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Real-Time Transient Stability Analysis/Assessment Based Proposed Parallel Algorithms

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Abstract: In this study, a method for online Transient Stability Analysis/assessment (TSA) of large scale power systems is proposed. The method is based on an exact mathematical transformation of (n+m) machine system into n-equivalent Single Machine to Equivalent Bus (SMEB) Models and m-Load to Equivalent Bus (LEB) Models, where n number of machine buses and m number of load buses in the system. Then implementing proposed Parallel Algorithms (PAs) for power system TSA on developed Matlab/M-files models constructed by the researchers for system simulation. Comparative simulation results between the proposed PAs and Conventional Time Domain Method (CTDM) are presented to show the effectiveness and the validation of the proposed PAs.

Key words: Transient stability analysis, transient stability assessment, parallel algorithms, real-time, online

INTRODUCTION

In order to make the most suitable solution from the existing methods and the new technology for solving the complexity of simulating the power systems for TSA, variety of approaches have been undertaken. One group of methods adapts the fastest sequential algorithms for parallel implementations on special purpose parallel processing computers (Hong and Shen, 2000; Bruggencate and Chalesani, 1995; Wu and Bose, 1996). Another group of methods applies new algorithms that are written specifically for applications on the existing hardware of parallel processing computers (Ferreira *et al*., 2000; Moon *et al*., 2000; Chai *et al*., 1999; Wang, 1998). There are no obvious parallelisms inherent in the mathematical structure of the power system transient stability problem. Thus, for this specific problem, a parallel (or near-parallel) formulation has to be found that is useful for constructing a parallel algorithm. This solution has to be implemented on parallel micro-processors or particular multiprocessing computer. The computational efficiency of such art implementation is dependent on the suitability of the parallel architecture to the parallel algorithm. Therefore, it is no longer meaningful to develop the best parallel algorithm without reference to the target hardware architecture. There are available various single processor software packages which run the traditional stability program solution at or near real-time for small or midsize systems. For solving large power systems, one common trend is to adapt these standard solution methods and use the commercially available multiprocessing hardware as their computational tools. High efficiency is usually hard to reach because computation and communication takes too much time during each calculation time-step, thus for the solution of large scale power system networks, it is possible to substantially reduce the computation time if special purpose parallel processing hardware and parallel programming were used. There are various types of commercially available parallel processing computers, shared-memory multi processor computers, distributed memory parallel computers (Taoka *et al*., 1992) and the Real-Time Digital Simulator (RTDS) (Lee *et al*., 1991). The biggest challenge facing the use of parallel processing computers for the power system stability solution in real-time is the communication and data exchange that may be very extensive for large power system models. The RTDS has been successfully applied for real-time electromagnetic transients simulations of power systems and it handles communication problems very effectively. Therefore, this parallel processing hardware has been chosen for a prototype implementation of the proposed multiprocessing method for solving the transient stability problem.

The main objective in this study is to develop suitable parallel algorithms for solving power system transient stability problem on many processors operating in parallel. Developed computer programs based on PAs and CTDM are developed on Matlab/M-files on computer Pentium IV, 3GB processor, 256MB RAM. The presented results show the time responses for both PAs and CTDM and also the computation times elapsed to show the effectiveness and the validity of the proposed PAs.

PROPOSED PAs DESCRIPTION

Generally power system network buses can be divided into two main categories, the first is the generator

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buses and the second one is the load buses and using these two categories in solving power system TSA to derive a non-iterative procedure for the purpose of computational time reduction. Consider a sample of power system network for generator and load shown in Fig. 1 and 2, respectively to show the proposed PA equivalent technique.

Using special procedure in the derivation to obtain the equivalent parameters which are equivalent admittance magnitude and angle Y_{eq} and ρ_{eq}, respectively. Also, equivalent bus voltage magnitude and angle respectively V_{eq} and α_{eq} for each SMEB associated to machine bus and koad to Equivalent Bus (LEB) associated to load bus according to the following derivation.

