Online Modern Philosophy for Stability Detection Based on Critical Energy of Individual Machines

Wagdy M. MANSOUR
Email: wagdy_ibrahim2010@yahoo.com

Mohamed A. ALI
Email: mohamed.mohamed02@feng.bu.edu.eg

Nader SH. ABDELHAKEEM
Email: eng_nader2011@yahoo.com

Faculty of Engineering (Shoubra), Benha University, Electrical Engineering Department, 108 Shoubra St., Cairo, Egypt.

Abstract – **This paper introduces a proposed modern philosophy/algorithm for transient stability assessment based on critical energy function of individual machines. The algorithm depends on the creation of energy function for individual machines using the online measurements via the Synchronized Phasor Measurement Units (SPMUs). For further speeding up the algorithm for online assessment, a parallel algorithm for stability assessment is implemented. The proposed algorithm makes online calculation the potential and kinetic energies for each machine in power system and then compares the total system energy to the critical energy of the system. A decision based on the online comparison produces an output operand according to stability situation of the power system. The proposed algorithm is tested by two machine infinite Bus test system to ensure its effectiveness and validity.**

Keywords – **Transient Stability, Transient Energy Function, Critical Clearing Time (CCT), On-Line, Synchronized Phasor Measurement Units (SPMUs), Parallel Algorithms, MATLAB/SIMULINK Software.**

I. INTRODUCTION

Transient stability has been evaluated using Time Domain (TD) approach [1], [2], but it is found that the computational time for evaluating stability for large system is much more than the real time. This has encouraged the expansion of various transient stability assessments, such as Equal Area Criterion (EAC), Extended Equal Area Criterion (EEAC) [3] and Transient Energy Function (TEF) [4]-[6], to calculate Critical Clearing Time (CCT). Transient Energy Function is known to be a very powerful tool of online assessing CCT of a power system without solving the system dynamics equations at post fault. This method is capable of providing the information about the degree of stability (or instability). The difficulty in this method is to find the suitable energy function of power system [7]. At the instant of fault occurrence, the electrical power output reduces, accelerates the rotor angle and the system kinetic energy eventually builds up until it arrives its maximum value at the clearing time. At this instant, the excess of electrical power output decelerates the rotor angle and the system kinetic energy started decreasing while potential energy started growing up. This indicates that the conversion of system kinetic energy into potential energy is taking place. The successful conversion of accumulated kinetic energy resulted from a particular disturbance in potential energy would result in a constant system's energy towards the end of the transient period.

PMU devices have been developed to give synchronized data from the whole power system. Sampled data of three-phase voltages and currents, which are time-synchronized, give the voltage and current magnitude and phase of each

measured value in the power system to be used in real-time stability analyses [8], [9].

The scope of this paper is to introduce a method as an accurate algorithm to help in online transient stability assessment for multi-machine power systems during planning and operation (on-line assessment) phases. For this purpose, the transient energy function based on individual machine energy functions offer good insight into the forces causing the separation of a machine (or a group of machines) from the system, and the energy associated with that separation. Formulation of each machine equations with respect to the system's Center Of Inertia (COI) and implementation of the parallel algorithm [11] to detect the Transient Stability Assessment (TSA) on parallel microprocessors [10], [11], to achieve online decision for the separation of a machine (or a group of machines) are suggested.

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 [1]. 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:

$$\left.\begin{array}{l}\theta_i = \delta_i - \delta_o \\ \varpi_i = \theta_i^{\bullet} = \omega_i - \omega_o\end{array}\right\} \qquad (2)$$

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

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

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

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

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

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

Where:

$$C_{ij} = E_iE_jB_{ij} \quad , \qquad D_{ij} = E_iE_jG_{ij}$$

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:

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

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

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

The stable equilibrium point of the post fault system is found by solving the following nonlinear algebraic equations by the steepest descent method [12].

