Investigating the impacts of asynchronous torque affecting to the transient stability in multi-machine power system

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ABSTRACT:

A new algorithm simulating the impact of asynchronous torque to the transient stability of multi-machine power system is mentioned and some typical numerical examples are presented in this article. Based on the proposed algorithm this PC program uses the elements of the eigen-image matrix to bring the specific advantages for the calculations of the transient stability of multi-machine power system.The symmetrical and unsymmetrical transient voltages of the VAR supporting devices such as the static var compensators, synchronous machines are simulated under condition of action of the automatic voltage regulation system and the transient frequencies relating to the action of the asynchronous torque are simulated for analyzing of the transient stability in multi-machine power system.

Keywords: *Multi-Machine Power System; Transient Stability; Asynchronous Torque; Damping Torque; Effect of Automatic Excitation Regulation; Static VAR Compensator (SVC);*

1. INTRODUCTION

In recent years, transient stability problems have been reported in power systems which originated broad studies in many literatures concerning [4],[5]. The Power system is affected by high electromechanical oscillations while a disturbance occurs that may lead to loss of synchronism of generators. The asynchronous regime is tested and allowable with small slip of speed of the synchronous machines operating in the power system. Excepting the test of behavior of the synchronous generators assuming the asynchronous operation, the most important is the problem of assessment of the transient stability in power system including the reclosing with asynchronism. The asynchronous speed of the synchronous machines may be engendered in a power system during swings caused by symmetrical or unsymmetrical faults, its effect may be taken into account to the analyzing of the transient stability. The main features of the synchronous operation are as follows: The current circulating through the synchoronous machines and power network has components of two frequencies ω and ω_o. The synchronous machines assume the properties of an asynchronous machine, since the rotor current appears with a slip, the emf E_ω varies with the slip, the reactances of power network assume new value $X_\omega=X(\omega/\omega_o)$.

There are three methods to assess the asynchronous parameters [3] such as the currents, powers, torques and emf. The first method is supperposition method applicating to a machine model consisting of two machine components. The second method is finding the asynchronous emf. The third method is using the Park-Gorev' equations to calculate all variations associating to the change in the emf and torque of synchronous machine. Using the first method, the instantaneous value of the asynchronous torques can be determined as follow

$$torque_{as} = \frac{-V^2}{2}\left\{T_{2f}F_f(t) + T_{2D}F_D(t) + T_{2Q}F_Q(t)\right\}; \quad (1)$$

and the average value of the asynchronous torque is

$$T_{as} = \frac{-V^2}{2}\left(T_{asf} + T_{asD} + T_{asQ}\right); \quad (2)$$

where T_{asf} is the asynchronous torque component relating to the rotor winding

$$T_{asf} = \frac{X_d - X'_d}{X_d X'_d}\,\frac{sT'_d}{1+(sT'_d)^2}; \quad (3)$$

T_{asD} is the asynchronous torque components relating to the d-axis damper windings

$$T_{asD} = \frac{X'_d - X''_d}{X'_d X''_d}\,\frac{sT''_d}{1+(sT''_d)^2}; \quad (4)$$

T_{asQ} is the asynchronous torque components relating to the q-axis damper windings

$$T_{asQ} = \frac{X'_q - X''_q}{X'_q X''_q}\,\frac{sT''_q}{1+(sT''_q)^2}; \quad (5)$$

V is the voltage of observing busbar relating to the receiving system;

$s = -\frac{d\delta}{dt}$ is the slip of speed;

2. MATHEMATICAL MODELLING OF TRANSIENT STABILITY FOR MULTI-MACHINE POWER SYSTEM

The power system consists of the generators, exciters, governors, loads and other equipments such as the power transformers, the transmission lines, the synchronous condensers, the static var compensators... The equivalent models of the important components for the power system are illustrated below.

The figure 1 presents a multi-machine augmented network consisting of M generators with their pre-fault output power of turbine and of the j-th impedance loads Z_{Lj}

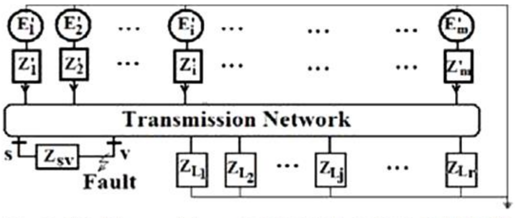

Fig.1 Multi- machine augmented power network pre-fault diagram

The figure 2 presents a fault condition in the augmented multimachine network with a fault impedance Z_F

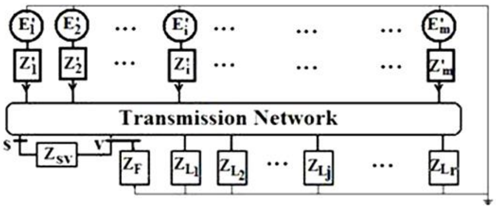

Fig.2 Multi- machine augmented power network fault diagram

At the t-th time interval, some automatic protective technical action of system protection can remove the fault element from the network, the figure 3 presents the post-fault multi-machine augmented network

