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A Novel Technique to Determine the Controlling Unstable Equilibrium Point in Power Systems

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***Abstract* – The computation of the Unstable Equilibrium Point (UEP) is a key step involved in the direct methods of power system transient stability analysis. This paper presents an idea for formulating generalized energy function for the stability detection of interconnected power systems and obtained the UEP in an easy way. The energy function is formulated based on Energy functions for individual machines. The technique is validated by computing the Stable Equilibrium Point (SEP), the controlling UEP, and The Critical Clearing Time (CCT). Then, a Conventional Time Domain Method (CTDM) is used to validate the novel technique's results.**

***Keywords* – Online Transient stability, Real-time Transient Stability, Transient Energy Function (TEF), Stable Equilibrium Point (SEP), Unstable Equilibrium Point (UEP), Critical Clearing Time (CCT).**

I. INTRODUCTION

In the past, transient stability has been evaluated using Transient Energy Function (TEF) [1-3], to calculate Critical Clearing Time (CCT). Transient Energy Function is known to be a very powerful tool of assessing CCT of a power system without solving the system dynamics equations at post fault. Alternatively, direct methods determine system stability based on energy functions. These methods adjudicate whether the system will remain stable or not once the fault is cleared, by comparing the system transient energy, at the end of a disturbance, to a critical energy value [4-7]. Assuming that the post fault system has a stable equilibrium, there is region of initial conditions in the state system space, from which the faulted system trajectories converge to a stable equilibrium. This is the stability region of the stable equilibrium point (SEP) [5]. When the power system is stressed, due to increase in volume and/or number of transactions or the occurrence of a major disturbance or both [8], [9], the system can lose stability. The computation of UEP is very important for stability region estimation. Among the transient energy function (TEF) methods, both the closest UEP method [11] and the controlling UEP method [10] need to compute the desired UEP. The closest UEP is the UEP having the lowest energy function value among all the UEPs on the stability boundary of the SEP. It is thus necessary to understand the characteristics of the equilibrium points and how these can affect the particular stability of the system. Several methods have been proposed to compute the closet UEP [11], [12].

This paper presents an efficient transient stability assessment using individual machines energy functions approach. A novel technique for computation of controlling unstable equilibrium points is proposed. The importance of the computation of the controlling UEP is further emphasized with a new methodology for improvement of stability margins based on the analysis of the controlling UEP. Thus, conditions for the separation of a machine (or a group of machines) are determined. Several test systems is employed to be simulated to prove the validity and effectiveness of the novel approach.

II. THE POWER SYSTEM MODEL

The power system is represented by the so-called classical model where generators are represented by constant voltage behind transient reactance and loads are modeled by constant impedance [13]. Furthermore, the motion of the generators is expressed with respect to the center of inertia (C.O.I.) of the system.

For an n-generator system, let for generator i,

E_i, δ_i	Magnitude and angle of voltage behind transient reactance, respectively.
ω_i	Rotor speed relative to asynchronous frame.
M_i	Generator inertia constant.

The position δo and speed ωo of the C.O.I. are defined by:

$$\delta_o = \frac{1}{M_t}\sum_{i=1}^{n} M_i\delta_i \quad , \quad \omega_o = \frac{1}{M_t}\sum_{i=1}^{n} M_i\omega_i \qquad (1)$$

Where: $M_t = \sum_{i=1}^{n} M_i$

The generator's motion in the C.O.I. frame is defined as:

$$\left.\begin{aligned}\theta_i &= \delta_i - \delta_o \\ \varpi_i &= \theta_i^{\bullet} = \omega_i - \omega_o\end{aligned}\right\} \quad (2)$$

Assume that the effect of damping is neglected in the system; the generator's equations of motion are given by the following differential equations:

$$\left.\begin{aligned}M_i \varpi_i^{\bullet} &= P_i - P_{ei} - \frac{M_i}{M_t} P_{COI} \\ \theta_i^{\bullet} &= \varpi_i \qquad i = 1,2,\cdots,n\end{aligned}\right\} \quad (3)$$

The expressions for Pi, Pei and PCOI are given by:

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

$$P_{ei} = \sum_{\substack{j=1\\ j\neq i}}^{n} \left[C_{ij} \sin\delta_{ij} + D_{ij} \cos\delta_{ij} \right] \quad (4)$$

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

Where:

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

P_{mi}	Mechanical power input.
G_{ii}	Real part of the ith diagonal element of the network's Y-matrix.
C_{ij}, B_{ij}	Real and imaginary components of the ijth element of the network's Y-matrix, respectively.

