TRANSIENT STABILITY STUDY OF A SIMPLIFIED SRI LANKA POWER SYSTEM

by

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Abstract

This paper presents a computer based transient stability study on a simplified power system of Sri Lanka. The performance of the transmission network during the transient period is obtained from a set of network performance equations based on nodal analysis, while the operating characteristics of synchronous machines are described by the use of differential equations. The transient stability analysis is performed by combining an iterative solution of the network performance equations, with a numerical solution of the machine differential equations. The load angle and terminal voltage variations of all machines, calculated as functions of time, reveal the transient characteristics of the system.

List of Symbols

A_i, B_i	- Constants based on the saturation characteristics
C_i	- damping constant
D_i	-
$\Delta^i(X)$	- change of quantity X between time steps
	- angle of E_i
f_s	- synchronous frequency
h	- time step length
H_i	- generator H - constant
i	- i^{th} load or machine
I_i	- nodal current
ITERA	- step count
$K_{(X)i}$	- Gain of Unit X
M_i	- angular momentum of generator
E_i	- voltage back of transient reactance
S_i	- base MVA rating of machine
$j \in i$	- j connected to i
$P_{Li}+jQ_{Li}$	- scheduled load
P_{gi}	- electrical Power generated
P_{Ti}	- turbine power
P_{refi}	- reference power setting
R_i	- governor regulation
$T_{(X)i}$	- time constant of unit X
t_f	- time of fault occurrence
t_{cl}	- time of fault clearance
t_{max}	- period of analysis
V_i	- terminal voltage
V_{refi}	- reference voltage setting
V_{Ri}	- amplifier output signal

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V_{Fi} - exciter output signal
Y'_{di} - generator transient admittance
Y_{ij} - elements of the nodal admittance matrix

01. Introduction

The stability of a system of interconnected dynamic components is its ability to return to normal or stable operation after having been subjected to a disturbance. A transient stability study provides information related to the capability of a power system to remain in synchronism during major disturbances resulting from loss of generation or transmission facility, sudden load changes, momentary faults etc. Specifically, these studies provide the changes in voltage, power and load angle of synchronous machines as well as the changes in system voltages and power flows during and immediately following a disturbance.

In view of the complex calculations involving a large number of dependent and independent variables this type of analysis is best performed using a digital computer. It will give ample flexibility to the system designer through the ability to modify the network and to simulate different disturbances in order to arrive at the most economical and reliable system configuration. In addition, there is always the possibility of using this programme for on-line control applications.

02. Mathematical Modelling

A model which exhibits the characteristics of the power system is formulated. The complexity of the model could be suitably chosen to give the required balance between accuracy and speed of solution.

2.1 Synchronous Machine

Operating characteristics of a synchronous machine are described by a set of differential equations. The simplest description is through the swing equation which consists of two first order differential equations.

$$\dot{\delta}_i = D_i \tag{2.1}$$

$$\dot{D}_i = \frac{1}{M_i}[P_{Ti} - P_{gi} - C_i D_i] \tag{2.2}$$

The turbine speed governing system, better defined as the Automatic Load Frequency Control Unit (ALFC), affects the generator performance in the transient state. The Automatic Voltage Regulator (AVR) also affects the generator performance. Hence a generator model which takes into account the operational characteristics of both AVR and ALFC loops is formulated.

Two typical arrangements of the ALFC & AVR loops are given in Figure (2.1) and Figure (2.2) respectively. The two control units are assumed to consist of sub systems characterised by constant gain, single time constant transfer function models.

Each composite model is characterised by 3 first order differential equations giving rise to a total of 6 + 2 state equations (2.1) to (2.8) of the form $\dot{X} = F(X)$ representing the generator performance.

for ALFC

$$\dot{P}_{refi} = - K_{Ii}/2\pi \, . \, D_i \tag{2.3}$$

$$\dot{P}_{Vi} = 1/T_{Hi} \left(P_{refi} - P_{vi} - \frac{1}{2\pi R_i} \, . \, D_i\right) \tag{2.4}$$

$$\dot{P}_{Ti} = 1/T_{Ti} \left(P_{vi} - P_{Ti}\right) \tag{2.5}$$

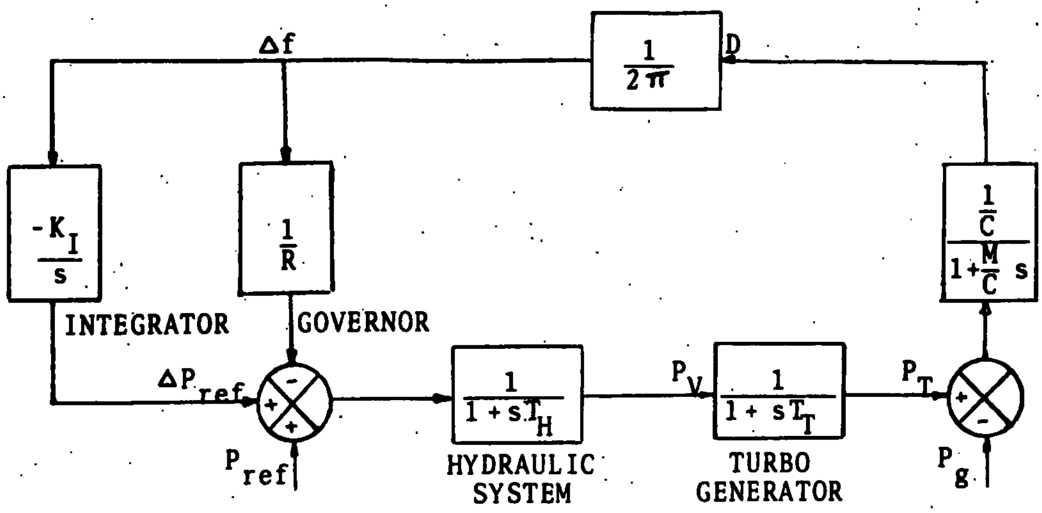


Figure 2.1 Automatic Load Frequency Control Unit (ALFC)

