AN ACCURATE SINGLE MACHINE TRANSIENT STABILITY PROGRAMME

G. G. Gamage and A. K. David

Summary

This report brings to the notice of prospective users in Sri Lanka the availability of an accurate computer programme for single machine transient stability studies. The alternator is represented by an accurate mathematical model using the Generalised Machine theory while prime mover, governor control loop and automatic voltage regulator are represented by differential equations. Provision is available for both hydro and steam prime mover representation. The system equations are formulated in state space form as fifteen simultaneous differential equations. Due to the non-linearities inherent in the problem a step-by-step solution technique based on the fourth-order Runge-Kutta method has been developed. An approximate version of the programme that makes numerous simplifications in respect of the machine, transmission network and control system and thereby reduces the number of state variables to six has also been developed. The computer time is reduced by a factor of over 10 times but programme accuracy is limited to slightly beyond the first swing only.

The List of Principal Symbols

r_a, x_a — Resistance and leakage reactance of the stator.

r_{fd}, x_{fd} — Resistance and leakage reactance of the field winding.

r_{kd}, x_{kd} — Resistance and leakage reactance of d axis damper winding.

r_{kq}, x_{kq} — Resistance and leakage reactance of q axis damper winding.

r_e, x_e — Resistance and reactance external to the machine.

x_{md}, x_{mq} — d and q axis mutual reactance between the stator and rotor.

v_d, v_q — axis components of generator terminal voltage.

v_{fd} — Field voltage.

V_b — Infinite busbar voltage (r.m.s).

v_{bd}, v_{bq} — d and q axis components of infinite busbar voltage

ψ — Flux linkage

w_o — Synchronous speed (rad/sec).

w — Instantaneous speed (rad/sec).

δ — Rotor angle respect to input busbar voltage.

p — $\frac{d}{dt}$

T_e — Electrical torque.

T_{in} — Input torque.

P_{in} — Input power.

K_d — Damping constant.

1. Introduction

Mathematical models for the representation and study of single machine transient stability have been available for some years now. The classical formulation of the machine equations will be found in (1) while a complete description of the mathematical model for the case of a steam driven turbo-alternator including the effects of control loops will be found in (2). There is a relative paucity of material in respect of hydro-powered prime mover representation but some useful suggestions towards building a mathematical model for this purpose will be found in (3). The state space method of formation of multi-variable system dynamic equations is now favoured both for its clarity of expression useful for conceptual thinking and ease of computational use (4, 5). The application of the theorem of Liapunov's Second Method to synchronous machine stability analysis also requires the state space formulation. In the case of linear systems with time varying parameters the state space approach provides a useful expression of the complete solution in integral form. In the case of synchronous machine swing equation calculations however due to the non-linearities that cannot be eliminated from the state space formulation it is necessary to employ a step-by-step computation based on the differential equations formulated in the state space mode. Predictor-Corrector methods, Runge-Kutta methods or techniques based on the repetitive computation of the eigen values of the system equation can be employed.

Although the development of machine and system models and computer programmes for obtaining accurate single machine swing curves have achieved a high degree of sophistication in countries where advanced computer facilities are available, as far as the authors are aware no computer programmes are available in this country for transient stability studies by accurate numerical computation of machine swing curves. Furthermore, in view of the less sophisticated nature of the computer software presently installed in this country, programmes developed on more advanced computers cannot be run on the available machines. Hence it was necessary, as the basis of already developed mathematical model and computational techniques, to build a single machine transient stability programme including a representation of prime mover, transmission system and control loops, for the first time for users in Sri Lanka. The programme has been written for and tested on the IBM 1130 machine of the University Computer Centre at Peradeniya. It will shortly be made available as a library facility for interested users and power engineers in the country.

G. G. Gamage is presently a research assistant at the Department of Electrical and Electronic Engineering, Peradeniya campus.

A. K. David, PhD, BSc (Eng), DIC, CEng, MIE(Cey), MIEE is a senior lecturer in Electrical Engineering at the Peradeniya campus.

A novel feature of the programme is availability of alternative sub-routines to represent thermal-powered or hydro-powered prime movers. The latter routine models the reverse surges that are set up in the penstock subsequent to changes in gate position. A large surge tank is assumed, that is to say transient effects occurring in the surge tank and tunnel are, for the present, ignored. Another feature of the programme is the availability of an approximate model as an option available on user demand. It is accurate up to the first swing and cuts down computer time by a factor of over ten times.

2. The State-Space Method of Formulation

The performance of a dynamic system when formulated in terms of n-variables of the system which can be composed into a n-dimensional vector lends itself to the state space method of formulation. The vector may be thought to represent a point in n-dimensional space and the dynamic process to be described by the trajectory of the point.