Firstly, determining the injected current at machine bus-i from the original configuration of the system shown in Fig. 1:

$$\tilde{I}_i = \frac{\tilde{S}_i}{\tilde{V}_i^*} = \sum_{\substack{j=1\\ j\neq i}}^{n} \left(\tilde{V}_i - \tilde{V}_j\right)\tilde{Y}_{ij} + \tilde{V}_i\tilde{Y}_{pi} \qquad (1)$$

Where:

$$\tilde{V}_i = V_i e^{j\alpha_i}$$
$$\tilde{V}_j = V_j e^{j\alpha_j}$$
$$\tilde{Y}_{ij} = Y_{ij} e^{j\rho_{ij}}$$
$$\tilde{S}_i = P_i + jQ_i$$
$$\tilde{Y}_{pi} = \tilde{Y}_{shi} + \tilde{Y}_{1di}$$

After rearranging Eq. 1, Eq. 2 will be derived:

$$\frac{P_i}{V_i} = V_i Y_{ii}\cos\rho_{ii} \sum_{\substack{j=1\\ j\neq i}}^{n} V_j Y_{ij}\cos\left(\rho_{ij}\ \alpha_i + \alpha_j\right) \qquad (2)$$
$$= V_i B_i \quad D_i\cos\alpha_i \quad C_i\sin\alpha_i$$

Also:

$$\frac{Q_i}{V_i} = V_i Y_{ii}\sin\rho_{ii} \sum_{\substack{j=1\\ j\neq i}}^{n} V_j Y_{ij}\sin\left(\rho_{ij}\ \alpha_i + \alpha_j\right) \qquad (3)$$
$$= V_i A_i - C_i\cos\alpha_i + D_i\sin\alpha_i$$

Where:

$$\tilde{Y}_{ii} = \tilde{Y}_{pi} + \sum_{\substack{j=1\\ j\neq i}}^{n} \tilde{Y}_{ij};\ \tilde{Y}_{ii} = Y_{ii} e^{j\rho_{ii}}$$

Where:

$$A_i = Y_{ii}\sin\rho_{ii};\ B_i = Y_{ii}\cos\rho_{ii};$$
$$C_i = \sum_{\substack{j=1\\ j\neq i}}^{n} V_j Y_{ij}\sin\left(\rho_{ij} + \alpha_j\right);$$
$$D_i = \sum_{\substack{j=1\\ j\neq i}}^{n} V_j Y_{ij}\cos\left(\rho_{ij} + \alpha_j\right)$$

From the equivalent SMEB Model shown in Fig. 3, another equation could be obtained for the injected current at bus-i.

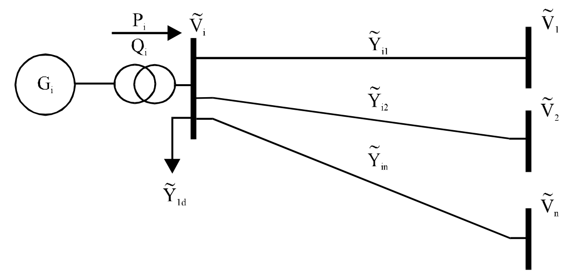

Fig. 1: Generator bus sample

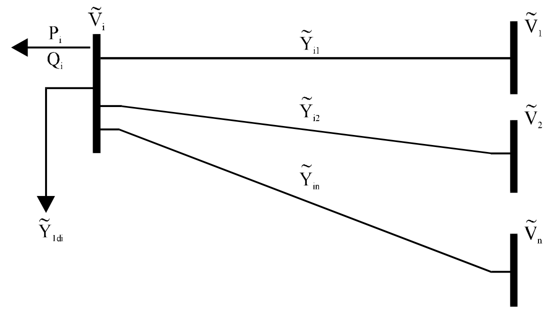

Fig. 2: Load bus sample

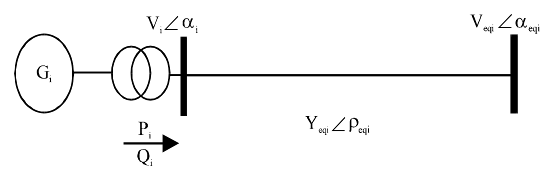

Fig. 3: Single machine to equivalent bus SMEB Model

Secondly, determining the injected current at machine bus-i from the equivalent SMEB Model:

$$\tilde{I}_i = \frac{\tilde{S}_i}{\tilde{V}_i^*} = \left(\tilde{V}_i - \tilde{V}_{eqi}\right)\tilde{Y}_{eqi} \qquad (4)$$