III. The Transient Energy Function for Individual Machine

Rearrange (3) for each machine at the post-fault condition and multiplying it by θi˙, the following equation can be obtained [14]:

$$\left[M_i \varpi_i^{\bullet} - P_i + P_{ei} + \frac{M_i}{M_t} P_{COI} \right] \theta_i^{\bullet} = 0, \quad i = 1,2,\cdots,n \quad (5)$$

Integrate (5) with respect to time, using to as lower limit, where $\varpi_i^{\bullet}(t_o) = 0$ and $\theta_i(t_o) = \theta_i^s = \delta_i^s - \delta_0$ which is called the Stable Equilibrium Point (SEP), yields

$$V_i = \frac{1}{2} M_i \varpi_i^2 - P_i(\theta_i - \theta_i^s) + \sum_{\substack{j=1\\ j\neq i}}^{n} C_{ij} \int_{\theta_i^s}^{\theta_i} \sin\theta_{ij}\, d\theta_i + \sum_{\substack{j=1\\ j\neq i}}^{n} D_{ij} \int_{\theta_i^s}^{\theta_i} \cos\theta_{ij}\, d\theta_i + \frac{M_i}{M_t} \int_{\theta_i^s}^{\theta_i} P_{COI}\, d\theta_i \quad (6)$$

Eqn. (6) is evaluated using the post fault network configuration. The first term in Eqn. (6) represents the KE of machine i with respect to the system COI. The remaining terms are considered to be the PE. Thus, Eqn. (6) can be expressed as:

$$V_i = V_{KEi} + V_{PEi} \quad (7)$$

Eqn. (7) consists of two parts: kinetic energy and potential energy. Both energies need to be solved numerically. After rotor angles are found numerically, the energies can be represented by:

$$KE_i = \frac{1}{2} M_i \varpi_i^2 \quad (8)$$

$$PE_i = -P_i(\theta_i - \theta_i^s) + \sum_{\substack{j=1\\ j\neq i}}^{n} C_{ij} \begin{bmatrix} \cos(\theta_i^s - \theta_j) - \\ \cos(\theta_i - \theta_j) \end{bmatrix} + \sum_{\substack{j=1\\ j\neq i}}^{n} D_{ij} \begin{bmatrix} \sin(\theta_i - \theta_j) - \\ \sin(\theta_i^s - \theta_j) \end{bmatrix} + \frac{M_i}{M_t} \int_{\theta_i^s}^{\theta_i} P_{COI}\, d\theta_i \quad (9)$$

$$\int_{\theta_i^s}^{\theta_i} P_{COI}\, d\theta = \sum_{i=1}^{n} P_i(\theta_i - \theta_i^s) - \sum_{i=1}^{n} \sum_{\substack{j=1\\ j\neq i}}^{n} C_{ij} \begin{bmatrix} \cos(\theta_i^s - \theta_j) - \\ \cos(\theta_i - \theta_j) \end{bmatrix} - \sum_{i=1}^{n} \sum_{\substack{j=1\\ j\neq i}}^{n} D_{ij} \begin{bmatrix} \sin(\theta_i - \theta_j) - \\ \sin(\theta_i^s - \theta_j) \end{bmatrix} \quad (10)$$

The critical energy of machine i $V_{critical\_i}$ is evaluated where $\theta_i = \theta_{iu}$, $w_i = 0$ as indicated in eqn. (11).

$$V_{Critical\_i} = -P_i(\theta_i^u - \theta_i^s) + \sum_{\substack{j=1\\ j\neq i}}^{n} C_{ij} \begin{bmatrix} \cos(\theta_i^s - \theta_j^u) - \\ \cos(\theta_i^u - \theta_j^u) \end{bmatrix} + \sum_{\substack{j=1\\ j\neq i}}^{n} D_{ij} \begin{bmatrix} \sin(\theta_i^u - \theta_j^u) - \\ \sin(\theta_i^s - \theta_j^u) \end{bmatrix} + \frac{M_i}{M_t} \int_{\theta_i^s}^{\theta_i^u} P_{COI}\, d\theta_i \quad (11)$$

$$\int_{\theta_i^s}^{\theta_i^u} P_{COI}\, d\theta = \sum_{i=1}^{n} P_i(\theta_i^u - \theta_i^s) - \sum_{i=1}^{n} \sum_{\substack{j=1\\ j\neq i}}^{n} C_{ij} \begin{bmatrix} \cos(\theta_i^s - \theta_j^u) - \\ \cos(\theta_i^u - \theta_j^u) \end{bmatrix} - \sum_{i=1}^{n} \sum_{\substack{j=1\\ j\neq i}}^{n} D_{ij} \begin{bmatrix} \sin(\theta_i^u - \theta_j^u) - \\ \sin(\theta_i^s - \theta_j^u) \end{bmatrix} \quad (12)$$

Where: θu is the Unstable Equilibrium Point (UEP).