$$P_i - P_{ei} - \frac{M_i}{M_t}P_{COI} = 0, \qquad i=1,2,\cdots,n \qquad (7)$$

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

Eqn. (6) is evaluated using the post fault network configuration. The first term in (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:

$$V_i = V_{KEi} + V_{PEi} \qquad (8)$$

Eqn. (8) 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:

$$KE_i = \frac{1}{2}M_i\varpi_i^2 \qquad (9)$$

$$PE_i = -P_i(\theta_i - \theta_i^s) + \sum_{\substack{j=1 \\ j\neq i}}^{n}C_{ij}\begin{bmatrix}\cos(\theta_i^s - \theta_j) - \\ \cos(\theta_i - \theta_j)\end{bmatrix}$$
$$+ \sum_{\substack{j=1 \\ j\neq i}}^{n}D_{ij}\begin{bmatrix}\sin(\theta_i - \theta_j) - \\ \sin(\theta_i^s - \theta_j)\end{bmatrix} + \frac{M_i}{M_t}\int_{\theta_i^s}^{\theta_i}P_{COI}d\theta_i \qquad (10)$$

$$\int_{\theta_i^s}^{\theta_i}P_{COI}d\theta = \sum_{i=1}^{n}P_i(\theta_i - \theta_i^s) -$$
$$\sum_{i=1}^{n}\sum_{\substack{j=1 \\ j\neq i}}^{n}C_{ij}\begin{bmatrix}\cos(\theta_i^s - \theta_j) - \\ \cos(\theta_i - \theta_j)\end{bmatrix} -$$
$$\sum_{i=1}^{n}\sum_{\substack{j=1 \\ j\neq i}}^{n}D_{ij}\begin{bmatrix}\sin(\theta_i - \theta_j) - \\ \sin(\theta_i^s - \theta_j)\end{bmatrix} \qquad (11)$$

By simulating a sustained fault (or a fault of long duration), the potential energy term of (10) are computed VPEi, i = 1, 2, …, n for each instant of time. The values of VPEmax are noted for the different machines (or groups of machines). These represent the value of Vcritical for each machine.

$$V_{Critical\_sys} = \max(V_{PE\max\_i}) \qquad (12)$$

$$V_{Critical\_i} = V_{PE\max\_i} \qquad (13)$$

The value of $V_{PEmax-i}$ in (12) represents the energy absorbing capacity for each machine. It gives a measure of the amount of kinetic energy converted to potential energy.

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

IV. PARALLEL MICROPROCESSORS

The adaptation of parallel microprocessors is suitable using the parallelized algorithms [10], [11], [13]-[16]. The system consists of Central Micro-Processor (CMP) and De-Centralized Micro-Processor (DCMP) for each machine. The CMP receives the output variables from each machine microprocessor DCMP then CMP is transferring the required variables to each machine DCMP which will be used to compute the updated parameters of the machines. Schematic diagram to represent the adaptation of parallel microprocessors using the parallelized algorithms is shown in Fig.1.
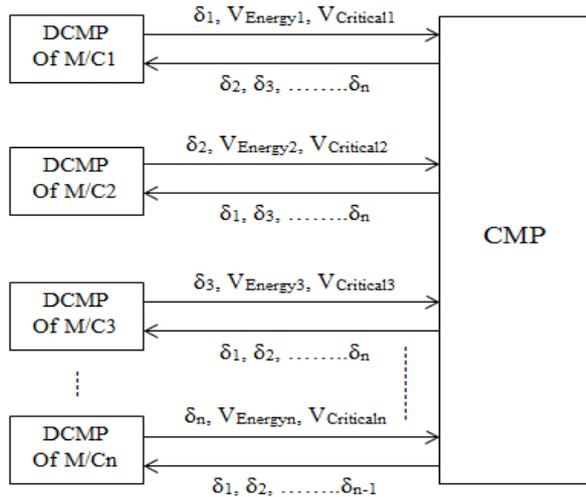
Fig.1. Schematic Diagram Represent the Parallelized Algorithm.

V. ONLINE TRANSIENT STABILITY ALGORITHM BASED ON PMU TECHNOLOGY

The proposed algorithm uses the online measurements via SPMUs then makes rotor angle monitoring and control instant by instant. The algorithm uses the measurements of currents and voltages via the installed SPMUs located at generator terminal buses to calculate the electrical active power Pe and reactive power Qe.

The expressions for Pe and Qe for individual machine are given by:

$$\left. \begin{array}{l} P_{ei} = REAL\,(V_{ti}\,I_{ti}^{*}) \\ Q_{ei} = IMAG\,(V_{ti}\,I_{ti}^{*}), \qquad i = 1,2,\cdots,n \end{array} \right\} \tag{14}$$

Where:

V_{ti} Generator terminal bus voltage via the PMU.

