Stability Control using PEBS method and Analytical Sensitivity of the Transient Energy Margin

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Abstract-- **This paper introduces a stability control scheme based on a Lyapunov direct method, the Potential Energy Boundary Surface (PEBS) method, and analytical sensitivity of the transient energy margin. It classifies the stability control means into two categories, admittance-based control (ABC) and generator input-based control (GIBC), and uses a comprehensive method to analyze the contribution of each control. The scheme can get the optimal control from all the available control means by sensitivity analysis and then verify it in the transient stability program. Fast and accurate control goal is obtained from this stability control scheme.**

Index Terms-- **Transient Stability, Stability Control, PEBS, Energy Margin, Sensitivity Analysis, Control Classification**

I. Introduction

Transient stability control is more difficult in current deregulated environment than before. This is due to the frequently changing generation/load patterns and network topology during normal power system operations. Competitive market, steady increasing load, and limited transmission capacity stress the power system closer to the security margin. Several unexpected disturbances may put the system into an emergency state, resulting in cascading outages or system collapse if there are no fast and appropriate stability controls in action. Conventional off-line study and pre-defined stability control scheme can no longer adapt to the fast changing conditions. The need for fast and adaptive stability analysis and stability control is more visible.

Lyapunov-like direct methods have the advantages of speed and security margin information. Therefore, many good results have been obtained by many researchers' continuous efforts. There are some useful investigations in the transient stability analysis by using analytical sensitivity of the transient energy margin. In [1], small parameter changes of generation, load and network are analyzed and sensitivity analysis is used for stability analysis, with the assumption that the mode of disturbance (MOD) is not altered by the small changes. In [2], big changes can be of concern for the stability analysis. In [3], the sensitivity-based BCU method can analyze the transient stability no matter whether the MOD is altered or not. However, these interesting papers focus more on the stability analysis by using sensitivity information. Stability control is discussed less.

This paper classifies current stability control means into two categories, admittance-based control (ABC) means and generator input-based control (GIBC) means. The proposed method can quickly find the parameter variance of each stability control means for the transient stability analysis. Analytical sensitivity of the transient energy margin is used to find the most suitable control to make the possibly unstable system stable. One of the Lyapunov methods, PEBS method, is used. Some simulation results are provided.

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II. Mathematical Formulation

A. Lyapunov-like Transient Energy Function

In the Center of Angle (COA) reference [1],

$$\dot{\theta}_i = \tilde{\omega}_i \tag{1}$$

$$M_i \dot{\tilde{\omega}}_i = P_i - P_{ei} - \frac{M_i}{M_T} P_{COI} \tag{2}$$

where

$$P_{ei} = \sum_{j=1, j\neq i}^{n} [C_{ij}\sin(\theta_i - \theta_j) + D_{ij}\cos(\theta_i - \theta_j)]$$

$$P_i = P_{mi} - E_i^2 G_{ii}$$

$$P_{COI} = \sum_{i=1}^{n}(P_i - P_{ei})$$

$$M_T = \sum_{i=1}^{n} M_i$$

$$C_{ij} = E_i E_j B_{ij},\ D_{ij} = E_i E_j G_{ij}$$

Cij, Dij : real and reactive parts of the admittance matrix. They change during conditions of pre- , during- and post-fault.

As for the transient angle stability, transient energy margin can be calculated by following equation:

$$\Delta V = -\frac{1}{2} M_{eq} \tilde{\omega}_{eq}^{cl^2} - \sum_{i=1}^{n} P_i^{pf} (\theta_i^u - \theta_i^{cl}) - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} [C_{ij}^{pf} (\cos\theta_{ij}^u - \cos\theta_{ij}^{cl}) - \beta_{ij} D_{ij}^{pf} (\sin\theta_{ij}^u - \sin\theta_{ij}^{cl})] \quad (3)$$

where,

$$\beta_{ij} = \frac{\theta_i^u + \theta_j^u - \theta_i^s - \theta_i^s}{\theta_{ij}^u - \theta_{ij}^s} \text{ (linear dependence direction)}$$

θ^{cl} : rotor angle positions at the end of disturbance,

θ^u : controlling u.e.p (unstable equilibrium point), $M_{eq} = M_{cr} M_{sys} / (M_{xr} + M_{sys})$,

$\tilde{\omega}_{eq}^{cl} = \tilde{\omega}_{cr}^{cl} - \tilde{\omega}_{sys}^{cl}$,

M_{cr}, M_{sys} : inertia constants of the critical generators and rest generators respectively,

$\tilde{\omega}_{cr}^{cl}, \tilde{\omega}_{sys}^{cl}$: speed of inertia centers of the critical generators and the rest of generators respectively at the end of a disturbance.