Where:

$$\tilde{V}_{eqi} = V_{eqi} e^{j\alpha_{eqi}};\ \tilde{Y}_{eqi} = Y_{eqi} e^{j\rho_{eqi}}$$

After some calculations, Eq. 5 and 6 will be obtained:

$$\frac{P_i}{V_i} = V_i Y_{eqi}\cos\rho_{eqi} - V_{eqi} Y_{eqi}\cos\left(\rho_{eqi}\ \alpha_i + \alpha_{eqi}\right) \qquad (5)$$

Also:

$$\frac{Q_i}{V_i} = V_i Y_{eqi}\sin\rho_{eqi} - V_{eqi} Y_{eqi}\sin\left(\rho_{eqi}\ \alpha_i + \alpha_{eqi}\right) \qquad (6)$$

Comparing Eq. 2 and 3 with Eq. 5 and 6, respectively; the equivalent parameters of the SMEB Model can be obtained as shown in Eq. 7-10:

$$Y_{eqi} = \sqrt{A_i^2 + B_i^2} \quad (7)$$

$$\rho_{eqi} = \tan^{-1}\left(\frac{A_i}{B_i}\right) \quad (8)$$

$$V_{eqi} = \frac{\sqrt{C_i^2 + D_i^2}}{Y_{eqi}} \quad (9)$$

$$\alpha_{eqi} = \tan^{1}\left(\frac{C_i}{D_i}\right) - \rho_{eqi} \quad (10)$$

The problem here is to find an expression to compute the terminal voltage of the generator and load buses directly without any iterative procedure and adequate to be used in the proposed PA. Thus, deriving direct equations to compute both generator and load terminal voltages will be presented according to the derived Eq. 7-10, each generator bus can be transformed to SMEB Model as shown in Fig. 3 and using the configuration of the mentioned figure to derive direct equation for generator terminal voltage for Swing Model and Detailed 7th Order Current Model which described in this study.

SWING MODEL FOR SYNCHRONOUS MACHINE REPRESENTATION

The generator current can be calculated according to Eq. 11:

$$\left(\tilde{E}'_{di} - \tilde{V}_{eqi}\right)\tilde{Y}_{eqgt} = \left(\tilde{V}_i - \tilde{V}_{eqi}\right)\tilde{Y}_{eqi} \quad (11)$$

Solving Eq. 11 for $\tilde{V}_i$ yields:

$$\tilde{V}_i = \frac{\left(\tilde{E}'_{di} - \tilde{V}_{eqi}\right)\tilde{Y}_{eqgt}}{\tilde{Y}_{eqi}} + \tilde{V}_{eqi} \quad (12)$$

Where:

$$\tilde{V}_i = V_i\angle\alpha_i$$

$$\tilde{V}_{eqi} = V_{eqi}\measuredangle\alpha_{eqi}$$

$$\tilde{Y}_{eqi} = Y_{eqi}\angle\rho_{eqi}$$

$$\tilde{Y}_{eqgt} = \frac{1}{\frac{1}{\tilde{Y}_{eqi}} + \frac{1}{\tilde{Y}_{trans}} + \frac{1}{\tilde{Y}'_d}}$$

This will be simplified as:

$$\tilde{Y}_{eqgt} = \frac{1}{\tilde{Z}_{eqi} + \tilde{Z}_{trans} + \tilde{Z}'_d} \quad (13)$$

DETAILED CURRENT MODEL

When the Detailed 7th Order Current Model for synchronous machine representation is adopted, some modifications will occurred in generators terminal voltage which will be computed using the generator state variables and the associated equivalent bus voltage:

$$V_{adi} = -r_d i_d - \frac{\omega}{\omega_o}\left(X_{hq} i_{Dq} - X_q i_q + X_q i_q\right) + \frac{1}{\omega_o}\left(-X_d \frac{d}{dt} i_d - X_{hd}\frac{d}{dt} i_f + X_{hd}\frac{d}{dt} i_{Dd}\right) \quad (14)$$

$$V_{aqi} = -r_q i_q + \frac{\omega}{\omega_o}\left(-X_d i_d + X_{hd} i_f + X_{hd} i_{Dd}\right) + \frac{1}{\omega_o}\left(X_{hq}\frac{d}{dt} i_{Dq} - X_q \frac{d}{dt} i_q\right) \quad (15)$$