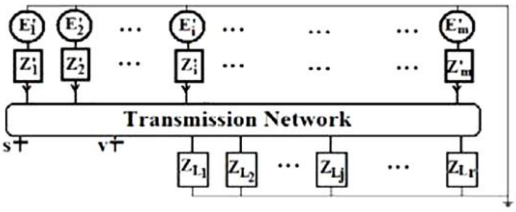

Fig.3 Multi- machine augmented power network post-fault diagram

Referring to [1], [2], [3], [4], [5], [7], the mathematical model for analyzing of the transient stability in a multi-machine power system involving the asynchronous torque is developed from [7] as follow

$$\begin{cases} \dfrac{d^2\delta_i^t}{dt^2} = \dfrac{\omega_o}{M_{Ji}} \left(\begin{array}{l} p_{i\ turbin}(x_i, \Delta\delta_i^t) - \dfrac{p_i(E_i^t, \delta_i^t)}{1 + \dfrac{d\delta_i^t}{dt}\dfrac{1}{\omega_o}} \\ -T_{COI}^t - T_{asi}^t - \dfrac{p_{di}^t}{\omega_o}\dfrac{d\delta_i^t}{dt} \end{array} \right); \\ i = 1,2..M\_generator\ number; \end{cases} \quad (6)$$

where T_{COI}^t is an equivalent torque simulating the effect of an infinite bus at the t-th time interval in multi-machine power system; T_{asi}^t is the asynchronous torque calculated for i-th synchronous machine at the t-th time interval; p_{di}^t is i-th variable damping factor depending on a set of different parameters such as the i-th elements of the eigen-image matrix, the phase angles δ_i^t at the t-th time interval, the voltages V_i^t at the i-th observing bus in power network at the t-th tim interval, the subtransient time constants T''_d, T''_q, the transient and subtransient reactances X'_d, X'_q, X''_d, X''_q and the rated frequency of the power system.

Synchronous Machine Model

The synchronous machines will be taken into account with the transient and subtransient effects. It is assumed that the d-axis and q-axis all have damping coils. The parameters of the synchronous machine will be taken as the input data concerning a set of numbers such as the inertia constant M_J, the d-axis and q-axis synchronous, transient, subtransient, negative sequence reactances X_d, X_q, X'_d, X'_q, X''_d, X''_q, X_2 and the time constant of machine windings under no-load condition T_{fo}.

The synchronous electrical powers at the terminal of i-th synchronous machine is [5]

$$\begin{cases} p_i(E'^t_i, \delta_i^t) = \sum_{j=1}^{M} E'^t_i E'^t_j Y_{ij}^t \cos(\phi_{ij}^t - \delta_i^t + \delta_j^t); \\ q_i(E'^t_i, \delta_i^t) = -\sum_{j=1}^{M} E'^t_i E'^t_j Y_{ij}^t \sin(\phi_{ij}^t - \delta_i^t + \delta_j^t); \end{cases} \quad (7)$$

where $Y^t_{ij}\angle\Phi^t_{ij}$ is the transfer element (if i≠j) or the driving-point element (if j=i) of the equivalent augmented bus admittance matrix Y_{bus} at t-th time interval; $E''^t_i\angle\delta^t_i$ is the transient e.m.f. of i-th synchronous machine taking into account of AVR at t-th time interval.

Exciter Model

The transfer function of the automatic excitation system may be written as [3]

$$W_E = \frac{K_V}{(1 + p\tau_1)(1 + p\tau_2)}; \quad (8)$$

According to (8), the mathematical model simulating the action during the fault of automatic excitation system including the electromagnetic transient effects of i-th synchronous machine should be written as follow

$$E_i^t + T_{doi}\frac{dE'^t_i}{dt} = e_i(t, T_{Ei}, K_{Ei}^t, V_i^+, V_i^-, V_{Gi}^t); \quad (9)$$

where E^t_i and E''^t_i are the synchronous and transient e.m.f taking into account of excitation control at t-th time interval; T_{doi} is the d-axis time constant of machine windings under no-load condition; $e_i(t, T_{Ei}, K_{Ei}^t, V_i^+, V_i^-, V_{Gi}^t)$ is a function simulating the proportional action of automatic excitation system of i-th synchronous machine at t-th time interval; T_{Ei} is the equivalent time constant of the automatic excitation system; K_{Ei}^t is the equivalent gain of excitation; V_i^+ and V_i^- are the upper and under bounds of stator voltage allowing to decide a suitable action of automatic excitation regulation of i-th synchronous machine; V_{Gi}^t is the actual voltage at the terminal of synchronous machine under condition of excitation control at t-th time interval;