2.1 Linear Fixed System

If the n-vector X represents the set of state variables, A is a (n x n) matrix of constant coefficients, B is a (n x m) matrix of constant coefficients and u is a m-vector of forcing functions, the system equation in state space is given in the well-known matrix form

$$\dot{X} = AX + Bu \qquad \text{where } X = X(t)$$

The solution of this system equation can be written (Ref. 6) in an explicit form either in terms of the state transtion matrix or in terms of the eigen values and eigen vectors of the A matrix. In terms of the state transition matrix the solution of the equations in the absence of forcing functions, (u = O) is

$X(t) = e^{At} X(O)$, where e^{At} is the transition matrix. When the forcing function u is non-zero the solution requires the evaluation of a matrix integral and takes the form

$$X(t) = e^{At} X(O) + \int_0^t A(t-\tau).\ Bu(t).d\tau$$

Both equations are readily amenable to numerical computation. The solution can also be conveniently written in terms of the eigen values (characteristic roots) and eigen vectors (characteristic vectors) of the A matrix. If the set λ_j and the set of vectors q_j represent eigen values and corresponding eigen vectors the solution of the enforced system can be written

$$X(t) = \sum_{j=1}^{n} [r_j . X(O)]\ e^{\lambda_j} q_j$$

Where r_j is the reciprocal basis of q_j defined by

$$[r_j.q_k] = O \text{ if } j \neq k \text{ and}$$
$$= 1 \quad \text{if } j = k$$

and (a.b) refers to the scalar product of the vectors a and b. The solution of the forced system can be obtained in similar fashion as

$$X(t) = \sum_{j=1}^{n} [r_j.X(O)]\ e^{\lambda_j} q_j \ + \sum_{j=1}^{n} \int_0^t [r_j.Bu()]\ e^{\lambda_j(t-\tau)}\ q_j\, d\tau$$

2.2 Linear System with Time Varying Coefficients

Where the system equation in state space takes the form—

$$\dot{X} = A(t).X + B(t).u$$

we obtain a system of linear differential equations with time-varying coefficients. An explicit solution can still be written in the form

$$X(t) = \phi(t,o).X(o) + \int_0^t \phi(t,\tau).B(\tau).u(\tau).d\tau$$

However the state transition matrix is now more difficult to obtain. If the A matrix possesses the commutativity condition of matrix multiplication

$$\phi(t,\tau) = e^{\int_\tau^t A(\lambda).d\lambda}$$

however as this is rarely the case it is necessary to obtain the transition matrix from the more complex series integration indicated below.

$$\phi(t,\tau) = 1 + \int_\tau^t A(\tau).d\tau + \int_\tau^t A(\tau_1)\ [\int_\tau^{\tau_1} A(\tau_2).d\tau_2]\ d\tau_1 + \ldots\ldots\ldots$$

If the time step t is small the higher integrals become negligibly small and the method can be used for numerical integration.

2.3 Synchronous Machine and System Equations

In the formulation of the machine and system equations below the following choice of state variables has been made.

(a) Synchronous Machine

i_d = d-axis current

i_q = q-axis current

ψ_f = field winding flux linkage

ψ_{kd} = d-axis damper winding flux linkage

ψ_{kq} = q-axis damper winding flux linkage

(b) Voltage control circuit

E_{m2} = final magnetic amplifier input voltage

E_x = exciter control input voltage

V_{fd} = voltage applied to synchronous machine field winding by exciter

E_{ms} = magnetic amplifier stabiliser feedback voltage

E_{xs} = exciter-stabiliser feedback voltage

(c) Prime Mover and governor control

Y_2 = Pilot valve control input signal

Y = Steam or water inlet valve position

P_{in} = Machine shaft power input

(d) Mechanical motion

δ = machine power angle in electrical degrees

$\dot{\delta}$ = $\frac{d\delta}{dt}$

The transmission system is represented by voltages V_{bd} V_{bq} which are the infinite busbar voltages referred to instantaneous machine axis.

As the equation formulation in Appendix A will show the appearance of explicit control inputs (forcing functions) have been suppressed. If the programme was intended for optimisation studies, it would have been necessary to make explicit provision for control inputs. An examination of the equation formulation will also show that at best the equations can be obtained in the form

$$\dot{X} = AX + F(X)$$

where certain residual non-linearities inherent to the system which cannot be removed are carried in the Matrix F(X). For small disturbance analysis and for certain other purposes the equations can be linearised and the techniques indicated in the above sections can be usefully employed. However this is not suitable for the analysis of large disturbances and swing curve computation. Hence step by step Runge Kutta or other numerical techniques have to be used for computing the trajectory of the X vector in state space.

3. Accurate Model

3.1.1 Mathematical Model of Machine

According to the two-axis theory, the general equations which describe the voltages, flux linkages and electrical torque for an alternator in per-unit form are,

$$v_d = p\psi_d + \omega\psi_q + r_a i_d \qquad \ldots(1)$$

$$v_q = p\psi_q - \omega\psi_d + r_a i_q \qquad \ldots(2)$$

$$v_{fd} = p\psi_{fd} + r_f i_{fd} \qquad \ldots(3)$$

$$0 = p\psi_{kd} + r_{kd} i_{kd} \qquad \ldots(4)$$

$$0 = p\psi_{kq} + r_{kq} i_{kq} \qquad \ldots(5)$$

$$\omega_o \psi_d = x_{dd} i_d + x_{md} i_{fd} + x_{md} i_{kd} \qquad \ldots(6)$$

$$\omega_o \psi_{fd} = x_{md} i_d + x_{ffd} i_{fd} + x_{md} i_{kd} \qquad \ldots(7)$$

$$\omega_o \psi_{kd} = x_{md} i_d + x_{md} i_{fd} + x_{kkd} i_{kd} \qquad \ldots(8)$$

$$\omega_o \psi_q = x_{qq} i_q + x_{mq} i_{kq} \qquad \ldots(9)$$

$$\omega_o \psi_{kq} = x_{mq} i_q + x_{kkq} i_{kq} \qquad \ldots(10)$$

$$T_e = \frac{\omega_o}{2} (\psi_d i_q - \psi_q i_d) \qquad \ldots(11)$$

terminal voltage

$$V_t = \frac{1}{\sqrt{2}} \sqrt{(v_d^2 + v_q^2)} \qquad \ldots(12)$$

Mechanical equation of motion

$$\frac{\omega_o}{2H} (T_{in} - T_e - T_{loss}) = p^2\delta \qquad \ldots(13)$$

3.1.2 Automatic voltage regulator

Block diagram of AVR is shown in fig.1.