I_{ti} Generator terminal bus current via the PMU.

Similarly,

$$\left. \begin{array}{l} P_{ei} = \dfrac{E_i V_{ti}}{X_{di}} \sin(\delta_i - \alpha_i) \\[2mm] Q_{ei} = \dfrac{E_i^2}{X_{di}} - \dfrac{E_i V_{ti}}{X_{di}} \cos(\delta_i - \alpha_i) \end{array} \right\} i = 1,2,\cdots,n \tag{15}$$

According to (14) and (15), the generator rotor angle of machine i can be deduced as follows;

$$\delta_i = \alpha_i + \tan^{-1}\left(\frac{P_{ei}}{(E_i^2 / X_{di}) - Q_{ei}} \right) \tag{16}$$

Also, the generator rotor speed of machine i can be given by:

$$\omega_i = \frac{\delta_i(n) - \delta_i(n-1)}{\Delta t} \tag{17}$$

Then the above calculated values will be used to the pre-constructed TEF and plot the maximum energy, state trajectory. The protection relay (micro-controller based) is used to compare the results. If the system energy approaches or into borders the maximum energy, the algorithm provides an output states a system disturbance but the system will stay synchronized (Alarm message states normal power swing condition).
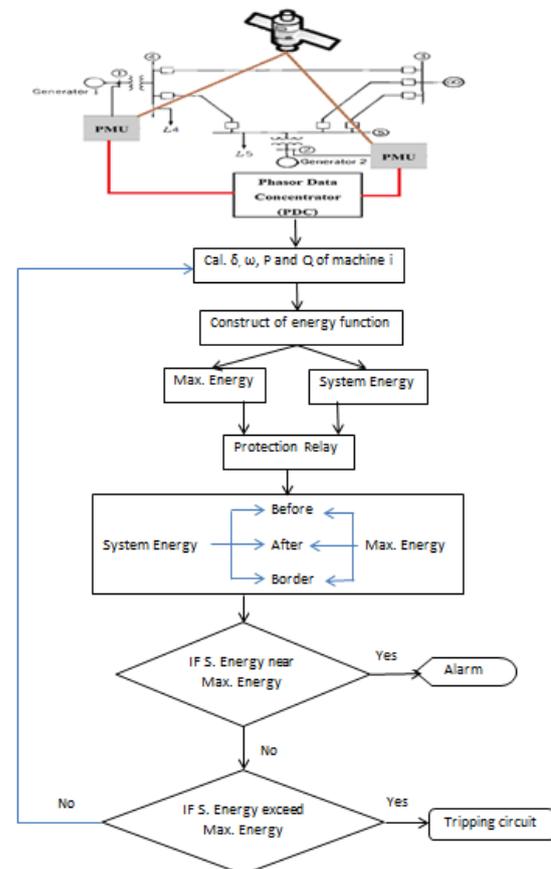
Fig.2. Protection Algorithm for Multi-machine System.

If the system energy exceeds the maximum energy, the algorithm will stop and sends an output stating OOS (warning message, the system is OOS). Selectivity algorithm should be adopted to clear the faulted area only by selecting the appropriate circuit breaker to be tripped.

VI. CASE UNDER STUDY

The test system used contains two generators with finite inertia and an infinite bus, as shown in Fig.3..
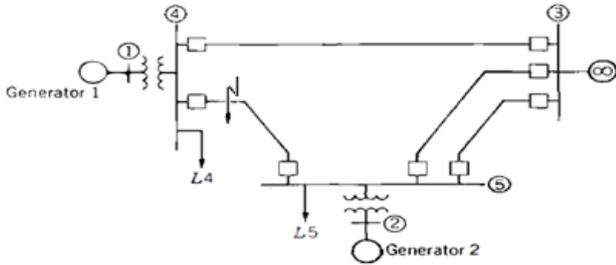
Fig.3. Network Configuration of the Test System.

The system parameters and the 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

VII. SIMULATION RESULTS

Once the Y matrix for each network condition (pre-fault, during and after fault) is calculated, we can eliminate all the nodes except for the internal generator nodes and obtain the Y matrix for the reduced network.