B. *PEBS method*

Potential Energy Boundary Surface (PEBS) method [4]-[5] is based on physical intuition. Its procedure is: from the post-fault SEP first draw a number of rays in every direction in the angle space with COA as reference. Along each ray, search for the first point where the potential part of the Lyapunov energy function attains its relative maximum. The points of δs are thus obtained and these rays are then joined to form the boundary surface of interest (stability boundary). This characterizes the PEBS. Mathematically, PEBS can be obtained by setting the directional derivative (along the rays emanating from stable equilibrium point (SEP)) of $V_P(\delta)$ to zero, as follows:

$$[f(\delta)]^T \bullet (\delta - \delta^s) = 0 \quad (4)$$

i.e., $\sum_{i=1}^{n} (\delta_i - \delta_i^s) f_i(\delta) = 0$

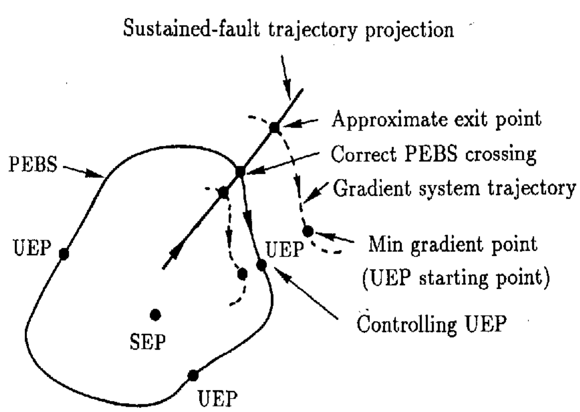

Fig. 1. PEBS crossing and Controlling UEP

Fig. 1 gives the relationship among unstable equilibrium point (UEP), PEBS crossing point, exit point, Controlling UEP [4]. Fig. 2 gives a simple example of the system trajectory in the rotor angle space [5].

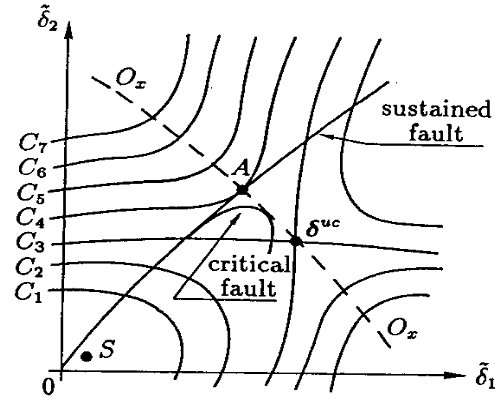

Fig. 2. System trajectory in the rotor angle space

PEBS method assumes that the system critical energy value is equal to the system potential energy maximum value along the system trajectory. We can see from Fig. 1 and Fig. 2 that when the system is not very ill-conditioned, the controlling UEP, and the PEBS crossing points of fault-on and critical trajectories are very close. Therefore, PEBS method can get an accurate approximation of critical clearing time (CCT). The advantage of PEBS method is that it does not need the Controlling UEP calculation, which is very complex and time consuming. The system post-fault trajectory path is not known before the CCT solution. It may give either an optimistic or pessimistic estimate of the CCT. Iterative PEBS [5] and Corrective PEBS [6] are proposed to give more accurate solution of CCT.

Step 1, integrate the fault-on trajectory, use the fault-on δ and post-fault Y to get the first PEBS crossing point δ_{cross}, that is, at time T, (4) changes the sign from '-' to '+', and V_{PE} gets its local maximum which is the first estimate of Vcr.

Step 2, use the fault-on δ, ω and Y to find the transient energy V equal to V_{PE}. That time point Tu is the estimate of the CCT.

Step 3, integrate the post-fault trajectory from Tu to T.