$$E_{m1} = G_v (V_{ref} - V_t) \qquad \ldots(14)$$

$$E_{m2} = \frac{G_{m1}}{1 + pT_{m1}} (E_{m1} + E_{xs} + E_{ms}) \qquad \ldots(15)$$

$$E_{m2(min)} \leq E_{m2} \leq E_{m2(max)}$$

$$E_x = \frac{G_{m2}}{1 + pT_{m2}} E_{m2} + K_{m2} \qquad \ldots(16)$$

$$E_{x(min)} \leq E_x \leq E_{x(max)}$$

$$v_{fd} = \frac{G_x E_x}{1 + p T_x} \qquad ..(17)$$

$$E_{ms} = - \frac{G_{ms} T_{ms} p}{1 + T_{ms} p} E_x \qquad ..(18)$$

$$E_{xs} = - \frac{G_{xs} T_{xs} p}{1 + T_{xs} p} v_{fd} \qquad ..(19)$$

3.1 Prime Mover and Governor

Block diagram of hydro prime mover and governor is shown in Fig. 2.

The reverse surges which accompany a change in gate position in water turbines were approximated by a first order transfer function with the assumptions:

1. The pipe and water are incompressible.
2. The velocity of water varies directly with the gate opening.
3. The turbine output is proportional to the product of head and volume of flow.
4. The head losses in the conduit and gate may be neglected.

Therefore transfer function for water turbine

$$P_{in} = \frac{1 - T_w p}{1 + \frac{T_w}{2} p} Y G_3 \qquad ......(20)$$

For steam turbines

$$P_{in} = \frac{1}{1 + T_s p} YG_3 \qquad ......(20\ s)$$

Where T_w = penstock delay

T_s = entrained steam delay.

The transfer functions of speed sensor and relay valves

$$Y_1 = Y_0 - G_1 \ p\delta \qquad ...(21)$$

$$Y_2 = \frac{G_r Y_1}{1 + T_1 p} \qquad ......(22)$$

$$Y = \frac{G_p Y}{1 + T_2 p} + k \qquad ......(23)$$

Where k = Relay bias

k_o = Governor setting

3.1.4 Transmission Line

The axis components of machine terminal voltages and currents are related to the axis components of the infinite bus voltages as follows:

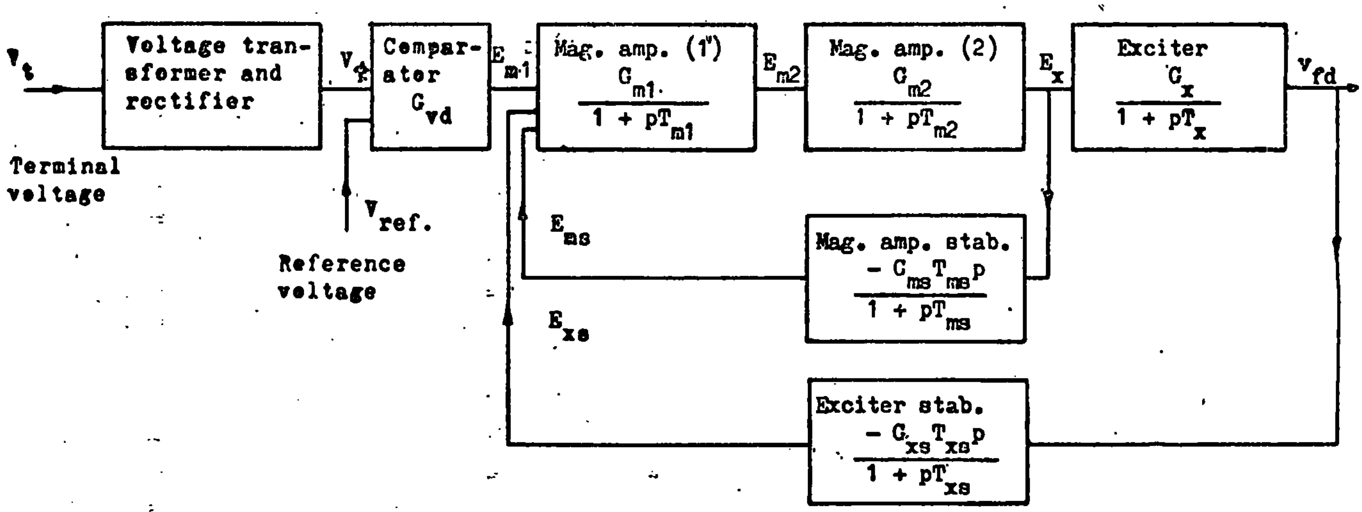

Fig. 1

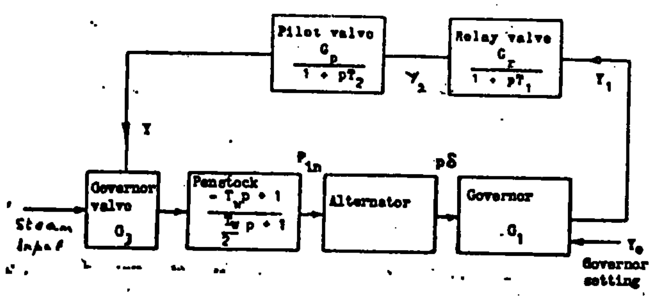

Fig. 2

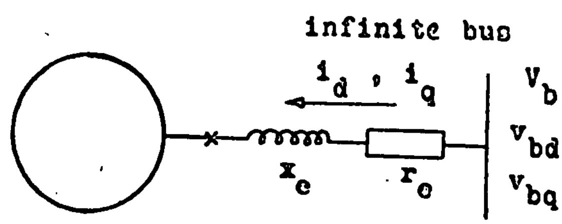

Fig. 3

$$\begin{bmatrix} v_{bd} \\ v_{bq} \end{bmatrix} = 2.V_b \begin{bmatrix} \sin\delta \\ -\cos\delta \end{bmatrix}$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = -\begin{bmatrix} r_e + p.\dfrac{x_e}{\omega_0} & x_e\dfrac{\omega}{\omega_0} \\ -x_e.\dfrac{\omega}{\omega_0} & r_e + p.\dfrac{x_e}{\omega_0} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} v_{bd} \\ v_{bq} \end{bmatrix} \quad \begin{matrix} \ldots\ldots\ldots (24) \\ \ldots\ldots\ldots (25) \end{matrix}$$

With these simplifications of the system number of state variables reduced to six as shown in Appendix B and the time step could be increased to about 25 to 50 ms, because the time constants of the system were large compared to step size. Hence computer time was reduced by a factor of about 10 - 20.

In deriving this relation the shunt admittance, magnetising currents in the transformers and charging currents in the transmission lines are neglected.

3.2 Description of the Computer Programme

Equations 1 to 25 were written as a set of 15 first order differential equations as shown in Appendix A and were solved by step-by-step integration using fourth order Runge-Kutta method of integration. A Runge-Kutta method has been chosen because of its high accuracy and ability to integrate through discontinuities (self-starting property). However the method is prodigal in the use of computer time because of the need to compute four values of effective slope at each integration step.

The time step must be small compared with the a.c. cycle period, since the terms $p\psi_d$ and $p\psi_q$ result in changes of the axis quantities at about supply frequency. The time step selected for test calculations of the programme was 2.5 ms. Each step of integration consumes about 1 second of computer time on an IBM 1130 Machine. Therefore to obtain a numerical computation up to about the second swing of the rotor, the computer time was about 20 minutes. Clearly the programming of an IBM 1130 type small computer for swing equation computation is of interest in the off-line mode only.

4. Approximate Method

Even though the use of the accurate method gives results closer to the practical ones, it consumes a large amount of computer time. Therefore to reduce computing time the following approximations were made.

(1) The rate of change of flux linkage in the stator voltage expressions were negligible.

(2) Transients in transmission lines were negligible.

(3) No damper windings.

(4) In equations (1,)(2), (24) and (25) and value of $\omega = \omega_0$.

The simplifications made in the control systems:

(1) Negligible time delay in magnetic amplifiers. Hence AVR can be represented by a transfer function of order 2.

(2) The governor loop simplified to order 1.

5. Results

For test calculations of the programme a machine of 37.5 MVA with a steam prime mover was selected.

TABLE 1

Parameters of the System

(1) Synchronous Generator

Machine ratings: 37.5 MVA, 30 MW, 0.8 p.f., 11.8 kV, 3000 r.p.m.

r_a	= 0.002 p.u.	X_a	= 0.14 p.u.
r_{fd}	= 0.00097 p.u.	X_{fd}	= 0.14 p.u.
r_{kd}	= 0.125 p.u.	r_{kq}	= 0.0125 p.u.
X_{kd}	= 0.04 p.u.	X_{kq}	= 0.04 p.u.
X_{md}	= 1.86 p.u.	X_{mq}	= 1.58 p.u.
H	= 5.3 S		

(2) Exciter

G_v	= 0.00079	G_{m1}	= 52.1
T_{m1}	= 0.044 sec	K_{m1}	= 0.00018
$E_{m2(min)}$	= 0.0	$E_{m2(max)}$	= 0.000298 p.u.
G_{m2}	= 12.2	T_{m2}	= 0.1 sec
K_{m2}	= —0.00186	$E_{x(min)}$	= —0.000854 p.u.
$E_{x(max)}$	= 0.000854 p.u.	G_x	= 3.06
T_x	= 0.2 sec	G_{ms}	= 0.0139
T_{ms}	= 0.1 sec	G_{xs}	= 0.00525
T_{xs}	= 2.0 sec		

(3) Governor and Prime mover

G_1	= 0.0149	Gr	= 1.0
G_p	= 1.33	T_1	= 0.1 sec
T_2	= 0.188 sec	K	= —0.267
G_3	= 1.43	T_s	= 0.49 sec

(4) Transformer and Transmission Line

X_e	= 0.20	p.u.	before fault
X_e	= 0.34	p.u.	after fault cleared
r_e	= 0.0194	p.u.	before fault
r_e	= 0.025	p.u.	after fault cleared

TABLE 2

Initial Conditions

Input bus voltage	= 1.0 p.u.
Generator output	= 0.8 p.u.
Power Factor	= 0.8 lagging