$$V_{ti} = \sqrt{V_{ad_i}^2 + V_{aq_i}^2} \quad (16)$$

$$\alpha_i = \delta_i - \tan^{1}\left(\frac{V_{ad_i}}{V_{aq_i}}\right) \quad (17)$$

$$\tilde{V}_{ti} = V_{ti}\angle\alpha_i \quad (18)$$

TERMINAL VOLTAGE OF LOAD BUSES

Also according to the derived Eq. 7-10, each load bus can be transformed to LEB Model as shown in Fig. 4 and using the configuration of the mentioned figure to derive direct equation for load terminal voltage computation purpose will be shown as in Fig. 4.

The loads current can be calculated using the two equations described in Eq. 7-10:

$$\tilde{V}_{eqi}\ \tilde{Y}_{eqlt} = \left(\tilde{V}_{eqi} - \tilde{V}_i\right)\ \tilde{Y}_{eqi} \quad (19)$$

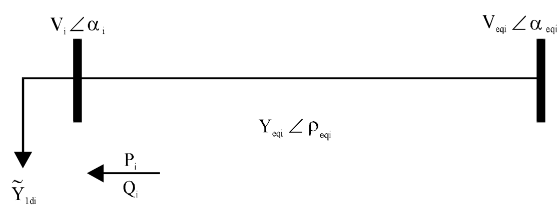

Fig. 4: The transformed LEB Model

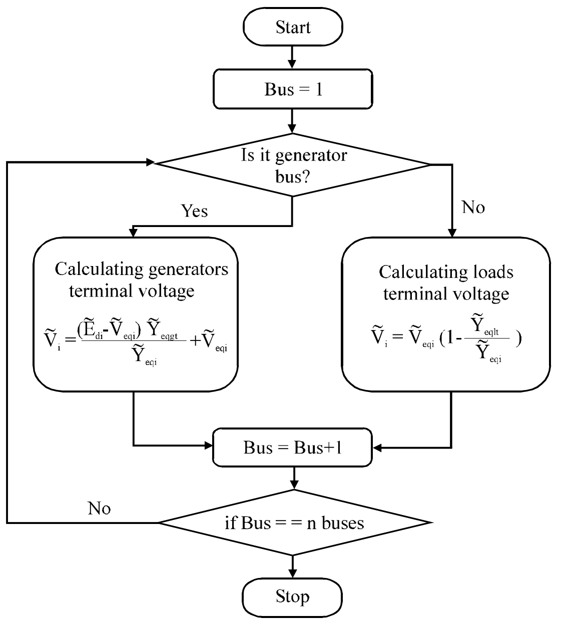

Fig. 5: Buses voltage calculations using Swing Model and the proposed PA in cascade manner

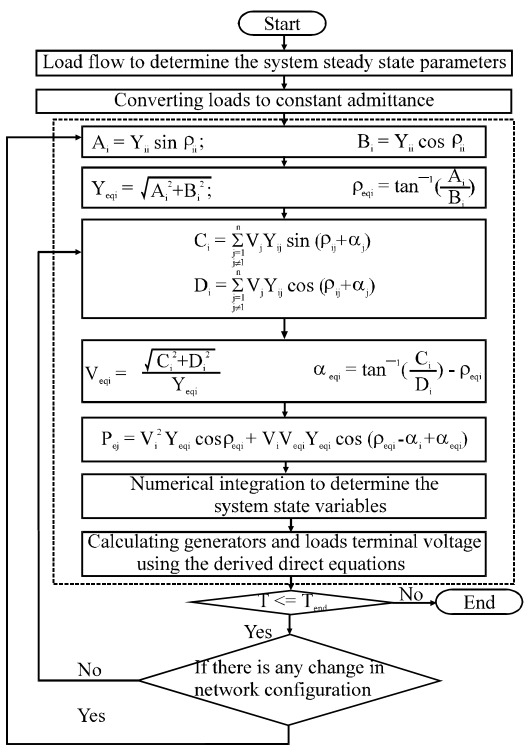

Fig. 6: Flowchart represents the proposed PAs for TSA

Solving Eq. 13 for $\tilde{V}_i$ yields:

$$\tilde{V}_i = \tilde{V}_{eqi} - \tilde{V}_{eqi}\frac{\tilde{Y}_{eqlt}}{\tilde{Y}_{eqi}} \tag{20}$$