Speed Governor Model

In general, the impact of speed governor affects only slightly to the transient process. If the speed varies more than (1.5-2)% and the transient process is longer than (2-3)sec, then the turbine power variation caused by the speed governor should be taken into account as some turbine torque changement. The transfer function of the governor [3] can be written as

$$W_{ASG} = \frac{K_{ASG}}{\left(\rho + p\tau_{ASR}\right)\left(1 + p\tau_{AE}\right)}; \qquad (10)$$

where ρ is the efficiency of the feedback; $\tau_{AE}$is the time constant of the amplifying element, τ_{ASG} is the time constant of the servo-piston;

According to (10), the torque of i-th turbine at the t-th time interval should be found as a function as follow

$$p^t_{iT}(x_i, \Delta\delta^t_i) = P_{oT} + \Delta p^t_{i\,ASG+AFR}(x_i, t); \quad (11)$$

where $\Delta p^t_{i\,ASG+AFR}(x_i, t)$ is the change of the i-th turbine power depending on a set of parameters $x_i = \left\{R_{i\,ASG}, \tau_{i\,ASG}, R_{i\,AFR}, \tau_{i\,AFR}\right\};$

where $R_{i\,ASG}, \tau_{i\,ASG}$ are the speed drop and time constant of the i-th automatic speed governor (ASG) system; $R_{i\,AFR}, \tau_{i\,AFR}$ are the frequency drop and time constant of the i-th automatic frequency regulation (AFR) system;

Static VAR System Model

A static VAR system is an aggregation of Static VAR Compensator and mechanical switched capacitors or reactors whose outputs are coordinated. The SVC can enhance the transient stability and the damping of system oscillations.

The performance of the SVC [4] is instantaneously provide unlimited Q_power to hold the voltage at a specific bus in power network with its V/I characteristic showing in figure 4 as follow

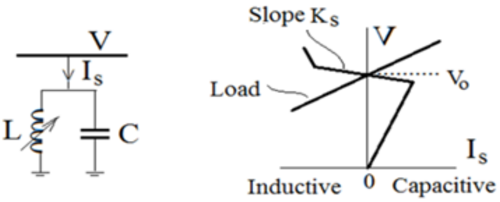

Fig.4 Equivalent circuit and V/I Characteristic of SVC

The composite characteristic of SVC - Power System, within the control range defined by the slope K_S with reactance X_{SL} may be expressed as

$$V_o + X_{SL} I_S = E_{The} - X_{The} I_S; \qquad (12)$$

where E_{The} and X_{The} are the thevenin e.m.f and thevenin reactance at the bus of SVC location in multi-machine power system.

Referring to [7], the main process of calculation of multi-machine transient stability by our PC program is developed and shown in the figure 5 as follows

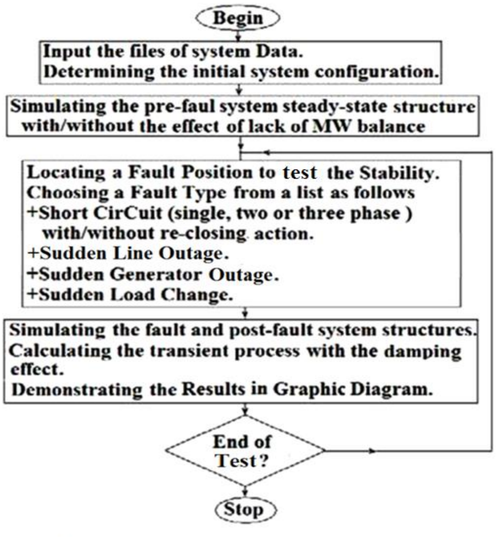

Fig.5 Multi-machine transient stability Simulation

3. NUMERICAL EXAMPLE

Let’s survey the electro-mechanical transient process of a 38-bus power system consisting of 5 thermal stations, 1 synchronous condenser, 4 SVC stations and 28 composite loads. Total MW load power demand is 2682.5MW. Basic power is 100MVA. The linedata is given in table 1 as follow