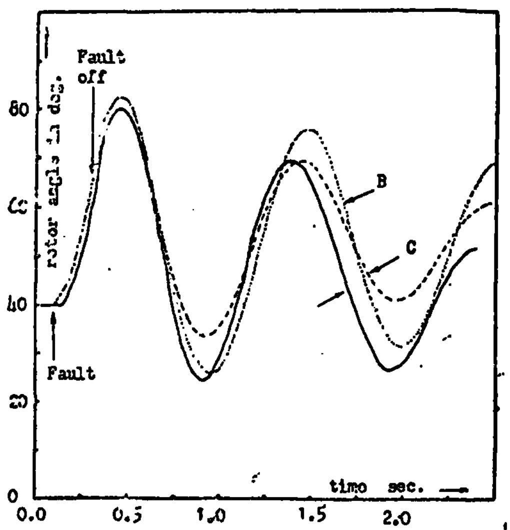

Fig. 4

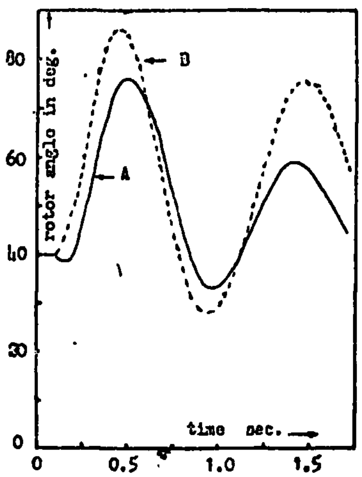

Fig. 5

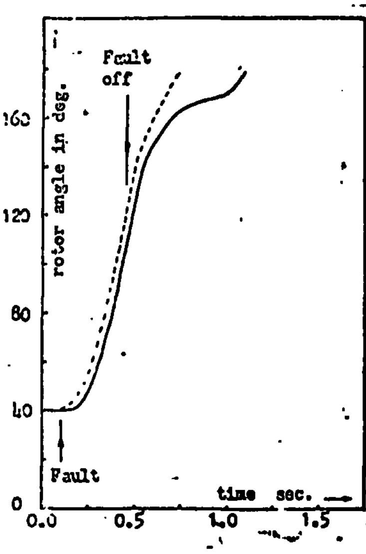

Fig. 6

Fig. 4 shows the swing curves computed for a three phase short circuit lasting for 200ms. at the infinite bus. Curve A is that obtained using the accurate method neglecting mechanical damping (kd = o), since it is negligibly small compared to other damping present in the system. Curve B and curve C have been obtained from the approximate method for the same fault with kd = o and 0.5 respectively. The significant difference between the curves A and B can be attributed to the electrodynamic damping which was neglected in the latter case. Representing this damping effect by an arbitrarily assumed mechanical damping constant of 0.5 in the approximate method (curve C) it was found that the accurate (curve) A could be approximated at least during the first swing for this type of fault.

The swing curves computed for a three phase short circuit of duration 200 ms. directly at the machine terminals are shown in fig. 5 from both accurate (curve A) and approximate (curve B) methods. In using approximate methods a damping factor of 0.5 was introduced to take into account the effect of damper windings. This damping factor which was sufficient to represent the electrodynamic damping in the previous case is found to be insufficient here, mainly because of the severity of this fault. A significant feature of curve A is the back swing which lasts for about 150 ms. immediately after fault. This back swing was not prominent in previous case. as that the fault is less severe. As a consequence of neglecting the $p\psi_d$ and $p\psi_q$ terms in analysis using the approximate method this back swing is not observed in curve B.

From fig. 6 it is seen that the machine is just unstable for a 3 phase short circuit lasting for 350 ms. at the infinite bus.

The electrical torque curves for the same fault of swing curves fig. 4 are shown in fig. 7. Very large electrical torque swings at power frequency are observed in the accurate analysis (curve A) and are features of the accurate method only. Since the variations in flux linkages are not fully represented in the approximate method of analysis only an averaged out form of these large torque swings appears in the output (curve B). This is a serious and well known drawback in approximate methods of analysis of this type.

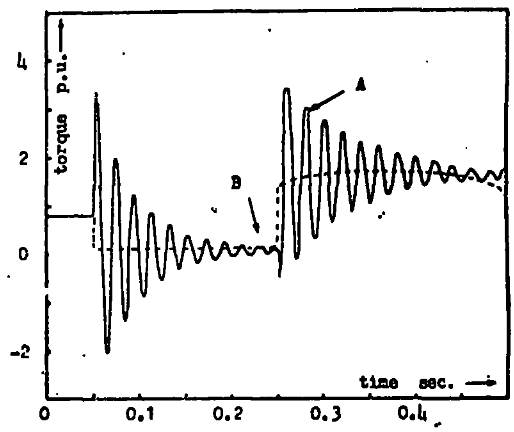

Fig. 7

6. Conclusions

A working computer programme has been built for the accurate or approximate study of single machine stability by obtaining the swing curves subject to various types of faults. The programme has been tested for various types of faults and output results reported.

Further work is now in progress to analyse multimachine stability problems in small power systems in view of the relevence of this problem to Sri Lanka.

7. Acknowledgements

The authors wish to thank Dr. J. B. X. Devotta of the Faculty of Engineering, University, Peradeniya for many useful discussions and the computer centre staff for their assistance.

Prof. W. P. Jayasekara, Head of the Department of Electrical and Electronic Engineering, University Peradeniya is thanked for his constant encouragement, making available departmental and computer facilities and for permission to publish this paper.

8. References

(1) B. Adkins and R. G. Harley, *The General Theory of Alternating Current Machines* (*Book*), Chapman and Hall, 1975.

(2) G. Shackshaft, *General Purpose Turbo-Alternator Model*, Proc. IEE, Vol. 110, No. 4, pp. 703, 1963.