Step 4, if (4) doesn't change the sign, that Tu is the CCT, stop. Else, find the new V_{PE} and δ_{cross}, go to Step 2 to find new Tu, say it is Tu2. If $|Tu2 - Tu| \le \varepsilon$, stop, either Tu or Tu2 is the CCT. Else, let Tu=Tu2, go to Step 3.

From this iterative or corrective PEBS method, we can get the more accurate results of the CCT.

For the transient energy margin, we can use δ_{cross} as the approximate δ^u, and then use (3) to get the energy margin. If we do not use PEBS method, we can use other Lyapunov-like methods, i.e., the MOD method, [1], [5], to get the real Controlling UEP and finally get the energy margin. But it may be much slower than PEBS method because the grouping pattern of the machines at instability is fairly complex and also arriving at the Controlling UEP may be very difficult.

C. *Control Classification*

There are many fast stability control means in the literature [7] and real practice. From the generator side, we have the generator tripping, fast valving, dynamic braking, etc. From the load side, we have the load reduction (by voltage reduction), load shedding, etc. From the network side, we have FACTS controllers (TCSC, SVC, etc.), shunt reactors and capacitors, switching on/off lines, etc. For all the above control means, there are two comprehensive ways: either change the Pm (fast valving), or change the admittance matrix. The generator tripping is the combination of the two. Therefore, we can define two stability control categories, generator-input-based control (GIBC) means, and admittance-based control (ABC) means.

For generator-input-based control (GIBC) means, the variance of Pm can be easily obtained. For admittance-based control (ABC) means, the variances of admittance matrix Y can be obtained as follows:

For a g-generator-l-bus system, the augmented admittance matrix:

$$\hat{Y} = \begin{bmatrix} Y_{gg} & Y_{gl} \\ Y_{lg} & Y_{ll} \end{bmatrix} \tag{5}$$

where

$Y_{ll} = Y_{bus} + Y_{gen} + Y_{load}$

Y_{bus}: load flow node admittance matrix

Y_{gen}: at generator-connected bus, admittance of generator branch, others, 0

Y_{load}: at load bus, constant admittance of load, others, 0

Y_{ll}: lxl bus admittance matrix

Y_{gg}: gxg generator admittance matrix

Y_{gl}: gxl generator-bus admittance matrix

Y_{lg}: lxg bus-generator admittance matrix

The reduced admittance matrix is:

$$Y = Y_{gg} - Y_{gl}(Y_{ll})^{-1} Y_{lg} \tag{6}$$

For all the single admittance-based control (excluding generator tripping), from fast decoupled power flow method [8], we know that

$$Y_{ll,new} = Y_{ll} - b * M^T * M \tag{7}$$

$$(Y_{ll,new})^{-1} = (Y_{ll})^{-1} - c * X * M * (Y_{ll})^{-1} \tag{8}$$

where

$c = (-1/b + M * X)^{-1}$ and $X = (Y_{ll})^{-1} * M^t$

Therefore, we get the reduced admittance matrix variance for each control means,

$$\begin{aligned} \Delta Y = Y_{new} - Y_{old} &= Y_{gl}[(Y_{ll})^{-1} - (Y_{ll,new})^{-1}] Y_{lg} \\ &= Y_{gl}[cXM(Y_{ll})^{-1}] Y_{lg} \end{aligned} \tag{9}$$

There are different network control means to change the reduced admittance matrix as follows:

<u>Case (1)</u>. one line i-j outage or switching off

M: row vector which is null except for Mi=a and Mj=-1

a: off-nominal turns ratio referred to the bus corresponding to column i, for a transformer

1, for a line

b: line or nominal transformer series admittance

<u>Case (2)</u>. one line i-j switching on

M: row vector which is null except for Mi=-a and Mj=1

a, b are the same as above.

<u>Case (3)</u>. inserting TCSC at line i-j, compensation k, 0<k<1

M: row vector which is null except for Mi=a and Mj=-a, $a = \sqrt{1/k - 1}$

b is the same as above.