Table 1. Linedata

Bus		R (pu)	X (pu)	0.5B (pu)	t
m	n				
10	13	0.0062	0.0353	0.1090	1
10	12	0.0146	0.0831	0.0642	1
10	11	0.0104	0.0591	0.0456	1
11	12	0.0103	0.0582	0.0449	1
12	28	0.0073	0.0415	0.1283	1
8	6	0.0124	0.0706	0.0545	1
8	7	0.0127	0.0720	0.0556	1
6	7	0.0090	0.0509	0.0393	1
19	21	0.0045	0.0313	0.0996	1
21	22	0.0064	0.0361	0.1115	1
19	20	0.0079	0.0449	0.1388	1
14	17	0.0046	0.0318	0.1013	1
14	15	0.0038	0.0267	0.0851	1
15	16	0.0036	0.0205	0.0634	1
8	9	0.0049	0.0276	0.0852	1
17	18	0.0039	0.0223	0.0689	1
18	19	0.0079	0.0446	0.1379	1
23	26	0.0039	0.0223	0.0689	1
26	27	0.0051	0.0291	0.0899	1
23	24	0.0051	0.0356	0.1136	1
24	25	0.0063	0.0360	0.1112	1
2	3	0.0076	0.0659	0.4284	1
4	5	0.0091	0.0791	0.5146	1
1	2	0.0025	0.0217	0.5635	1
12	27	0.0091	0.0635	0.2026	1
3	4	0.0101	0.0875	0.5692	1
2	8	0.0004	0.0098	0.0000	1
3	10	0.0004	0.0098	0.0000	1
4	19	0.0004	0.0098	0.0000	1
1	14	0.0006	0.0131	0.0000	1
5	23	0.0004	0.0098	0.0000	1
29	2	0.0013	0.0482	0.0000	1
32	16	0.0020	0.0651	0.0000	1
33	22	0.0020	0.0651	0.0000	1
30	5	0.0013	0.0482	0.0000	1
31	28	0.0020	0.0651	0.0000	1
37	8	0.0006	0.0262	0.0000	1
34	23	0.0004	0.0150	0.0000	1
35	27	0.0014	0.0376	0.0000	1
36	19	0.0005	0.0200	0.0000	1
38	10	0.0004	0.0150	0.0000	1

The busdata of composite loads is given in the table 2 and the initial generation data is given in the table 3 as follows

Table 2. Data of the bus loads

Bus	Load			Bus	Load	
	MW	MVAr			MW	MVAr
1	0.69	3.375		15	121.2	48.901
2	0.46	2.25		16	89.23	35.997
3	0.92	4.5		17	129.2	52.121
4	0.92	4.5		18	118.8	47.923
5	0.92	4.5		19	185.8	74.955
6	104.82	42.29		20	113.2	45.668
7	97.889	39.49		21	119.2	48.086
8	0.375	2.524		22	82.57	33.321
9	81.241	32.78		23	182.7	73.719
10	194.04	78.28		24	121.7	49.064
11	99.887	40.3		25	103.6	41.811
12	121.19	48.9		26	111.1	44.813
13	114.94	46.38		27	123.2	49.703
14	169.55	68.41		28	93.23	37.45

Table 3. Initial generation busdata

Bus	Device	Generation	
		MW	MVAR
29	Static VAR Compensator	0	5
30	Static VAR Compensator	0	5
31	Static VAR Compensator	0	28
32	Static VAR Compensator	0	55
33	Synchronous Condenser	0	31
34	Thermal Plant Generator	685	197.04
35	Thermal Plant Generator	345	91.92
36	Thermal Plant Generator	505	202.14
37	Thermal Plant Generator	535	195.11
38	Thermal Plant Generator	660.62	174.46

Let's assume that the V/I characteristics of the SVCs in p.u. at the buses 29, 30, 31 and 32 are given for inputdata of this example and shown in the figures 6, 7 and 8 as follows

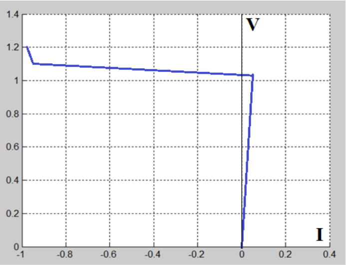

Fig. 6 V/I Characteristic of SVC at the bus 29 and bus 30

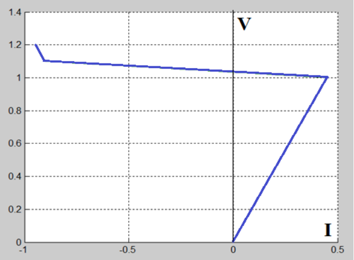

Fig. 7 V/I Characteristic of SVC at the bus 31

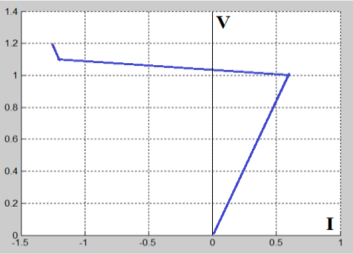

Fig. 8 V/I Characteristic of SVC at the bus 32

The inputdata for the reactances and time constants of the synchronous machines are given in the tables 4 and 5 as follows

Table 4. Synchronous Machine Reactances

Bus	Xd	Xq	X'd	X"d	X"q	X2
	p.u.					
33	0.635	0.351	0.137	0.06	0.92	0.14
34	0.225	0.214	0.04	0.028	0.045	0.04
35	0.757	0.727	0.119	0.079	0.102	0.06
36	0.304	0.292	0.054	0.037	0.06	0.05
37	0.308	0.295	0.035	0.024	0.043	0.03
38	0.225	0.214	0.04	0.028	0.045	0.04