By the first integration of real power mismatch in eqn. (3). The overall system energy function V_{system} [4] can be written as:

$$V_{system} = \sum_{i=2}^{n} V_i = \sum_{i=1}^{n} \frac{1}{2} M_i \varpi_i^2 - \sum_{i=1}^{n} P_i(\theta_i - \theta_i^s) - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left[C_{ij} (\cos_{ij} - \cos_{ij}^s) - I_{ij} \right] \quad (13)$$

Where:

$$I_{ij} = D_{ij} \frac{(\theta_i + \theta_j) - (\theta_i^s + \theta_j^s)}{\theta_{ij} - \theta_{ij}^s} (\sin_{ij} - \sin_{ij}^s) \quad (14)$$

Thus, the sum of the individual machine energies is equal to the total system energy and the critical energy for overall system $V_{sys-critical}$ is given by:

$$V_{sys-critical} = -\sum_{i=1}^{n} P_i(\theta_i^u - \theta_i^s) - \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \left[C_{ij} (\cos_{ij}^u - \cos_{ij}^s) - I_{ij}^u \right] \quad (15)$$

Where:

$$I_{ij}^u = D_{ij} \frac{(\theta_i^u + \theta_j^u) - (\theta_i^s + \theta_j^s)}{\theta_{ij}^u - \theta_{ij}^s} (\sin_{ij}^u - \sin_{ij}^s) \quad (16)$$

IV. PROPOSED ALGORITHM

Correct determination of the SEP and UEP are essential for the successful use of the transient energy function, based on eqn. (3), the stable equilibrium point of the post fault system is found by solving the following nonlinear algebraic equations by the steepest descent method [15].

$$P_i - P_{ei} - \frac{M_i}{M_t} P_{COI} = 0, \qquad i = 1, 2, \cdots, n \quad (17)$$

The solution of such equations depends on the initial values of δ_i, i = 1, 2, …, n, which can be chosen to be the steady-state values of the prefault system.

If the fault is kept long enough for one or more machines to become critically unstable, the potential energy of the critical machine goes through a maximum before instability occurs. Furthermore, this maximum value (of the potential energy along the post disturbance trajectory) of a given machine has been found to be a safe estimate of the individual machine critical energy.

It was also shown in eqns. (8, 9, and 10) that a reasonable choice for the critical value of V_i is $V_{Pei-max}$ along the system trajectory, and the value can be obtained from the sustained fault conditions. By simulating a sustained fault (or a fault of long duration), the potential energy term of eqn. (9) are computed V_{Pei}, i = 1, 2, …, n for each instant of time. The values of V_{Pe-max} are noted for the different machines (or groups of machines). These represent the value of $V_{critical}$

$$V_{Critical\_i} = V_{PE\max\_i} \quad (18)$$

The value of V_{Pe-max} obtained represents the energy absorbing capacity for each machine. It gives a measure of the amount of kinetic energy converted to potential energy.

The unstable equilibrium point is found in the same way as the stable equilibrium point by solving the following nonlinear algebraic equations of (11, 18) by the steepest descent method [15].

$$\begin{aligned} & V_{Critical\_i} + P_i(\theta_i^u - \theta_i^s) \\ & - \sum_{\substack{j=1 \\ j \neq i}}^{n} C_{ij} \left[\cos(\theta_i^s - \theta_j^u) - \cos(\theta_i^u - \theta_j^u) \right] \\ & - \sum_{\substack{j=1 \\ j \neq i}}^{n} D_{ij} \left[\sin(\theta_i^u - \theta_j^u) - \sin(\theta_i^s - \theta_j^u) \right] \\ & - \frac{M_i}{M_t} \int_{\theta_i^s}^{\theta_i^u} P_{COI} \, d\theta_i = 0, \qquad i = 1, 2, \cdots, n \end{aligned} \quad (19)$$

But the initial guess of δ_i, i = 1, 2, …, n, for the minimization is chosen in such a way that the critical machine can be chosen to be π-θ^s and the remaining machines can be chosen to be θ_i^s.

To determine whether instability occurs, the total transient energy at the instant of fault clearing is compared with the value of $V_{Critical}$ for each machine. The mode of instability is then given by those machines whose transient energy at clearing exceeds their critical energy.