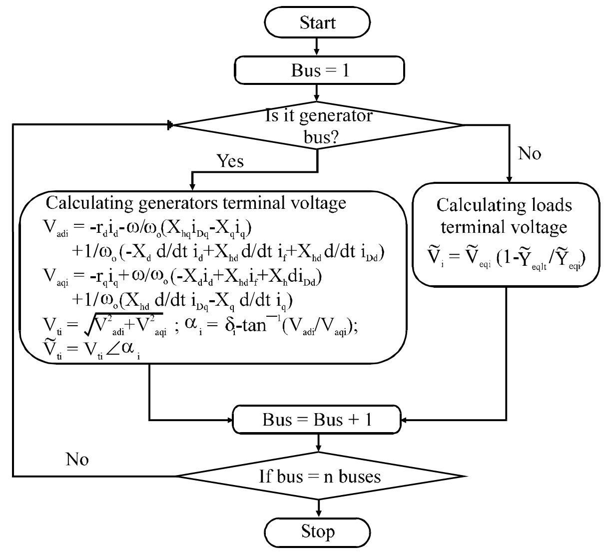

Fig. 7: Flowchart represents buses voltage calculations using detailed model and the proposed PAs

or:

$$\tilde{V}_i = \tilde{V}_{eqi}\left(1-\frac{\tilde{Y}_{eqlt}}{\tilde{Y}_{eqi}}\right) \tag{21}$$

Where:

$$\tilde{Y}_{eqlt} = \frac{1}{\frac{1}{\tilde{Y}_{eqi}}+\frac{1}{\tilde{Y}_{1di}}} \tag{22}$$

This will be simplified as:

$$\tilde{Y}_{eqlt} = \frac{1}{\tilde{Z}_{eqi}+\tilde{Z}_{1di}} \tag{23}$$

Finally, the derived Eq. 12, 16 and 21 can be used in calculating the power system buses voltages without using any iterative procedure, also these equations can be used in transient stability analysis using the proposed PAs.

A flowchart is shown in Fig. 5 presents the implementation of the direct derived bus voltage equations in transient stability program using the proposed PAs in cascade manner and Swing Model for synchronous machine representation. Figure 6 shows flowchart of the proposed PAs for TSA in cascade manner.

Figure 7 shows flowchart for Detailed 7th Order Current Model and Fig. 8 shows the proposed PAs for transient stability analysis.