<u>Case (4)</u>. at bus i, switching on shunt reactor, capacitor, braking-resistor, SVC

M: row vector which is null except for Mi=1

b: admittance of shunt reactor, capacitor, braking-resistor, SVC

<u>Case (5)</u>. at bus i, switching off shunt reactor, capacitor, braking-resistor, SVC, load reduction

M: row vector which is null except for Mi=-1

b: admittance of shunt reactor, capacitor, braking-resistor, SVC,

for load reduction or shedding, b=k, $0 \le k \le 1$

D. Sensitivity Analysis

For the transient energy margin, its sensitivity to a change in any parameter α_k (θ^{cl} , θ^{u} , $\tilde{\omega}^{cl}$, P_i^{pf} , B_{ij}^{pf} , G_{ij}^{pf}), can be given by the partial derivative of ΔV with respective to α_k .

$$\Delta V = \sum_{k=1}^{m} \frac{\partial \Delta V}{\partial \alpha_k} \Delta \alpha_k \tag{10}$$

For our control means, since the clearing time is known, we only consider the changes of θ^u , P_i^{pf} , B_{ij}^{pf} , G_{ij}^{pf} . We can get the change of energy margin by

$$\begin{aligned} \Delta V = &\sum_{i=1}^{n} \frac{\partial \Delta V}{\partial P_{mi}} \Delta P_{mi} + \sum_{i=1}^{n} \frac{\partial \Delta V}{\partial G_{ii}} \Delta G_{ii} + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\partial \Delta V}{\partial G_{ij}} \Delta G_{ij} \\ &+ \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \frac{\partial \Delta V}{\partial B_{ij}} \Delta B_{ij} + \sum_{i=1}^{n} \frac{\partial \Delta V}{\partial \theta_i^u} \Delta \theta_i^u \end{aligned} \tag{11}$$

where

$$\frac{\partial \Delta V}{\partial P_{mi}} = -(\theta_i^u - \theta_i^{cl})$$

$$\frac{\partial \Delta V}{\partial G_{ii}} = E_i^2 (\theta_i^u - \theta_i^{cl})$$

$$\frac{\partial \Delta V}{\partial G_{ij}^{pf}} = \beta_{ij} E_i E_j (\sin \theta_{ij}^u - \sin \theta_{ij}^{cl})$$

$$\frac{\partial \Delta V}{\partial B_{ij}^{pf}} = -E_i E_j (\cos \theta_{ij}^u - \cos \theta_{ij}^{cl})$$

$$\frac{\partial \Delta V}{\partial \theta_i^u} = -P_i^{pf} + \sum_{j=i+1}^{n} (E_i E_j B_{ij}^{pf} \sin \theta_i^u + \beta_{ij} E_i E_j G_{ij}^{pf} \cos \theta_i^u)$$

we get the ΔG_{ij} , ΔB_{ij} from (9).

For big parameter change (i.e., additional network topology change), controlling UEP may change. From [2] we get

$$(A)(\Delta \theta_i^u) = R_i \tag{12}$$

where

$$A_{ii} = (1 - 2\frac{M_i}{M_T}) \sum_{j=1, j \ne i}^{n} C_{ij} \cos \theta_{ij}^u$$

$$A_{ij} = (2\frac{M_j}{M_T}) \sum_{l=1, l \ne j}^{n} D_{lj} \sin \theta_{lj}^u + C_{ij} \cos \theta_{ij}^u - D_{ij} \sin \theta_{ij}^u$$

$$R_i = E_i^2 \Delta G_{ii} - \frac{M_i}{M_T}\sum_{j=1}^{n} E_j^2 \Delta G_{jj} - \frac{M_i}{M_T}\sum_{l=1}^{n}\sum_{j=1,j\neq l}^{n} E_l E_j \cos\theta_{lj} \Delta G_{lj}$$

$$+ \sum_{j=1,j\neq i}^{n} [E_i E_j \sin\theta_{ij}^u \Delta B_{lj} + E_i E_j \cos\theta_{ij}^u \Delta G_{lj}]$$

Therefore, we can get

$$\Delta\theta^u = A^{-1} R \qquad (13)$$

$$\theta_{i,new}^u = \theta_i^u + \Delta\theta_i^u \qquad (14)$$

if $\max(\Delta\theta^u) < \varepsilon$, assume controlling UEP does not change, ignore the 5th item of (11).