A Single Machine Infinite Bus (SMIB), this can be derived as a special case of a multi-machine system as follows. An infinite bus is equivalent to a machine having infinite inertia and constant terminal voltage. If M2 → ∞, the eqns. (7), (8), (9) and (11) respectively become:

$$\left. \begin{aligned} & V_{SMIB} = V_{KE\_SMIB} + V_{PE\_SMIB} \\ & KE_{SMIB} = \frac{1}{2} M \omega^2 \\ & PE_{SMIB} = -P_m(\delta - \delta^s) \\ & \qquad - P_{\max-postfault} (\cos\delta - \cos\delta^s) \\ & V_{Critical\_SMIB} = -P_m(\delta^u - \delta^s) \\ & \qquad - P_{\max-postfault} (\cos\delta^u - \cos\delta^s) \end{aligned} \right\} \quad (20)$$

V. SIMULATIONS AND RESULTS

Simulations have been conducted on both, single machine infinite bus system and multi-machine system. In this paper, the two machine infinite bus system shown in in Fig.5 is used as the multi-machine system. The conventional time domain solution and Transient Energy Function (TEF) have been applied for transient stability assessment. A three phase fault occurs on one of the double lines in SMIB system and at bus 4 for multi-machine system with line 4-5 cleared.

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V. I. Single Machine Infinite Bus System

Consider single machine infinite bus system as shown in Fig.1. A three-phase fault occurs on one of the double lines. SMIB system parameters used for simulation are shown in Table 1.

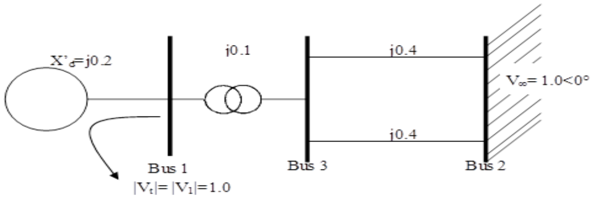

Fig.1. Single machine connected to infinite bus through two parallel lines.

Table 1: System parameters for SMIB

H	P_m	V_t	V_∞	X_d'	$X_{trans.}$	X_{line1}	X_{line2}
5	1	1	1	0.2	0.1	0.4	0.4

The prefault SEP, $(\delta, \omega) = (0.4964, 0)$ rad. The location of the SEP of the post fault system is ($\delta^s = 0.7298$ rad). Using the proposed technique, as outlined in the previous section, the machine critical energy is $V_{critical\text{-}SMIB} = 0.5538$ Pu. So, the controlling UEP relative to the fault outage is ($\delta^u = 2.4118$ rad).