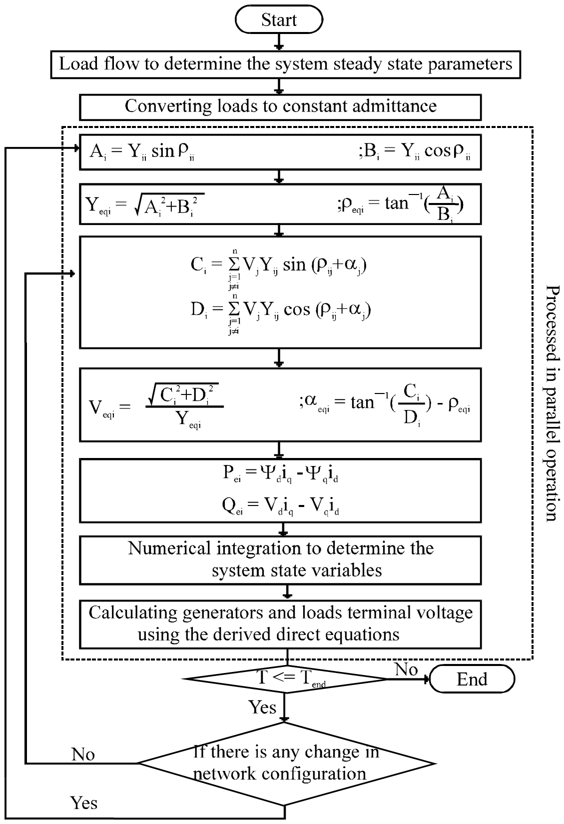

Fig. 8: Detailed flowchart represents the PAs in cascade manner

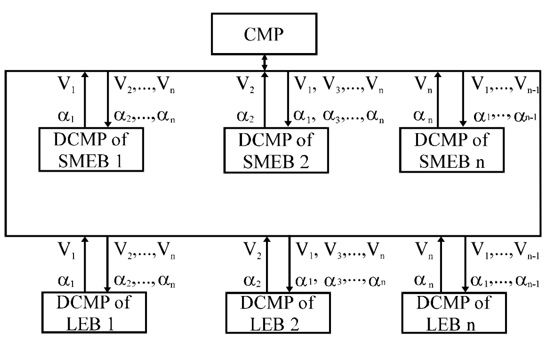

Fig. 9: CMP and DCMPs data telemetry

PAs IMPLEMENTATION ON TSA

The study proposes parallel processing operation to reach real-time in TSA. The parallel processing operation is based on Central Micro Processor (CMP) and DeCentralized Micro Processors (DCMPs) for each transformed SMEB and LEB using the proposed PAs. The data telemetry between CMP and DCMPs schematic diagram is shown in Fig. 9. The processing operations of DCMP associated to machine buses and load are shown in Fig. 10 and 11, respectively.

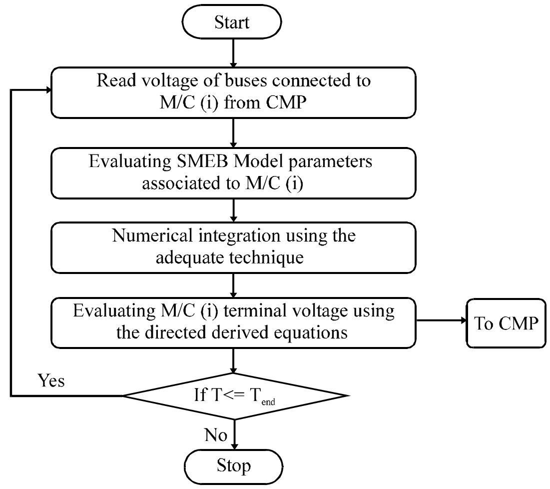

Fig. 10: A flowchart represents the operating steps of SMEB DCMP

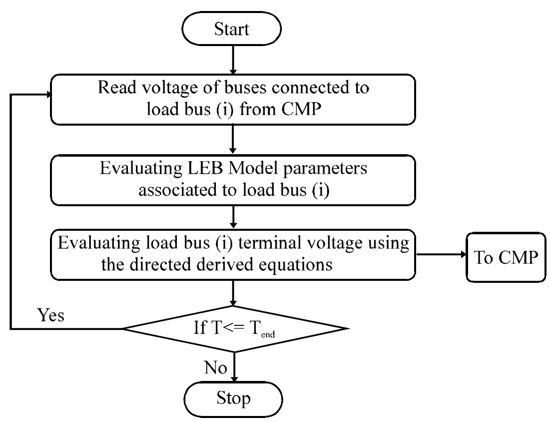

Fig. 11: Flowchart represents the operating steps of LEB DCMP

CASE STUDY

The test system used for adopting the proposed PAs is comprises of 2-machine bus, 3-load bus, 8-bus including the infinite bus as shown in Fig. 12. Thus, the system will be transformed to 2-SMEB Models and 3-LEB Models as shown in Fig. 13.

SIMULATION RESULTS

In this study, the system time responses due to 100 m sec 3-phase short circuit at the infinite bus, 200 m sec disconnection of transmission line (1-4), transmission line (2-4) and sustained 20% sudden