Table 5. Time and Inertia constants

Bus	T"d	T"q	Tdo	Te	H
	Second				
33	0.161	0.171	8.3	0.52	6.56
34	0.15	0.161	5.4	0.15	23.64
35	0.16	0.172	6.2	0.19	13.1
36	0.15	0.161	5.4	0.15	17.73
37	0.163	0.176	13	0.23	35.475
38	0.15	0.161	5.4	0.15	23.64

The typical surveying and obtained results

A single high voltage transmission line (2-3) connecting two power plants 37 and 38 is chosen simulating some type of fault to test the transient stability of the power system. Let's suppose that a fault of three phase short circuit occurs at the line

(2-3) near the bus 2, and the fault will be cleared at 0.1sec by a circuit breaker. The typical results of surveying of the transient states of the power system during 8sec are shown in the figures 9 - 18 as follows

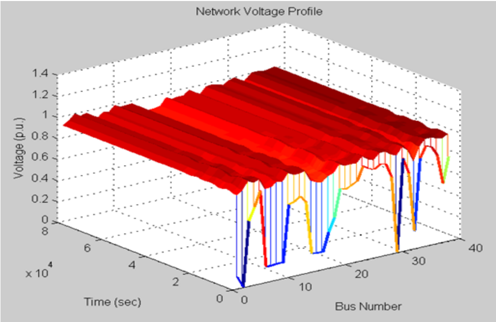

Fig. 9 Network Voltage Profile caused by 3 phase short circuit at line (2-3) near the bus 2

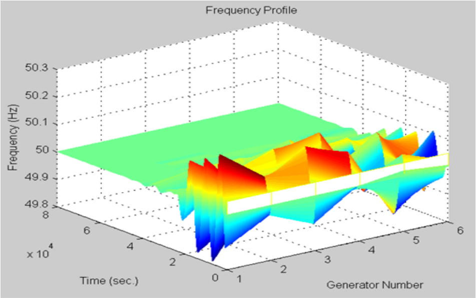

Fig.10 Frequency Profile of Synchronous Machine caused by 3 phase short circuit at line (2-3) near the bus 2

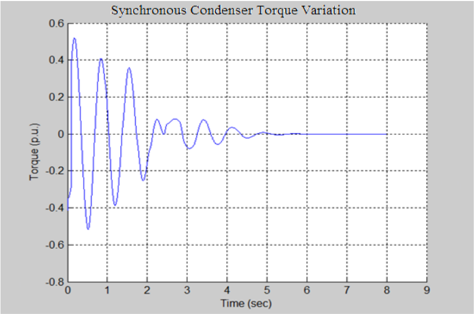

Fig.11 Torque Deviation of Synchronous Condenser at bus 33 causde by 3 phase short circuit at line (2-3) near the bus 2

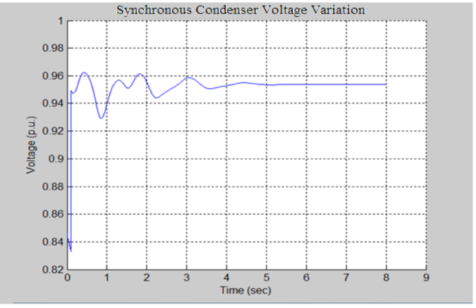

Fig.12 Voltage Variation of Synchronous Condenser at bus 33 causde by 3 phase short circuit at line (2-3) near the bus 2

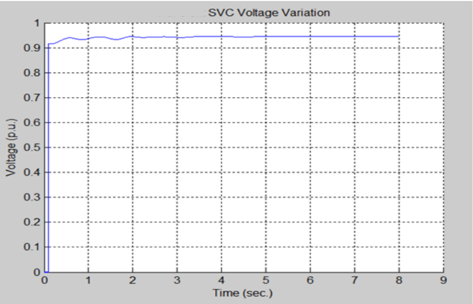

Fig.13 SVC Voltage Variation at bus 29 caused by 3 phase short circuit at line (2-3) near the bus 2

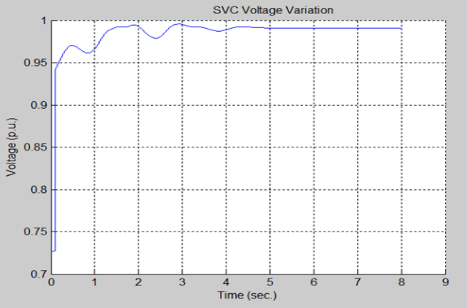

Fig. 14 SVC Voltage Variation at bus 31 caused by 3 phase short circuit at line (2-3) near the bus 2