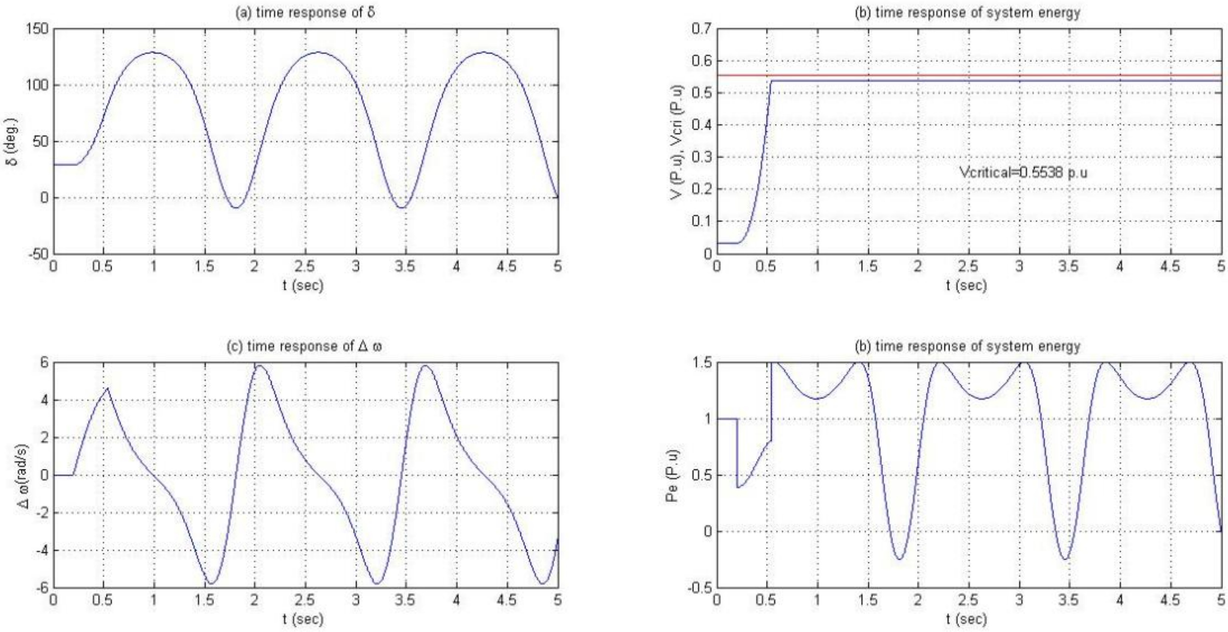

Fig.2. Time response with fault cleared at tc < tcc, tc =0.54 sec of δ, Δω, Pe and energy.

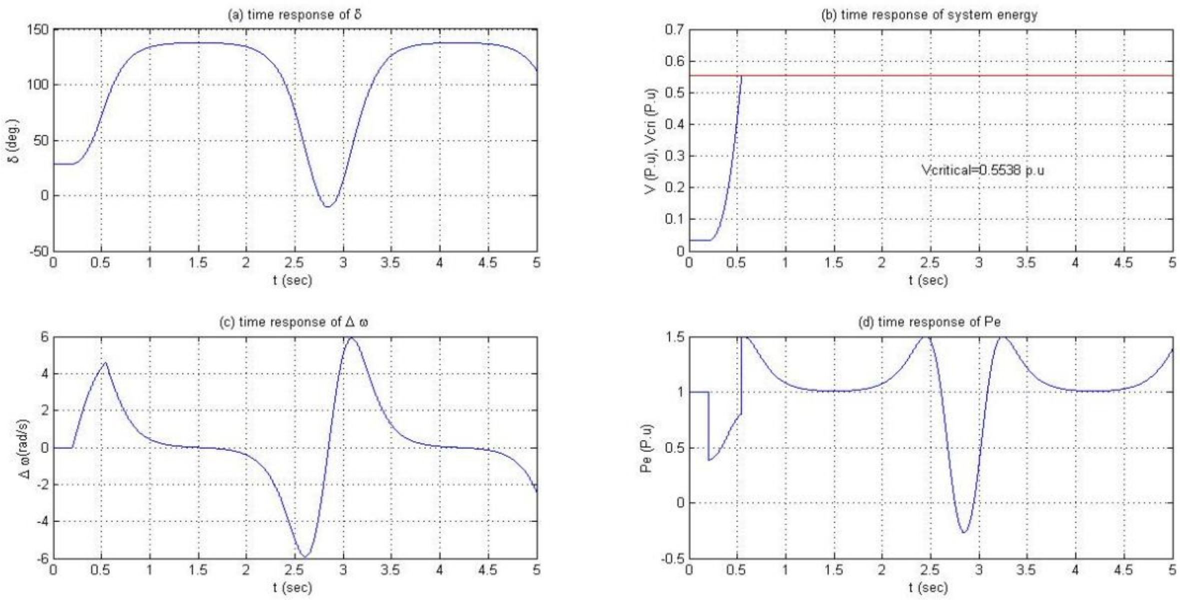

Fig.3. Time response with fault cleared at tc = tcc=0.5447 sec of δ, Δω, Pe and energy.