A MATLAB/SIMULINK model shown in Fig.4 is constructed based on the proposed method to obtain rotor angle (δ), angular speed (ω) and energy (V_{Energy}) of the two machines.

Also, MATLAB/SIMULINK model shown in Fig.5 is constructed based on conventional method to obtain the same parameters and identical time responses.
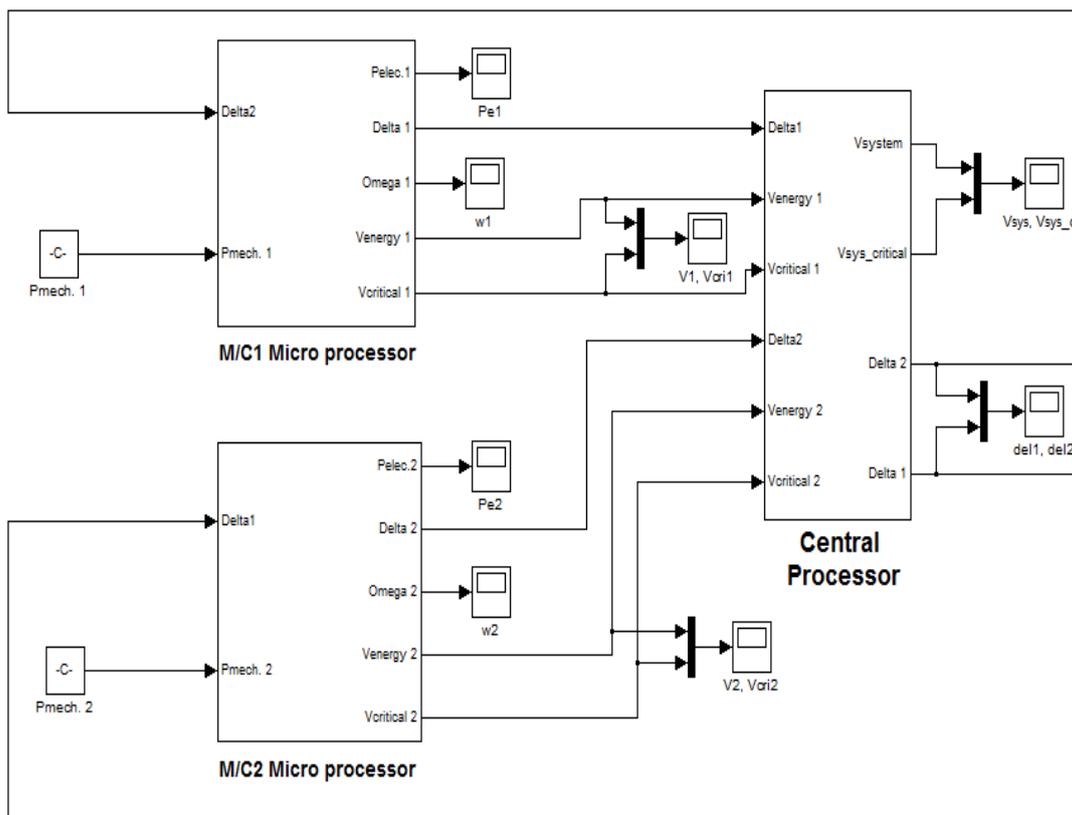