(3) C. Concordia and L. K. Kirchmayer, *Tie-Line Power and Frequency Control of Electric Power Systems*, Part II, Trans. AIEE, Vol. 73, Part III A, pp. 133, 1954.

4. James E. Van Ness, Frank B. Kern, *Use of the Exponential of the System Matrix to Solve the Transient Stability Problem*, Trans. IEEE, Vol. 89 PAS, No. 1, pp. 83, 1970.

(5) John and Undrill, *Power System Stability Studies by the Method of Liapunov I — State Space Approach to Synchronous Machine Modelling*, Trans. IEEE, Vol. 89 PAS, No. 7, pp. 791, 1967.

Appendix A

The equations 6 to 10 were solved to obtain,

$$\psi_q = \frac{x''_q}{\omega_o} \cdot i_q + \frac{x''_q - x_a}{x_{kq}} \cdot \psi_{kq}$$

$$\psi_d = \frac{x''_d}{\omega_o} \cdot i_d + (x''_d - x_a) \cdot \left(\frac{\psi_{kd}}{x_{kd}} + \frac{\psi_{fd}}{x_{fd}}\right)$$

$$i_{fd} = \frac{1}{x_{fd}}\left(-g_1 i_d + \omega_o\left(1 - \frac{g_1}{x_{fd}}\right)\psi_{fd} - \omega_o g_1 \frac{\psi_{kd}}{x_{kd}}\right)$$

$$i_{kd} = \frac{1}{x_{kd}}\left(-g_1 i_d + \omega_o\left(1 - \frac{g_1}{x_{kd}}\right)\psi_{kd} - \omega_o g_1 \frac{\psi_{fd}}{x_{fd}}\right)$$

$$i_{kq} = \frac{\omega_o \psi_{kq}}{x_{mq} + x_{kq}} - \frac{x_{mq}}{x_{mq} + x_{kq}} \cdot i_q$$

Where, $g_1 = x''_d - x_a$

These values of ψ_q, ψ_d, i_{fd}, i_{kd} and i_{kq} were substituted in equations 1 to 5, 24 and 25, and obtained the first five equations of the state space formulation. The equations 13 to 23 were rewritten to obtain the rest of the equations of the above formulation.

Where,

$$a_1 = -\left(r_a + r_e + \frac{x_{md} g_1^2}{g_3 \, \omega_o x_{fd} T''_{do}} + \frac{g_1 g_3}{\omega_o x_{kd} T''_{do}}\right) \cdot a_7$$

$$a_2 = -\frac{x_e + x''_q}{x_e + x''_d}$$

$$a_3 = \left(\frac{-g_1}{x_{fd} T''_{do}} + \frac{g_1^2 x_{md}}{x_{fd}^2 x_{kd} T'_{do}} - \frac{g_1 g_3}{x_{kd} x_{fd} T''_{do}}\right) \cdot a_7$$

$$a_4 = \left(\frac{g_1}{T''_{do} x_{kd}} - \frac{g_1 x_{md}}{g_3 x_{md} x_{fd} T'_{do}}\right) \cdot a_7$$

$$a_5 = -\frac{g_2 a_7}{x_{kq}}$$

$$a_6 = -\frac{g_1 a_7}{x_{fd}}$$

$$a_7 = \frac{\omega_o}{x_e + x''_d}$$

$$b_1 = \frac{x_e + x''_d}{x_e + x''_q}$$

$$b_2 = -\left(r_a + r_e + \frac{g_2 x_{mq}}{\omega_o x_{kq} T''_{qo}}\right) \cdot b_6$$

$$b_3 = \frac{g_1 b_6}{x_{fd}}$$

$$b_4 = \frac{g_1 b_6}{x_{kd}}$$

$$b_5 = \frac{g_2 b_6}{x_{kq} T''_{qo}}$$

$$b_6 = \frac{\omega_o}{x_e + x''_q}$$

$$c_1 = \frac{g_1 x_{md}}{\omega_o g_3 T'_{do}}$$

$$p \cdot \begin{bmatrix} i_d \\ i_q \\ \psi_{fd} \\ \psi_{kd} \\ \psi_{kq} \\ E_{m2} \\ E_x \\ v_{fd} \\ E_{ms} \\ E_{xs} \\ Y_2 \\ Y \\ P_{in} \\ \delta \\ p\delta \end{bmatrix} = \begin{bmatrix} a_1 & \omega a_2 & a_3 & a_4 & \omega a_5 & & & a_7 & & & & & & & \\ \omega b_1 & b_2 & \omega b_3 & \omega b_4 & b_5 & & & & & & & & & & \\ c_1 & & c_3 & c_4 & & & & 1 & & & & & & & \\ d_1 & & d_3 & d_4 & & & & & & & & & & & \\ & e_2 & & & e_5 & & & & & & & & & & \\ & & & & & \frac{-1}{T_{m1}} & & & \frac{G_{m1}}{T_{m1}} & \frac{G_{m1}}{T_{m1}} & & & & & \\ & & & & & \frac{G_{m2}}{T_{m2}} & \frac{-1}{T_{m2}} & & & & & & & & \\ & & & & & & \frac{G_x}{T_x} & \frac{-1}{T_x} & & & & & & & \\ & & & & & \frac{G_{ms}G_{m2}}{T_{m2}} & \frac{G_{ms}}{T_{m2}} & & \frac{-1}{T_{ms}} & & & & & & \\ & & & & & & \frac{G_{xs}G_x}{T_x} & \frac{G_{xs}}{T_x} & & \frac{-1}{T_{xs}} & & & & & \\ & & & & & & & & & & \frac{-1}{T_1} & & & & \frac{G_T G_1}{T_1} \\ & & & & & & & & & & \frac{G_p}{T_2} & \frac{-1}{T_2} & & & \\ & & & & & & & & & & f_1 & f_2 & \frac{-2}{T_W} & & \\ & & & & & & & & & & & & & & 1 \\ & & & & & & & & & & & & & & \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \psi_{fd} \\ \psi_{kd} \\ \psi_{kq} \\ E_{m2} \\ E_x \\ v_{fd} \\ E_{ms} \\ E_{xs} \\ Y_2 \\ Y \\ P_{in} \\ \delta \\ p\delta \end{bmatrix} + \begin{bmatrix} v_{bd} a_6 \\ v_{bd} b_6 \\ \cdot \\ \cdot \\ \cdot \\ \frac{G_{m1} E_{m1} + K_{m1}}{T_{m1} \quad T_{m1}} \\ \frac{K_{m2}}{T_{m2}} \\ \\ -\frac{G_{ms} K_{m2}}{T_{m2}} \\ \cdot \\ \frac{G_T Y_o}{T_1} \\ \frac{K}{T_2} \\ -\frac{2 G_3 K}{T_2} \\ \cdot \\ \frac{\omega_o}{2H}(T_m - T_e - T_{loss}) \end{bmatrix}$$