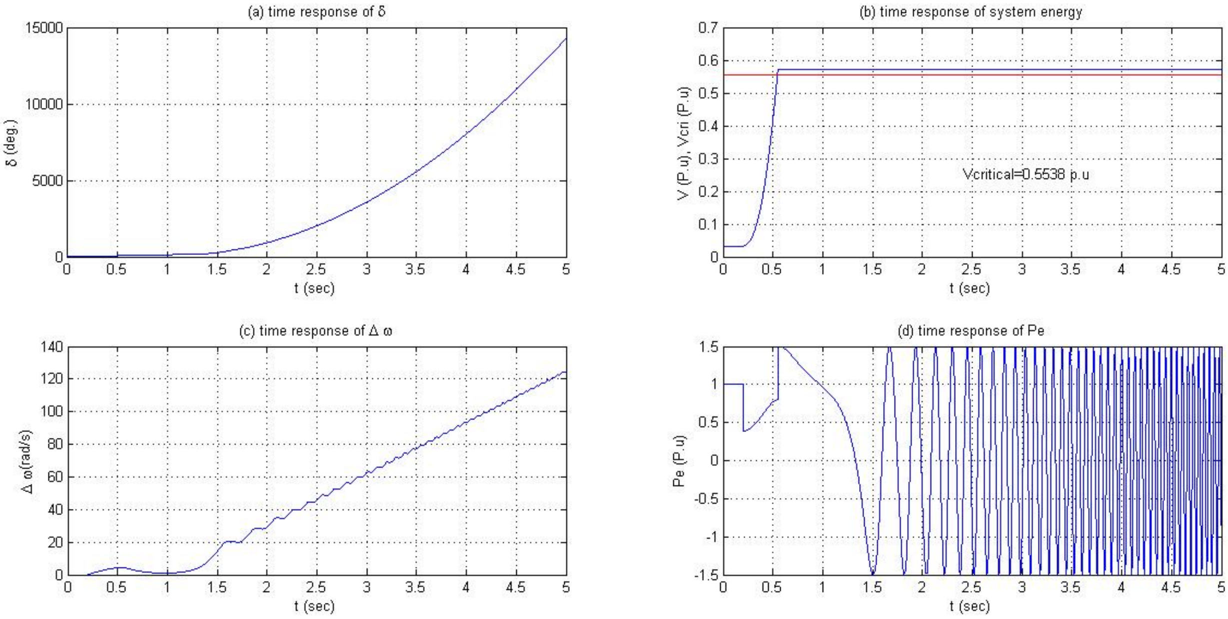

Fig.4. Time response with fault cleared at tc > tcc, tc=0.55 sec of δ, Δω, Pe energy.

Single machine swing curve and the energy under post-fault condition are plotted at clearing times of 0.54 sec, 0.5447 sec and 0.55 sec as shown in Figs. 2, 3 and 4. Fig.2 shows a stable case where the rotor angle oscillates and reach another stable equilibrium point towards the end of the transient and stability could be assured if the transient energy at clearing condition δ_{cl} and ω_{cl} remains in the stable region or $V(\delta_{cl}, \omega_{cl}) < V_{cr}$. The system is critically stable with fault cleared at 0.5447 sec, corresponding to a critical clearing angle δ_{cr} of 82.75 degrees and critical energy V_{cr} for the system investigated is 0.5538, which is shown to be the maximum energy as shown in Fig.3. When the fault is cleared at 0.55 sec, system instability resulted and $V(\delta_{cl}, \omega_{cl}) > V_{cr}$ as indicated in Fig.4.

The critical clearing time (tcc) can also be obtained from the Pe versus time curve. That mean when Pe touch Pm in the first swing, then tcc is obtained.

Fig.2 where tc<tcc, the Pe is higher than Pm in the first swing. Fig.3 where tc=tcc, Pe touch Pm. When tc>tcc, the system will be unstable as shown in Fig.4.

V.II. Multi-machine System

The test system used contains two generators of finite inertia and an infinite bus, as shown in Fig.5. The system and prefault load flow data are given in Appendix; the system has been simulated with a classical model for the generators. The disturbance initiating the transient is a three-phase fault occurring near bus 4 at the end of line 4–5. The fault is cleared by opening line 4–5.

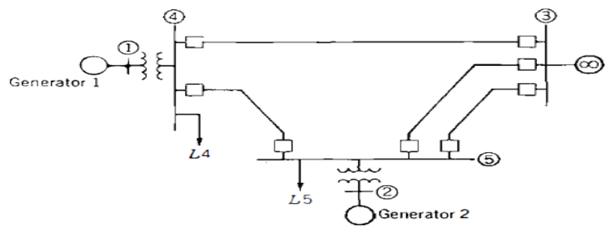

Fig.5. Network configuration of the test system.

The prefault SEP, $(\delta_1, \delta_2, \omega_1, \omega_2) = (0.3634, 0.2826, 0, 0)$ rad. The location of the SEP of the post fault system is (δ_1^s = 0.381058 rad, δ_2^s = 0.277517 rad). Using the proposed technique, the individual machines critical energies are $V_{critical\text{-}m/c1}$ =8.6872 Pu and $V_{critical\text{-}m/c2}$ =0.0284 Pu. So, controlling UEPs relative to the fault outage are (δ_1^u = 2.72937 rad1, δ_2^u = 0.365294 rad).

