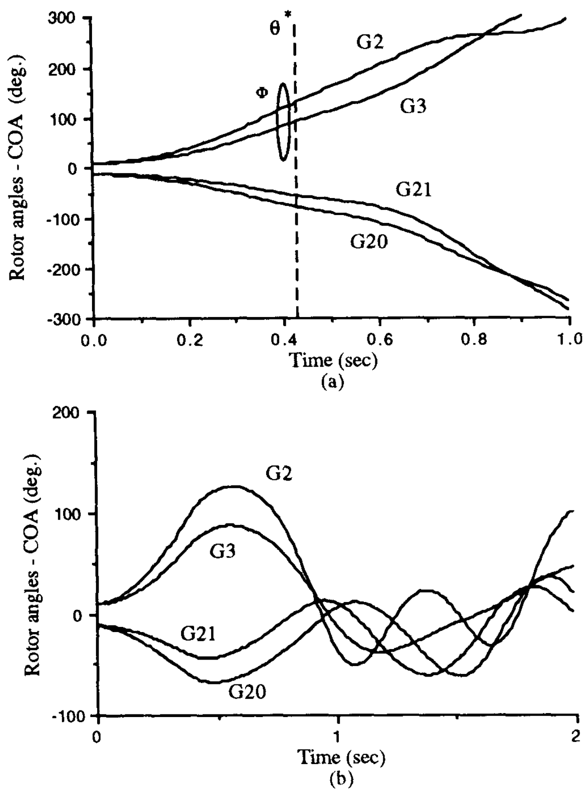

Fig. 3. Representative rotor angle responses for the Taipower system faulted at LB 3*-7, T_{cl}=0.36 seconds. (a) without generation-shedding; (b) with generation-shedding.

Table III. Relationship between the accuracy and the clearing time

Faulted Bus	T_{cl} (sec)	Critical Machine	ΔV_i	S_iP_{mi}	ΔP_{mi} (MW)	T_{cct} [SBS] (sec)	T_{cl}-T_{cct}
160*	0.15	G3	16.222	-1.807	-897.5	0.13	+0.02
160*	0.20	G3	12.671	-2.173	-583.1	0.19	+0.01
160*	0.25	G3	7.136	-2.824	-252.7	0.26	-0.01
160*	0.30	G3	-1.277	-3.669	34.6	0.30	0
160*	0.35	G3	-8.596	-4.327	198.7	0.35	0
160*	0.40	G3	-15.21	-4.099	371.2	0.42	-0.02

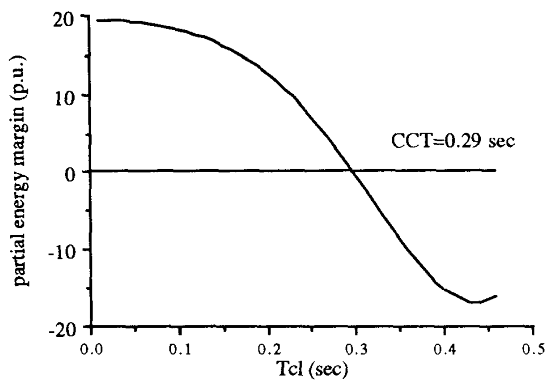

Fig. 4. Variation of partial energy margin for various clearing times (fault at GB 160*)

7. ACKNOWLEDGEMENT

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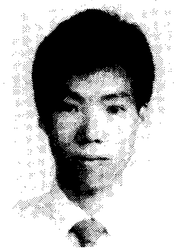
BIOGRAPHY

Hong-Chan Chang was born in Taipei, Taiwan on March 5, 1959. He received his B.S., M.S., and Ph.D. degrees all in Electrical Engineering from National Cheng Kung University in 1981, 1983, and 1987, respectively. In August of 1987, he joined National Taiwan Institute of Technology as a faculty member where he is presently an associate professor of the Electrical Engineering Department. His major areas of research include power system stability and neural network applications to power system.



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