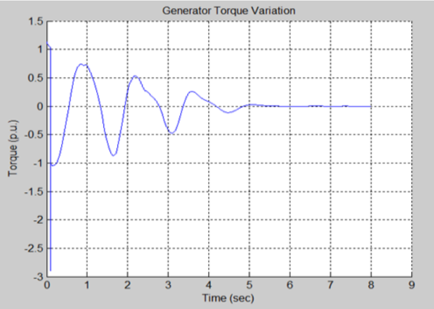

Fig. 15 Generator Torque Variation at bus 37 caused by 3 phase short circuit at line (2-3) near the bus 2

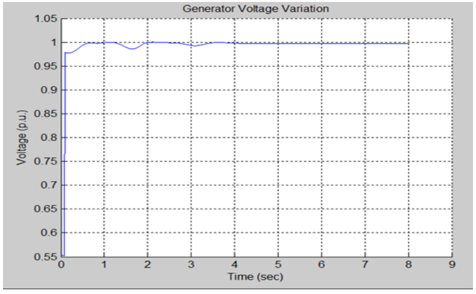

Fig. 16 Generator Voltage Variation at bus 37 caused by 3 phase short circuit at line (2-3) near the bus 2

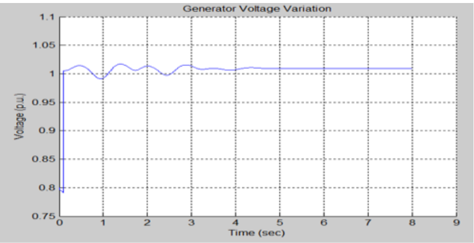

Fig. 17 Generator Voltage Variation at bus 38 caused by 3 phase short circuit at line (2-3) near the bus 2

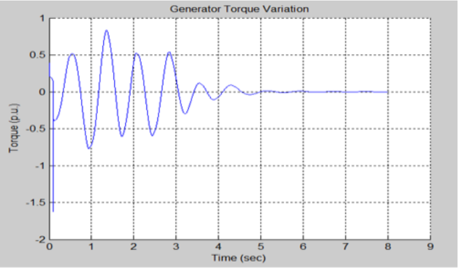

Fig. 18 Generator Torque Variation at bus 38 caused by 3 phase short circuit at line (2-3) near the bus 2

In case of neglecting of asynchronous torques in the calculation of transient process, the network voltage profile and the frequency profile will oscillate with amplitudes larger and are graphically shown in the figures 19 and 20 as follows

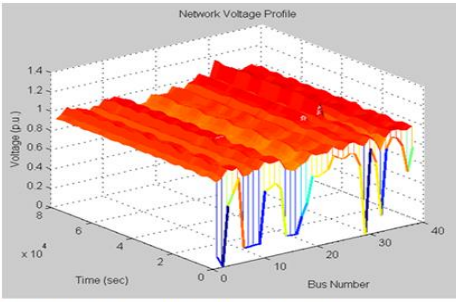

Fig.19 Network Voltage Profile neglecting the asynchronous torque

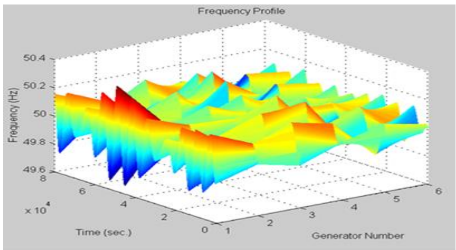

Fig. 20 Synchronous Machine Frequency Profile neglecting T_{as}

In case of three phase short circuit at line (2-3) near bus 2, the critical clearing time is 0.56sec. Let's suppose that the symmetrical fault at line (2-3) near the bus 2 will be late cleared at 0.57sec, the transient state of the power system will be very severe, the unstable transient process will lead to the voltage and frequency collapses. The collapses in power system are graphically shown in the figures 21 - 28 as follows

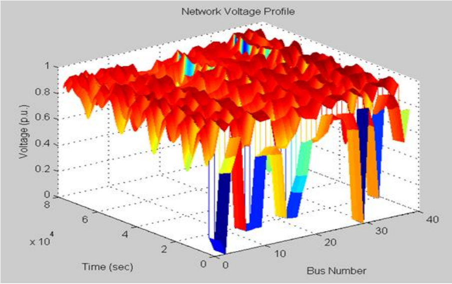

Fig. 21 Network Voltge Collapse Profile caused by a symmetrical fault at line (2-3) near the bus 2.

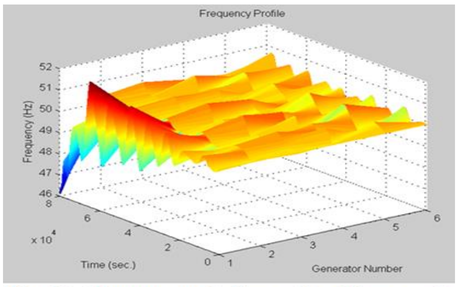

Fig.22 Frequency Collapse Profile caused by a symmetrical fault at line (2-3) near the bus 2.