Each machine swing curve, the phase trajectory in Δω-δ plot and Energy functions for individual machines under post-fault condition are plotted at clearing times of 0.4 sec, 0.405 sec and 0.41 sec as shown in Figs.6, 7 and 8. Fig.6 shows a stable case where the rotor angle oscillates, and reach another stable equilibrium point towards the end of the transient and stability could be assured if the transient energy V_1 $(\delta_{cl}, \omega_{cl}) < V_{critical1}$. The system is critically stable with fault cleared at 0.405 sec, corresponding to a critical clearing angle δ_{cr1} of machine 1 (critical machine) of 91.6588 degrees, critical energy $V_{critical1}$ of machine 1 and the system investigated are 8.6872, 8.7156 respectively. When the fault is cleared at 0.41 sec, system instability resulted and V_1 $(\delta_{cl}, \omega_{cl}) > V_{critical1}$ as indicated in Fig.8.

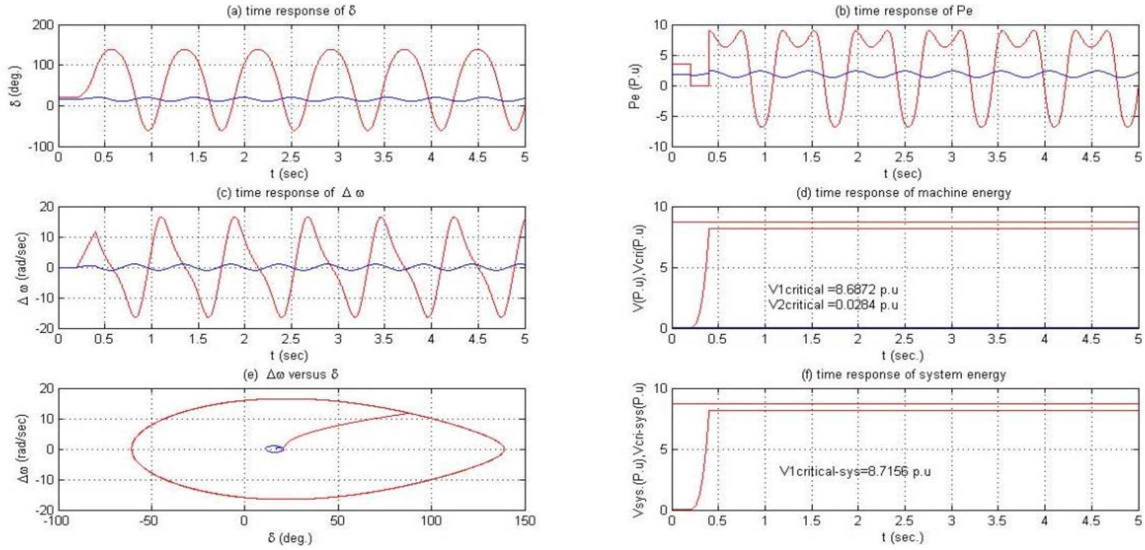

Fig.6. Time response with fault cleared at tc < tcc, tc =0.4 sec of δ, Δω, Pe, Δω versus δ and energy.

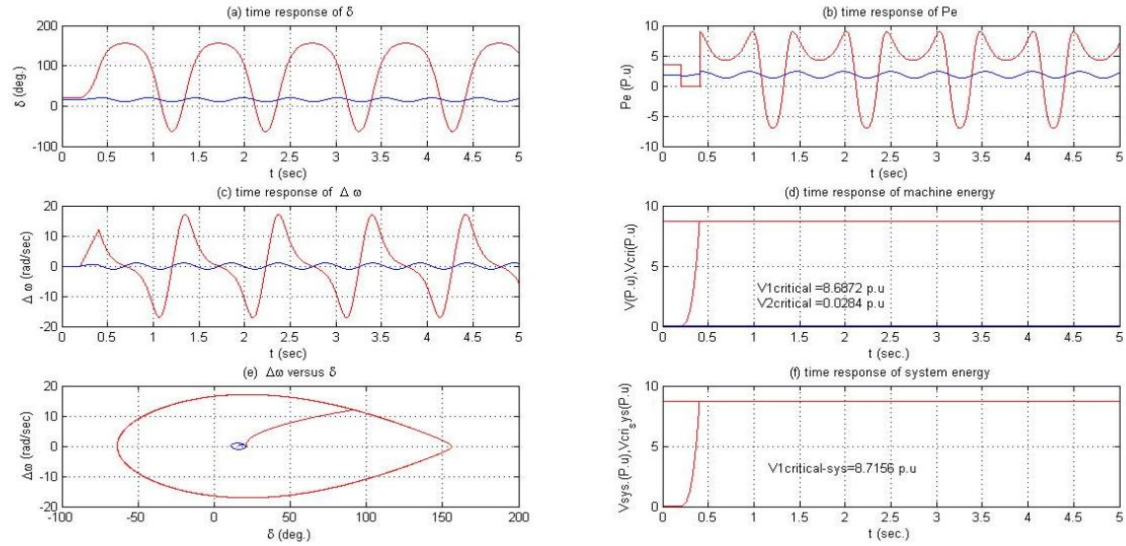

Fig.7. Time response with fault cleared at tc = tcc =0.405 sec of δ, Δω, Pe, Δω versus δ and energy.