III. Stability Control Scheme

After a big disturbance (fault) and its clearing, first we do the transient stability study (i.e., use PEBS method) to see if the system is stable or not. If yes, keep monitoring the system. If not, check all available control means being considered or not. If all control means have not been analyzed, use the sensitivity analysis of energy margin to find the suitable control to make the system stable, then check the solution in the transient stability program to make sure it will work. Finally, issue the control command to stabilize the system and keep monitoring the system. If all control means are analyzed and the system is still unstable, warning will be given and the process will stop. In general, as the last defense, load shedding and islanding may be deployed to try to keep the loss as minimal as possible to make the system stable.

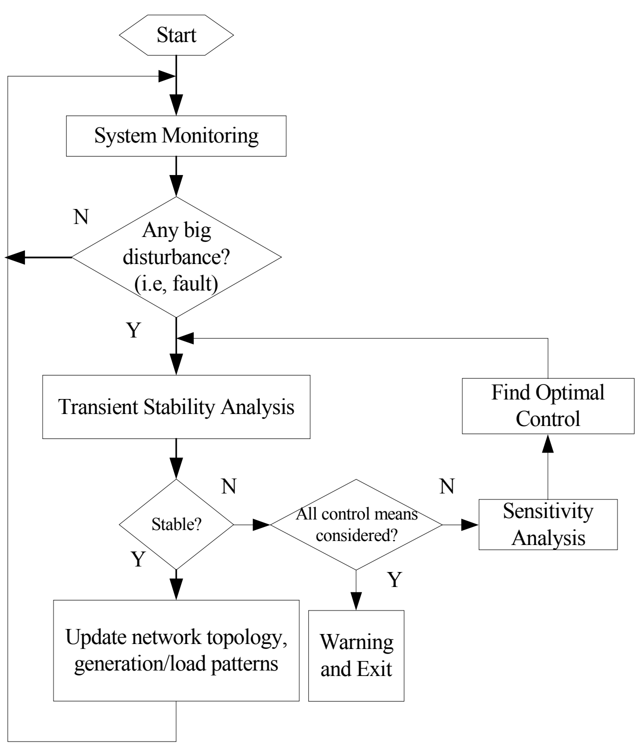

Fig. 3. Flow chart of the stability control scheme

IV. Numerical Results

Given a modified IEEE 14-bus system (modified load and generation conditions), assume the following control means are available: all generators have fast valving (decrease up to 20% capacity), braking resistors (up to 50% capacity), line switching, TCSC (up to 50% compensation capacity of that line), SVC (up to 50MVA capacity), all buses have shunt reactors and capacitors (up to 50MVA capacity), load shedding. Simply use the classical machine model as described in (1) – (2) for the step-by-step (SBS) method and PEBS method. Fig. 1 gives the modified IEEE-14 bus system configuration. Table I gives the base flow condition.

TABLE I
Base Flow Condition (Pd, Qd, Bs, Pg: MVA; V: pu)

Bus	Pd	Qd	Bs	Pg	V
1	0.00	0.00	0.	232.39	1.060
2	21.70	12.70	0.	40.00	1.045
3	94.20	19.00	0.	20.00	1.010
4	47.80	-3.90	0.	0.00	1.014
5	7.60	1.60	0.	0.00	1.015
6	11.20	7.50	0.	18.00	1.070
7	0.00	0.00	0.	0.00	1.063
8	0.00	0.00	0.	15.00	1.090
9	39.50	16.60	19.	0.00	1.057
10	9.00	5.80	0.	0.00	1.052
11	3.50	1.80	0.	0.00	1.058
12	29.10	1.60	0.	0.00	1.032
13	43.50	5.80	0.	0.00	1.040
14	24.90	5.00	0.	0.00	1.024

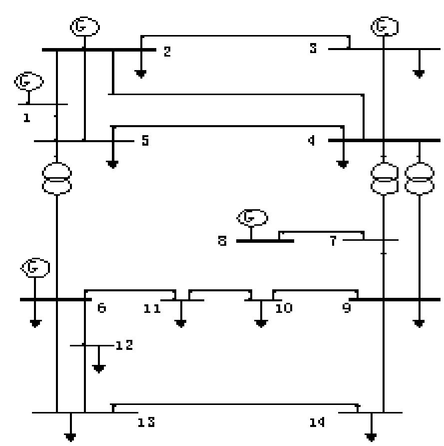

Fig. 4. Modified IEEE 14-bus system

Assume that at t=0s, a three-phase-to-ground-fault occurs at 95% of line 9-14. The critical clearing time (CCT) of step-by-step (SBS) method is 0.06s, and the CCT of PEBS method is 0.09s. There is a small difference between the SBS and PEBS methods due to numerical reason. When the fault is cleared at t=0.1s, we get the machine rotor angle curve given as below in Fig. 5, where Gen 1's angle goes upward and all other generators' angles go downward. The transient energy margin is –0.042 by PEBS method, as described in (3).