Appendix B

With the assumptions made the number of state variables reduced to six and the state variables selected are ψ, v, E^{**}, P^{**}, δ and p^{*}.

$$
p \cdot \begin{bmatrix} \psi_{fd} \\ v_{fd} \\ E_{xs} \\ P_{in} \\ \delta \\ p\delta \end{bmatrix} = \begin{bmatrix} c_1\omega_0 & 1 & \cdot & \cdot & \cdot & \cdot \\ \cdot & -\frac{1}{T_x} & \frac{G_x}{T_x} & \cdot & \cdot & \cdot \\ \cdot & \frac{G_{xs}}{T_x} & -\frac{1}{T_{xs}} - \frac{G_x G_{xs}}{T_x} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & -\frac{1}{T} & \cdot & -\frac{G_1 G_2 G_3}{T} \\ \cdot & \cdot & \cdot & \cdot & \cdot & 1 \\ \cdot & \cdot & \cdot & \cdot & \cdot & -K_d \end{bmatrix} \begin{bmatrix} \psi_{fd} \\ v_{fd} \\ E_{xs} \\ P_{in} \\ \delta \\ p\delta \end{bmatrix} + \begin{bmatrix} c_3 v_{bd} + c_4 v_{bq} \\ \frac{G_x E_{m1}}{T_x} + \frac{k_x}{T_x} \\ \frac{G_{xs}}{T_x}\left(k_x + G_x E_{m1}\right) \\ \frac{G_2 G_3 Y_0}{T} \\ \\ \frac{\omega_0}{2H}\left(T_{in} - T_e - T_{loss}\right) \end{bmatrix}
$$

Where,

$$X = x_{md} + x_a + x_e$$

$$C_1 = -r_f - \frac{r_f}{x_{md} + x_{fd}} + \frac{X}{C_2} \cdot \frac{(x'_d - x_a)^2}{x_{fd}^2}$$

$$C_2 = (r_a + r_e)^2 + (x'_d + x_e) \cdot X$$

$$C_3 = \frac{r_f}{x_{fd}} (x'_d - x_a) \frac{(r_a + r_e)}{C_2}$$

$$C_4 = \frac{X\, r_{fd}}{C_2} - \frac{(x_a - x'_d)}{C_2}$$

$$T = T_1 + T_2 + \frac{T_w}{2}$$

නිවැරදි තනි යන්ත්‍ර අනිත්‍ය ස්තායිතා ප්‍රක්‍රමයක්

මෙම වාර්තාව තනි යන්ත්‍ර අනිත්‍ය ස්තායිතා අධ්‍යයනය සඳහා අවශ්‍ය නිවැරදි ආගනක ප්‍රක්‍රමයක් ශ්‍රී ලංකාවේ ක්ෂේත්‍ර ගවේශකයන්ගේ අවධානය සඳහා ඉදිරිපත් කරයි. ප්‍රාථමික චාලකය, සංයාමක පාලක පුඩුව හා ස්වයංක්‍රියා විභව යාමකය අවකලන සමීකරණ මගින් පෙන්නුම් කරනු ලබන අතර ජනක යන්ත්‍රය සාමාන්‍ය කරණ යන්ත්‍ර සිද්ධාන්තය පාවිච්චි කරමින් ලබාගත් ගණිතමය ආකෘතියකින් නියෝජනය කරනුලබයි. ජල හා වාෂ්ප ප්‍රාථමික චාලක නියෝජනය සඳහා ඉඩ සලසා තිබේ. සමගාමී අවකලන සමීකරන පහලොවක් මගින් පද්ධති සමීකරණයේ තත්ත්ව අවකාශ ස්වරූපයෙන් සූත්‍රකරණය කරනු ලැබ ඇත. ගැටලුව තුළ නෛසර්ගිකව ඇති අරේඛීයත්වය හේතුකොට ගෙන එය විසඳීම සඳහා සිව්වෙනි ඇනවුමෙ රන්ජි කුට්ටා ක්‍රමය මත පදනම් වූ පියවරෙන් පියවර විසඳීමේ ක්‍රමය ඉදිරිපත් කරනු ලැබ ඇත. යන්ත්‍රය, සම්ප්‍රේෂණ ජාලය හා පාලන පද්ධතිය සම්බන්ධයෙන් නොයෙකුත් සරල කිරීම් කරන්නාවූ හා එමගින් තත්ව විචල්‍යයන්ගේ සංඛ්‍යාව හයක් දක්වා අඩුකිරීම පිළිබඳ ප්‍රක්‍රමයේ ආසන්න ස්වරූපයෝද ඉදිරිපත් කරනු ලැබේ. ආගනක කාලය මෙම සරල කිරීමෙන් දස ගුණයකට වඩා විශාල සාධකයකින් අඩුකරනු ලබන නමුදු ප්‍රක්‍රමක නිරවද්‍යතාවය පළමුවැනි පැද්දීමෙන් තරමක් ඇතට පමණක් සීමාකරනු ලබයි.