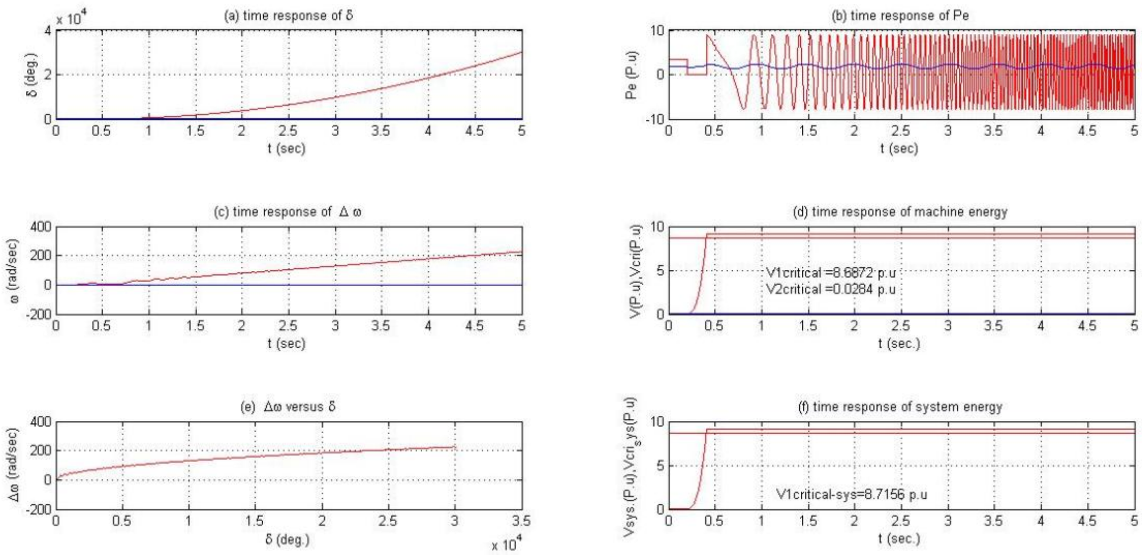

Fig.8. Time response with fault cleared at tc > tcc, tc=0.41 sec of δ, Δω, Pe, Δω versus δ and energy.

The Critical Clearing Time (tcc) can also be obtained from the Pe versus time curve. That mean when Pe of critical machine touch Pm in the first swing, then tcc is obtained.

Fig.6 where tc < tcc, the Pe is higher than Pm in the first swing. Fig.7 where tc ≈ tcc, Pe touch Pm. When tc > tcc, the system will be unstable as shown in Fig.8.

VI. CONCLUSION

In this paper complete model for transient stability assessment of a multi-machine power system was developed using MATLAB. The classical model of a multi-machine power system using relative machine angle reference formulation is employed and the individual machine energy function is constructed. The stable equilibriums are calculated from the solution of the power flow equations, whereas the proposed method is used to compute the unstable equilibrium point in easy way with respect to other methods. Test results conducted on the single and multi-machine power system. The results obtained by this proposed approach are in good agreement with those obtained by the time solution method.

APPENDIX

Line and transformer data*

From Bus	To Bus	Series Z		Shunt Y
		R	X	B
1	4	0.0	0.022	0.0
2	5	0.0	0.040	0.0
3	4	0.007	0.040	0.082
3	5 (1)	0.008	0.047	0.098
3	5 (2)	0.008	0.047	0.098
4	5	0.018	0.110	0.226

Generator data of test system*

Parameter	G1	G2
Rated MVA	400	250
KV	20	18
$X_{d`}$	0.067	0.10
H	11.2	8.0

Prefault load flow data*

Bus	Voltage	Generation		Load	
		P	Q	P	Q
1	1.03∟8.88º	3.5	0.712	---	---
2	1.02∟6.38º	1.85	0.298	---	---
3	1.00∟0º	---	---	---	---
4	1.018∟4.68º	---	---	1.00	0.44
5	1.011∟2.27º	---	---	0.50	0.16

*All values are in per unit on 100MVA base.

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