Fig.4. MATLAB/SIMULINK Model for Transient Stability Study in Conjunction with Parallel Microprocessors.
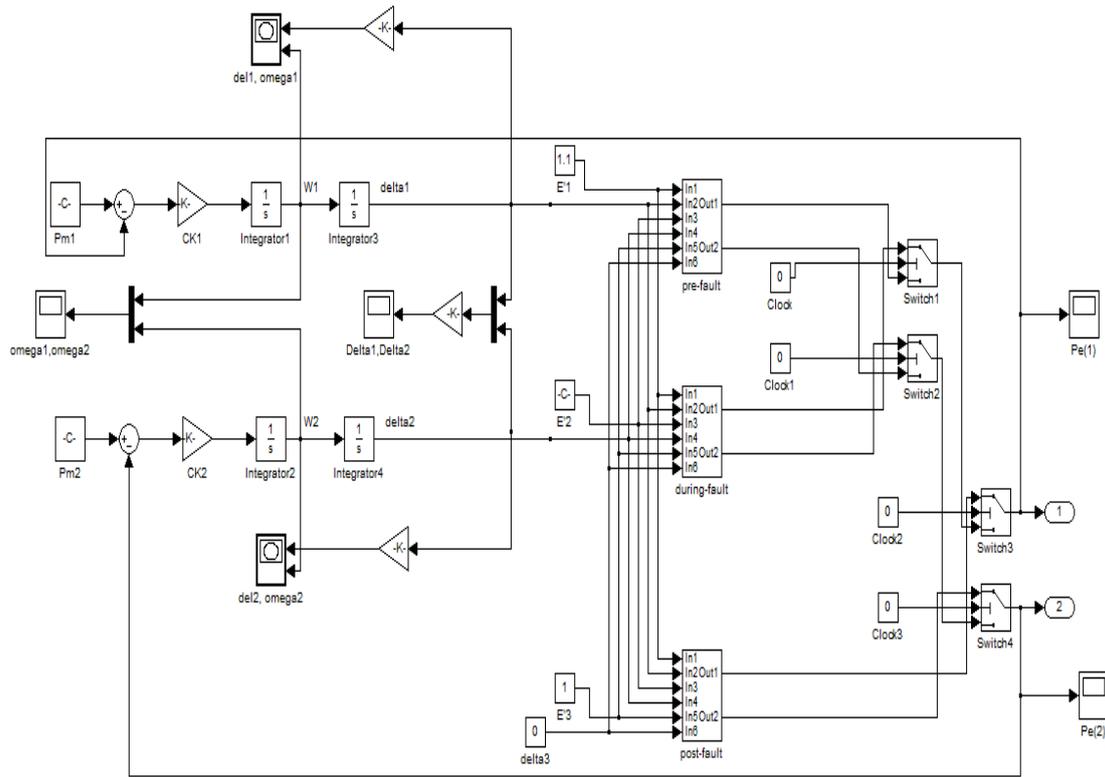
Fig.5. MATLAB/SIMULINK Model Using Conventional Method.
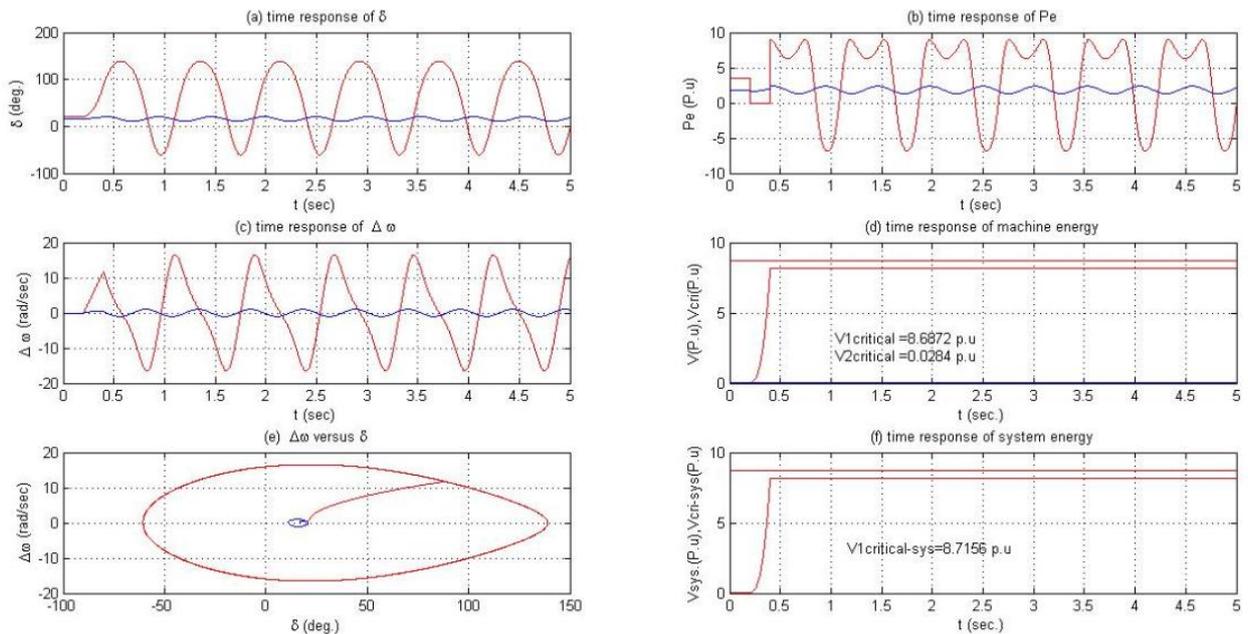
Fig.6. Time Response with Fault Cleared at $t_c < t_{cc}$, t_c =0.4 sec of δ, $\Delta\omega$, P_e, $\Delta\omega$ Versus δ and Energy.