திரட்டு

இந்த அறிக்கை தனிப்பொறியின் மாறும் உறுதிப்பாடுபற்றிய ஆய்வுக்கு ஒரு செம்மையான நிகழ்ச்சித் திட்டம் கிடைக்கக்கூடிய ஒரு வாய்ப்பினை இலங்கையிலுள்ள பாவனையாளராகும் வாய்ப்புள்ளவர்களின் கவனத்துக்குக் கொண்டுவருகிறது. முதலியக்கி ஆளி, அடக்கல், தடம், தானியங்கி அழுத்த ஒடுக்காக்கி ஆகியன வகையீட்டுச் சமன்பாடுகளால் குறிக்கப்படும் அதே வேளையில் ஆடலாக்கி பொதுவாக்கப்பட்ட பொறிக் கொள்கையைப் பாவித்துச் செம்மையான கணிதமாதிரியுருவினால் குறிக்கப்படுகிறது. நீர்வளி, நிராவி முதலியக்கிகள் இரண்டினதும் குறிபிட்டீற்கு வளி வகைகள் உள்ளன. தொகுதிச் சமன்பாடுகள் நிலைவெளி வடிவங்களில் பதினைந்து ஒருங்கமை வகையீட்டுச் சமன்பாடுகளாக தொகுக்கப்பட்டுள்ளன. இந்தப் பிரச்சனையில் உள்ள ஏகப்பிரமாணமின்மையால் ருங்கே - குட்டாவின் நாலாம் அடுக்கு வளி முறையின் அடிப்படையிலான தீர்வு நுட்பம் உருவாக்கப்பட்டுள்ளது. பொறி, செலுத்தல் வலை வேலை, அடக்கல் தொகுதி ஆகியவற்றுக்குச் சார்பான எண்ணற்ற சுருக்கங்களை செய்வதால் நிலை மாறிகளை ஆறாகக் குறைக்கக்கூடிய நிகழ்ச்சித் திட்டத்தின் அண்ணளவான ஒரு வடிவமும் உருவாக்கப்பட்டுள்ளது. தொகைக் கணிநேரம் பத்து மடங்குக் மேற்பட்ட காரணியால் குறைக்கப்பட்டுள்ள போதிலும் நிகழ்ச்சித் திட்டச் செம்மை முதலாம் அலைவுக்குச் சற்றே அப்பாலாக மாத்திரம் இருக்கக்கூடியதாக மட்டுப்பட்டுள்ளது.

உள்நாட்டுப் பொருட்களைக் கொண்டு குறைந்த திண்மையுடைய செங்கற் சுவர்களின் அமைப்பு வடிவம் அமைபதற்கான அடிப்படைத் தகைப்புகள்

தொகுப்பு

செம்பாறுங் கற்களையும், சீ. எஸ். 39ன் படி 3 ம் தரத்தைச் சேர்ந்த செங்கற்களையும், 3 ம் தரத்திலும் குறைந்த திண்மையுடைய செங்கற்களையும்: செம்பூரான் மண் சாந்துக்கலவை, 1:10 என்ற விகிதத்தில் சீமெந்தையும் மணலையும் கொண்ட சாந்துக்கலவை போன்ற வெவ்வேறு வகையான சாந்துக்கலவைகளைக் கொண்டு கட்டப்படும் செங்கற் சுவர்கள் சீ. பி. 111 ன் விரிவுக்குட்படாது. எனினும், மேற்கூறப்பட்ட செங்கற்களினதும், சாந்துக் கலவைகளினதும் சேர்க்கையின்மூலம் கட்டப்படும் செங்கற் சுவர்கள் இலங்கையில் பாவிக்கப்படலாம் — உண்மையில் இவை ஏற்கனவே பாவனையில் உள்ளன. இவ்வகையான சுவர்களின் அமைவியல்புகளை அறிவதும், இவ்வகைச் சுவர்களின் வடிவத்தினை உருவாக்குவதுமே இந்த ஆய்வின் நோக்கமாகும்.

இந்த ஆய்வானது வடிவமைக்கும் முறையை உருவாக்குவதோடு பின்வரும் விளைவுகளையும் எடுத்துக்காட்டுகின்றது:

(அ) செம்பூரான் கற்களுக்கும் 3 ம் தரத்திலும் குறைந்த திண்மையுடைய செங்கற்களுக்கும் 1:10 என்ற விகிதத்தில் சீமெந்தையும், மணலையும் கொண்ட சாந்துக்கலவை உகந்ததல்ல.

(ஆ) செம்பூரான் மண் சாந்துக்கலவை 3 ம் தர வகைச் செங்கற்களுடன் பாவிப்பதற்கு உகந்ததல்ல.