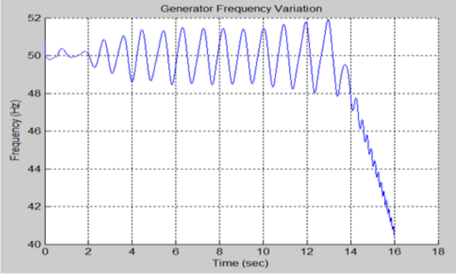

Fig.23 Frequency Collapse of the Synchronous Condenser at the bus 33

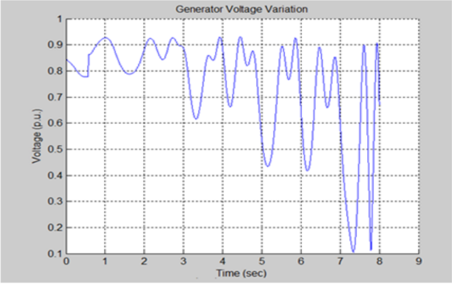

Fig. 24 Voltage Collapse of the Synchronous Condenser at the bus 33

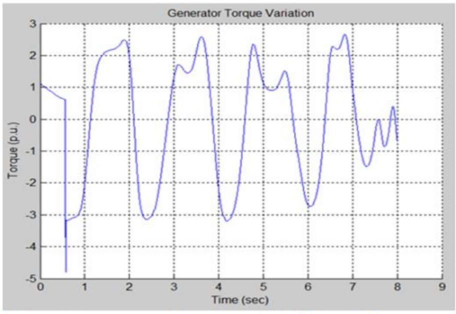

Fig. 25 Generator Torque Variation at the bus 37

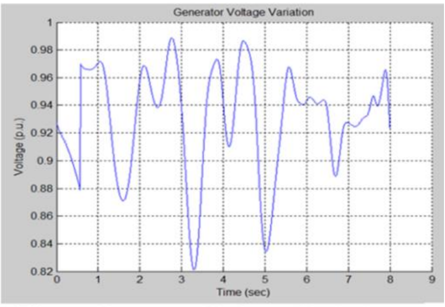

Fig. 26 Generator Voltage Variation at the bus 35

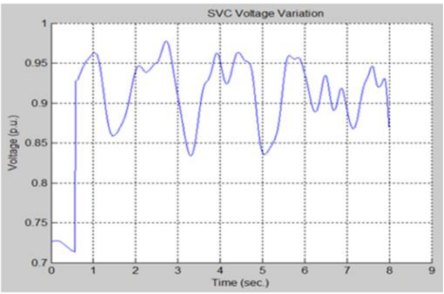

Fig.27 SVC Voltage Variation at the bus 31

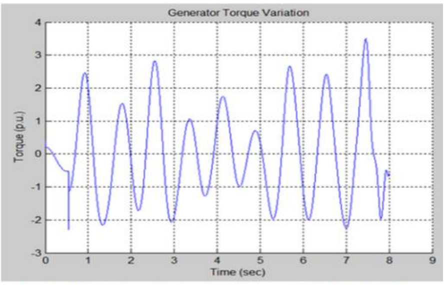

Fig.28 Generator Torque Deviation at the bus 38

In case of occurring of unsymmetrical fault at a distance of one-level tranformer from the generator locations in power system, the e.m.f components calculating for the synchronous machines are only positive sequence, taking into account of the action of automatic excitation regulation, the three phase voltages at the terminals of the synchronous machines are almost equals. During short time of the fault, the frequency variation is very small, neglecting the high harmonics, only the fundamental frequency is taken into account, the asynchronous torque may be approximately determined as how we calculated for the symmetrical fault mentioned above.The phase voltages may be determined by application of the symmetrical sequence components.

Let's survey an unsymmetrical fault of phase to phase to ground short circuit occurring at the line (2-3) near the bus 2, the clearing time is 0.1sec, the phase voltage are shown in the figures 29 - 31 as follows