All rotor angles in Fig. 5 ~ Fig. 8 are in degrees. Total simulation time is 3s. The maximal angle difference is chosen as the angle stability criterion. If the maximal angle difference among all machines is bigger than 90^0 at t=3s, the system is unstable. Otherwise, the system is stable.

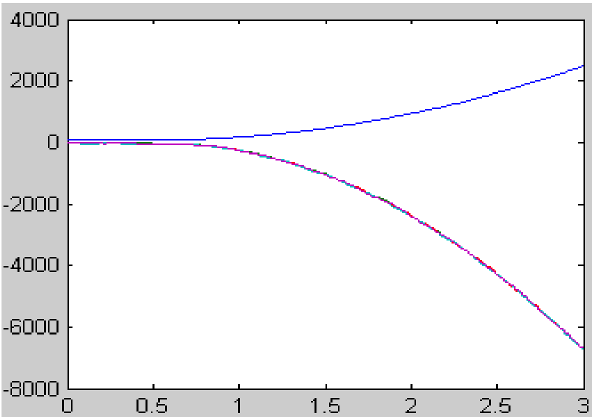

Fig. 5. Machine angles when clear fault at t=0.1s

Assume stability control command can be issued at t=0.1100s with the aid of the sensitivity analysis.

A. Stabilizing Switching

We get the new transient energy margin after switching additional single line as given in Table II.

TABLE II
NEW TRANSIENT ENERGY MARGIN AFTER STABILIZING SWITCHING

Line	1-2	7-9	4-7	4-9	5-6
Energy Margin	-0.007	-0.025	-0.027	-0.028	-0.033

We only list the top 5 lines, which contribute positively for stabilizing the system. Besides these 5 lines, the switching of line 2-3, 6-11, 13-14 also contributes positively for the stabilizing. Switching line 7-8 will result in islanding. The switching of other lines contributes negatively for stabilizing. The sensitivity analysis is not very accurate because of the first order approximation. Thus, we need to check with transient stability program. Take the example of line 1-2 switching, which contributes the most to stabilizing, as described in Fig. 6. We can see the energy margin after this switching is –0.007. That means the system is still unstable after this control. However, by the angle difference criterion in the time domain transient stability program, the system can be judged as stable.

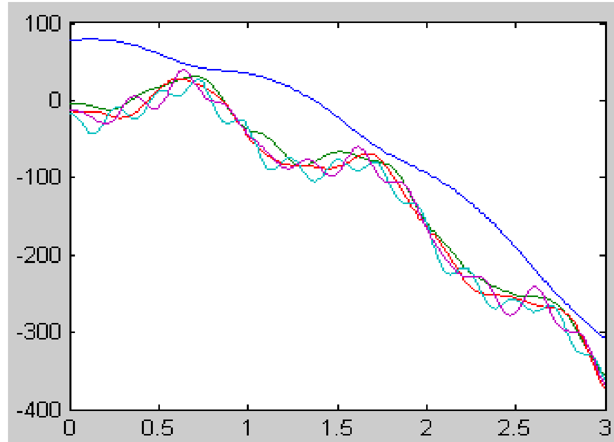

Fig. 6. Machine angles when switching line 1-2 at t=0.11s

B. TCSC Switching

Similarly, we get the top 5 lines by TCSC switching with compensation capacity of 50%, as described in Table III.

TABLE III
NEW TRANSIENT ENERGY MARGIN AFTER SWITCHING TCSC

Line	5-6	4-7	4-9	1-5	3-4
Energy Margin	-0.017	-0.034	-0.034	-0.037	-0.037

If we check with transient stability program, the system is still unstable.