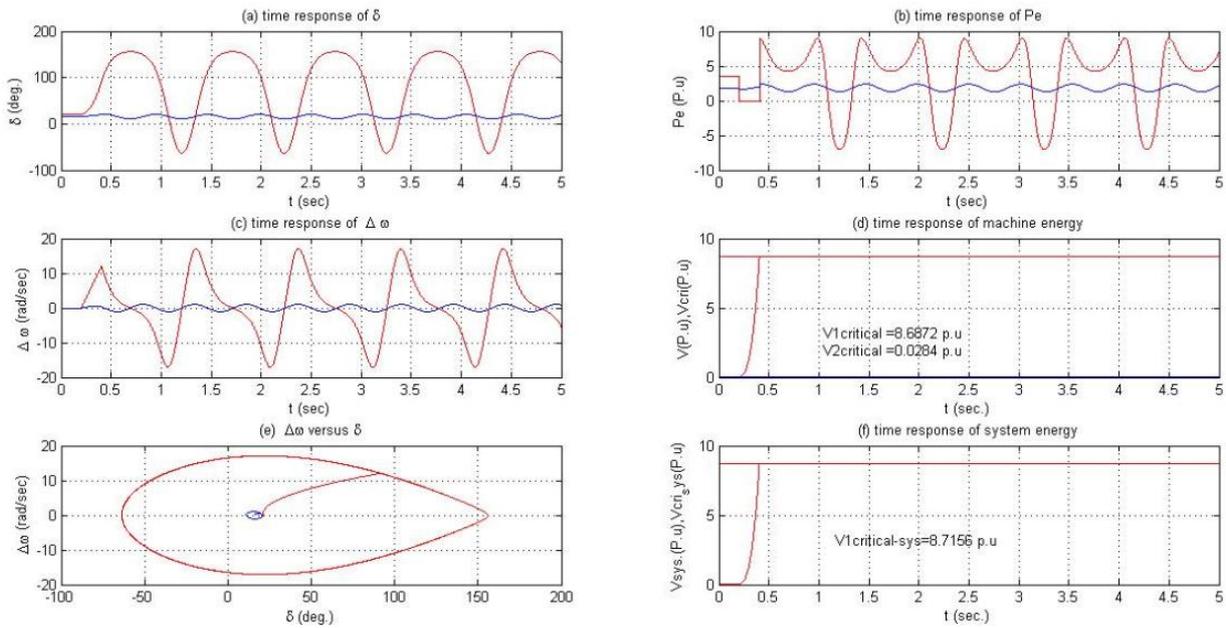
Fig.7. Time Response with Fault Cleared at $t_c = t_{cc}$ =0.405 sec of δ, $\Delta\omega$, P_e, $\Delta\omega$ Versus δ and Energy.
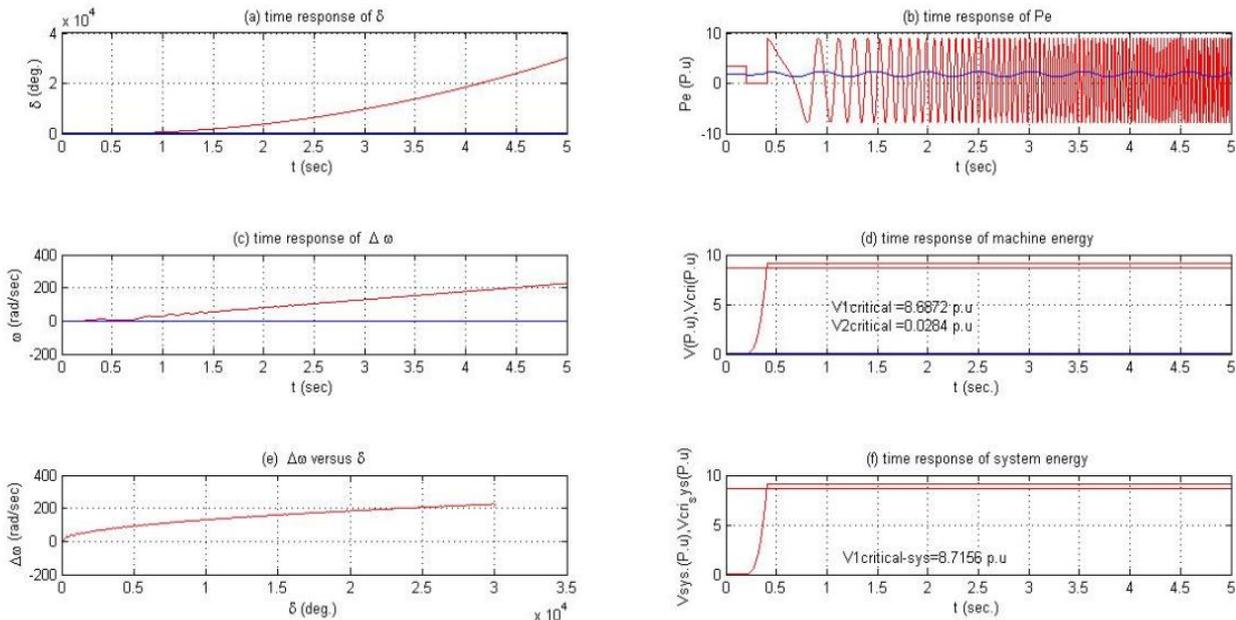
Fig.8. Time Response with Fault Cleared at $t_c > t_{cc}$, t_c=0.41 sec of δ, $\Delta\omega$, P_e, $\Delta\omega$ Versus δ and Energy