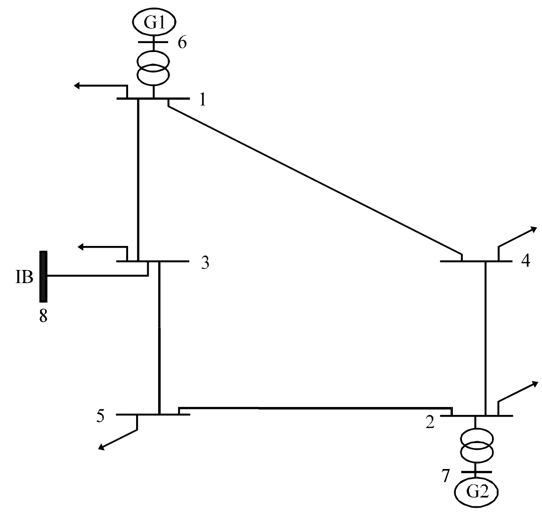

Fig. 12: The original network of the test system

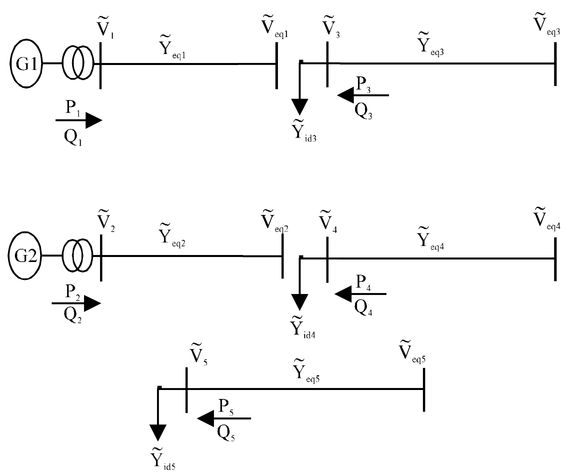

Fig. 13: The transformed SMEBs and LEBs

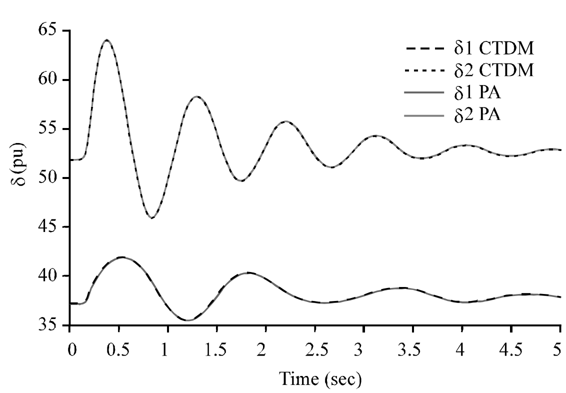

Fig. 14: Time domain comparison between CTDM and proposed PA due to 100 m sec 3 phase short circuit at the infinite bus

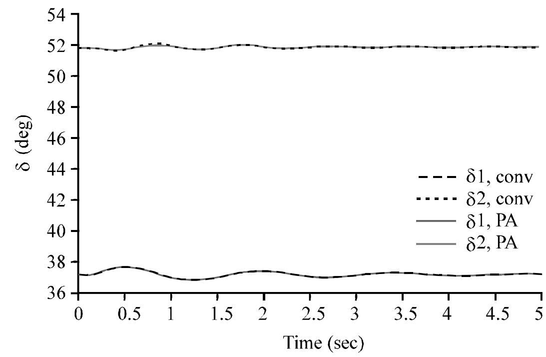

Fig. 15: Time domain comparison between CTDM and proposed PA due to 200 m sec disconnection of TL (1-4)

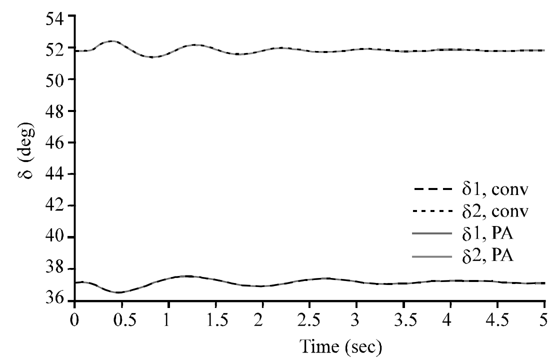

Fig. 16: Time domain comparison between CTDM and proposed PA due to 200 m sec disconnection of TL (2-4)

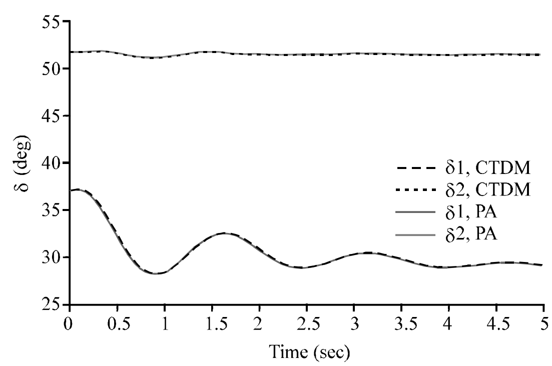

Fig. 17: Time domain comparison between CTDM and proposed PA due to sustained 20% sudden reduction in P_{mech} of machine 1