C. Load Shedding

Assume the constant impedance model and the area load can be shed simultaneously with the same ratio. From the analytical sensitivity of the transient energy margin, we can get that the 24.5% load shedding is needed for the energy margin changing from negative to positive value. In fact, by the transient stability program, only 5.5% load shedding can make the system stable. Fig. 7 is the rotor angle curve obtained by shedding 5.5% load. Fig. 8 is the rotor angle curve obtained by shedding 24.5% load.

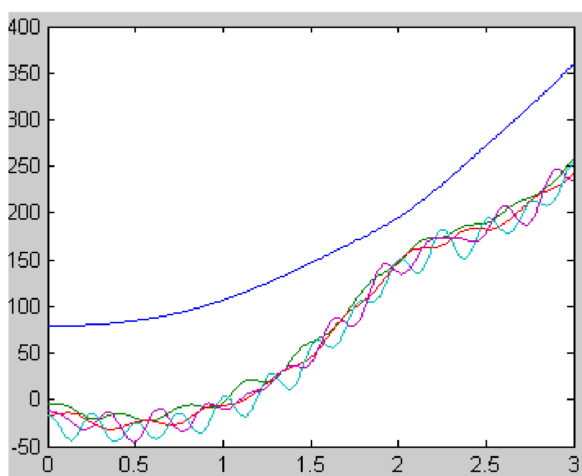

Fig. 7. Machine angles when 5.5% load shedding at t=0.11s

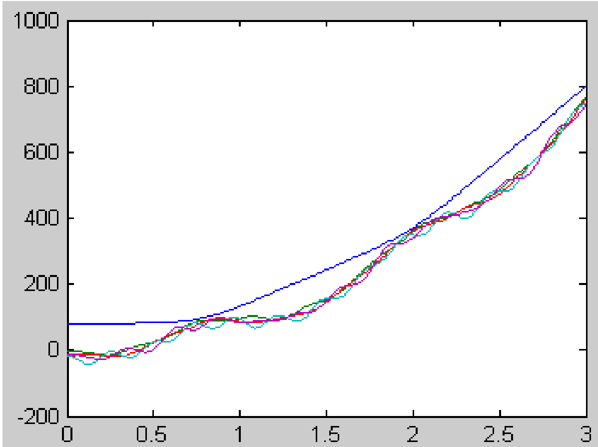

Fig. 8. Machine angles when 24.5% load shedding at t=0.11s

D. *Shunt Capacitor and Reactor Switching*

In general, when switching on shunt capacitor or reactor at the same bus, their contributions for the energy margin are opposite. For this modified IEEE 14-bus system, when switching on shunt capacitors with 50 MVA capacity at buses 1, 2, 3 and 14 respectively, the energy margin will increase. While doing it at other buses, the energy margin will decrease. When switching on shunt reactors at these buses, their contributions are opposite. When switching on shunt reactor with 50 MVA capacity at buses 4 to 13 respectively, the energy margin will increase. For switching shunt capacitor and reactor at buses by 50MVA capacity, the most contributing shunt capacitor switching is at bus 1, and the new transient energy margin is –0.038; the most contributing shunt reactor switching is at bus 9, and the new transient energy margin is –0.036. If we check with the transient stability program, both cases are sill unstable.

V. Conclusion

This paper presents a stability control scheme based on the PEBS method and analytical sensitivity of the transient energy margin. It analyzes the contribution of each of the control means by defining its sensitivity information and finds the suitable control to stabilize the system. Two categories of the stability control means are given, admittance-based control (ABC) and generator input-based control (GIBC). A modified IEEE 14-bus system is used to test the methodology. The time domain transient stability program is used as a reference. Some simulation results are provided. It needs to be considered that the PEBS method has limits, i.e., the assumption that the PEBS crossing point and Controlling UEP are close to each other for normal system. For some special cases, the error of this method may be a bit bigger. For example, if we find a solution by sensitivity analysis, the system may be stable after this control. However, in transient stability program, it may still be unstable. On the other hand, the system may be judged unstable by sensitivity analysis after the control action. But it may be stable by the transient stability program. The accuracy of the first order sensitivity analysis may be influenced by a big parameter change, which results in the change of Controlling UEP. We can also see from the results that the sensitivity analysis method can give good direction for the control but the final contribution needs to be verified in the transient stability program. Further research work is continuing to get further results.

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VII. Biographies

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Dr. Kezunovic is a Fellow of the IEEE and member of CIGRE-Paris.