Each machine swing curve, the phase trajectory in $\Delta\omega$-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 (δ_{cl}, ω_{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 (δ_{cl}, ω_{cl}) > $V_{critical1}$ as indicated in Fig.8.

The critical clearing time (t_{cc}) can also be obtained from the P_e versus time curve. That means when P_e touch P_m in the first swing, then t_{cc} is obtained.

Fig.6 where $t_c < t_{cc}$, the P_e is higher than P_m in the first swing. Fig.7 where $t_c \approx t_{cc}$, P_e touch P_m. When $t_c > t_{cc}$, the system will be unstable as shown in Fig.8.

VIII. CONCLUSION

The paper presents a comprehensive online modeling for transient stability assessment of a multi-machine power system in conjunction with Parallel Algorithms [10], [11]. The algorithm is developed using MATLAB/SIMULIK. Achieve online decision due to using parallel processing technology in conjunction with modified energy function for individual machines. The algorithm detects the CCT in online operation that can be used for circuit breaker tripping/blocking actions as per fault events. Also a MATLAB/SIMULIK model is constructed based on the conventional time domain method and identical responses due to various faults clearing times are obtained. The algorithm is validated for online stability detection based on critical energy of individual machines.

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
Xd`	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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AUTHOR PROFILE

Prof. Dr.-Eng. Wagdy M. Mansour
Receive the B.Sc. degree in electrical engineering from Mansoura University in 1967. In 1974 he received his M.Sc. from Helwan University and in 1980 a Ph.D. in control engineering from the Technical University of Braunshweig –Germany. Since 1990 he has been a professor of control of power systems at the faculty of engineering, Benha University, Cairo (Egypt). (Benha University, Faculty of Engineering, Elec. Eng. Dep., 108 Shoubra Street, Cairo/Egypt).

Assist. Lecturer-Eng. Nader Sh. Abd El-Hakeem
Receive the B.Sc. degree in electrical engineering from Benha University in 2006 and in 2012 he received his M.Sc. from Benha University. Since 2009 he has been an Administrator at the faculty of engineering, Benha University, Cairo (Egypt). (Benha University, Faculty of Engineering, Elec. Eng. Dep., 108 Shoubra Street, Cairo/Egypt).