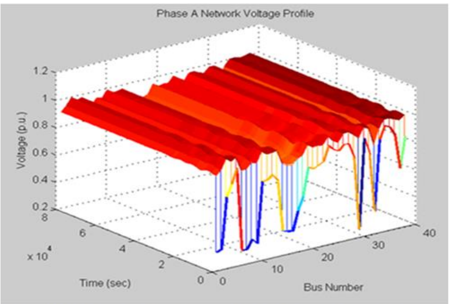

Fig.29 Phase A network Voltage Profile caused by phase-phase-ground fault

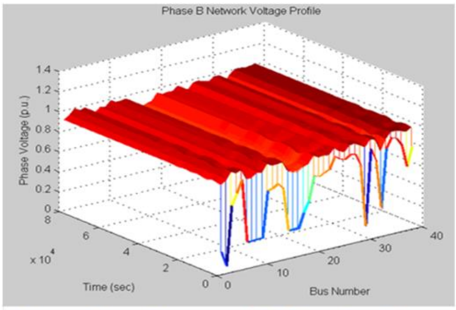

Fig.30 Phase B network Voltage Profile caused by phase-phase-ground fault

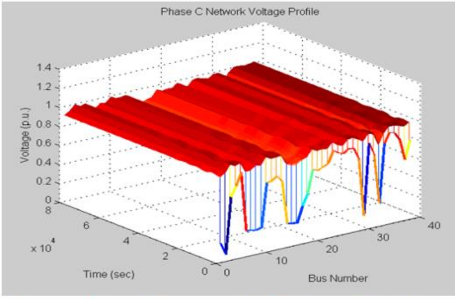

Fig.31 Phase C network Voltage Profile caused by phase-phase-ground fault

In this case, the critical clearing time is 0.7sec. If the clearing time is taken equal to 0.71sec, then the voltage and frequency will strongly oscillate leading to their collapses in a very short time. The collapses of voltage and frequency are shown in the figures 32 - 35 as follows

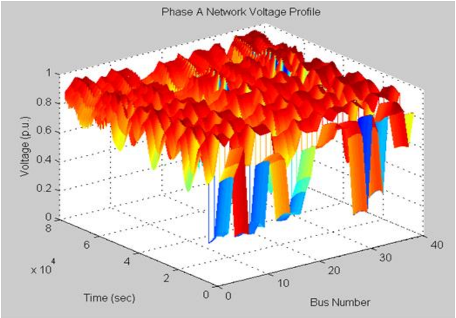

Fig. 32 Phase A network voltage collapse

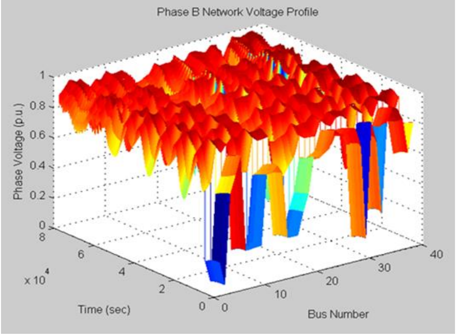

Fig. 33 Phase B network voltage collapse

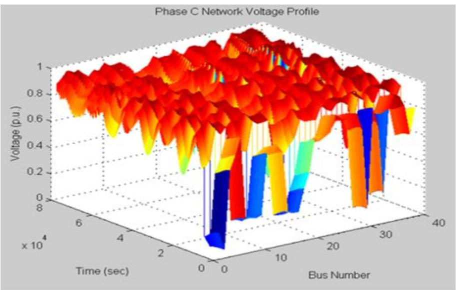

Fig. 34 Phase C network voltage collapse

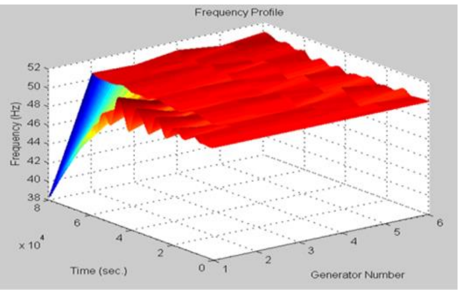

Fig. 35 Frequency Collapse

4. CONCLUSION

The results of the surveys showed that the asynchronous torque effects are to damp the electromechanical transients process, to slightly increase the critical clearing time for the different type of fault occurring in the power system, to strengthen the transient stability of the multi-machine power system.

New algorithm calculating the transient stability of power system is formed to test a number of simulations which consist the participation of the eigen-image matrix elements into the calculation of the asynchronous torque and is proven having good effective by the results of the calculations surveying a number of the numerical examples for the different structures of power system.

Khảo sát tác động của mô-men xoắn không đồng bộ ảnh hưởng đến ổn định động của hệ thống điện nhiều máy phát

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TÓM TẮT:

Một thuật toán mô phỏng tác động của mô-men xoắn không đồng bộ đến ổn định động của hệ thống điện nhiều máy phát được đề cập và một số ví dụ tiêu biểu được trình bày trong bài viết này. Dựa trên thuật toán mới đề xuất, chương trình này sử dụng các phần tử của ma trận ảnh lưới điện để mang lại các ưu điểm cụ thể đối với việc tính toán ổn định động của hệ thống điện nhiều máy phát. Điện áp quá độ đối xứng và bất đối xứng của các thiết bị hỗ trợ công suất phản kháng như SVC, máy đồng bộ được mô phỏng dưới sự tác động của hệ thống tự động điều chỉnh điện áp và tần số quá độ có liên quan đến tác động của mô-men không đồng bộ được mô phỏng nhằm phân tích ổn định động của hệ thống điện nhiều máy phát.

Từ khóa: *Hệ thống điện nhiều máy phát, Ổn định động, Mô-men không đồng bộ, Mô-men cản, Hiệu ứng điều chỉnh kích thích, Thiết bị bù VAR tĩnh.*

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