Table 1: Equivalent parameters of the fictitious (equivalent) transmission lines

Fictitious lines equivalent parameters	Y_{eq}	ρ_{eq}
SMEB (1)	37.1528	-77.4291
SMEB (2)	188.1469	-77.9685
LEB (3)	205.5655	-77.7845
LEB (4)	41.4056	-77.2135
LEB (5)	100.3804	-84.3251

Table 2: Comprehensive comparison per unit time between PAs in cascade, parallel and CTDM with iteration tolerance 1e-9 and integration step of 0.001 sec

Disturbance type	CTDM	PA Cascade	PA Parallel	Saving time (parallel, %)	Speed up ratio
100 m sec fault at IB	4.0270	1.5918	0.31836	92.094	12.649200
200 m sec disconnection of TL (2-7)	3.2782	1.8718	0.37436	88.580	8.756812
200 m sec disconnection of TL (4-7)	3.9844	1.8938	0.37876	90.494	10.519590
20% reduction of Pmech of M/C (1) for 2 sec duration	3.3530	1.7374	0.34748	89.637	9.649476
20% reduction of P_{mech} of M/C (2) for 2 sec duration	3.3782	1.7220	0.34440	89.805	9.808943

reduction in P_{mech} of machine 1 shown in Fig. 14-17, respectively using both CTDM and proposed PAs. Also, the fictitious transmission lines equivalent parameters for each SMEB and LEB are shown in Table 1 and 2.

CONCLUSION

It can be concluded from the results that the proposed PAs able to produced identical time domain responses with computational (simulation) time more less than the actual real-time.

NOMENCLATURE

$\tilde{I}_i$ = Injected current at bus-i
$\tilde{S}_i$ = Injected apparent power at bus-i
$\tilde{V}_i, \tilde{V}_j$ = Voltage of bus-i and bus-j, respectively
$\tilde{V}_{eqi}$ = Voltage of the equivalent artificial bus connected to machine-i
$\tilde{Y}_{ij}$ = Line admittance between bus-i and bus-j
$\tilde{Y}_{ii}$ = The self admittance of bus-i from the bus admittance matrix
$\tilde{Y}_{pi}$ = The summation of line shunt admittance and local load admittance at bus-i
$\tilde{Y}_{shi}$ = Line shunt admittance at bus-i
$\tilde{Y}_{ldi}$ = Local load admittance at bus-i
Y_G = Transmission line admittances between generator buses
Y_L = Transmission line admittances between load buses
Y_M = Transmission line admittances between generator and load buses
i_d, V_d = Direct axis component of the armature current and voltage
i_q, V_q = Quadrature axis component of the armature current and voltage
i_f, V_f = Field current and voltage
i_{Dd}, i_{Dq} = Direct and quadrature axis damper winding current
P_{elec} = The electric power developed by the machine
P_{mech} = The mechanical input power to the machine
P_i = Injected active power at bus-i
Q_i = Injected reactive power at bus-i
r_d, r_q = Direct and quadrature axis armature resistance
r_{Dd}, r_{Dq} = Direct and quadrature axis damper winding resistance
r_f = Field winding resistance
V_i, V_j = Voltage magnitude of bus-i and bus-j, respectively
V_{eqi} = Voltage magnitude of the equivalent artificial bus connected to machine-i
X_d, X_q = Direct and quadrature axis inductive reactance
X_{Dd}, X_{Dq} = Direct and quadrature axis damper winding inductive reactance
X_{hd}, X_{hq} = Direct and quadrature axis mutual inductive reactance
X_f = Field winding inductive reactance
Y_{ii} = Magnitude of self admittance of bus-i from the bus admittance matrix
Y_{ij} = Magnitude of line admittance between bus-i and bus-j
α_{eqi} = Voltage angle of the equivalent artificial bus connected to machine-i
α_i, α_j = Voltage angle of bus-i and bus-j, respectively
δ = Power angle of a synchronous machine
ρ_{eqi} = Angle of line admittance connected to machine-i
ρ_{ii} = Angle of self admittance of bus-i from the bus admittance matrix
ρ_{ij} = Angle of line admittance between bus-i and bus-j
ω = Rotor angular speed
ω_o = Synchronous angular speed

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