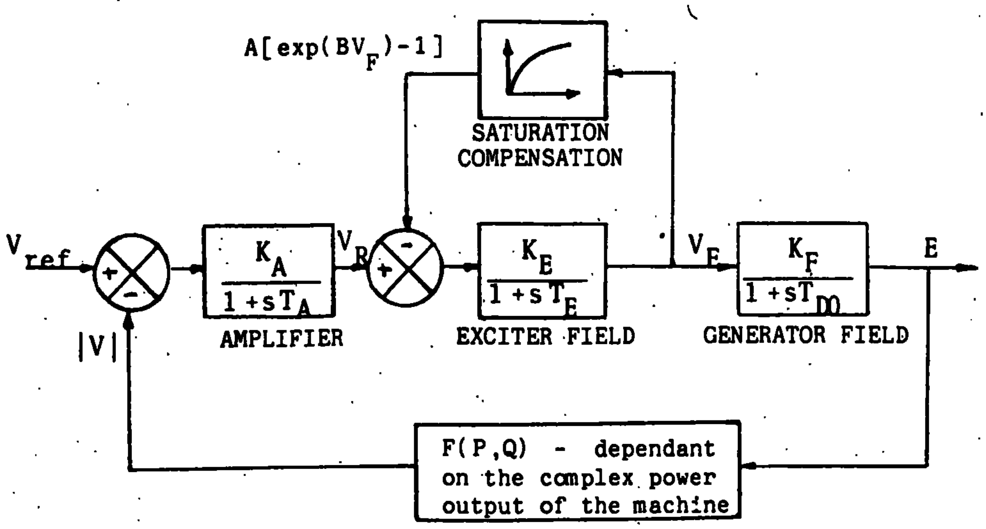


Figure 2.2 Automatic Voltage Regulator (AVR)

for AVR

$$\dot{V}_{Ri} = 1/T_{Ai}[(V_{refi} - |V_i|).\ K_{Ai} - V_{Ri}] \quad (2.6)$$

$$\dot{V}_{Fi} = 1/T_{Ei}[(V_{Ri} - A_i(e^{B_i V_{Fi}}-1)) K_{Ei} - V_{Fi}) \quad (2.7)$$

$$\dot{E}_i = 1/T_{DOi}\ (V_{Fi}.K_{Fi} - E_i) \quad (2.8)$$

(Refer Appendix 1 for derivations)

Values of gain and time constant settings together with other parameters change according to each machine while the basic model remains unchanged.

2.2 Transformers and Transmission Lines

The primary Transmission System is represented by the nodal admittance matrix. Each transmission line is modelled using a π equivalent circuit with the respective impedance and admittance parameters. Transformers are modelled by their winding impedance with the facility to include off-nominal tap-settings of Power Transformers.

Equation governing the node current for the i^{th} node is,

$$I_i = Y_{ii}V_i + \sum_{j\epsilon i} Y_{ij}V_j \quad (2.9)$$

For a generator node, assuming the d-axis transient admittance to remain constant,

$$I_i = (E_i - V_i).Y'_{di} \quad (2.10)$$

By substituting, the nodal voltage may be expressed in the form.

$$V_i = \frac{-1}{Y_{ii}+Y'_{di}} \left(\sum_{j\epsilon i} Y_{ij}.V_j - Y'_{di}.E_i \right) \quad (2.11)$$

2.3 Loads

Electrical loads that are connected to the transmission system could be represented using several models during the transient period. This paper makes use of the constant admittance representation. These admittances are calculated using the scheduled bus loads, which are known, and the bus voltages, which are obtained from a pre-fault load flow study.

At a load node, the pre-fault load $P_{Li} + jQ_{Li}$ is used to determine the pre-fault current I_i.

$$\text{i.e.} \quad I_i = \frac{P_{Li} - jQ_{Li}}{V_i^*} \quad (2.12)$$

The load admittance may then be calculated as

$$Y_{Li} = I_i / V_i \quad (2.13)$$

During the transient period, this admittance is assumed to remain constant so that the nodal equation for a load bus may be written as

$$- V_i.Y_{Li} = Y_{ii}.V_i + \sum_{j\epsilon i} Y_{ij}.V_j \quad (2.14)$$

from which the nodal voltage may be expressed as

$$V_i = - \frac{1}{Y_{ii} + Y_{Li}} \left(\sum_{j\epsilon i} Y_{ij}.V_j \right) \quad (2.15)$$

When either equations (2.11) or (2.15) are applied to all the nodes of the network, the resulting set of complex algebraic equations is called the set of network performance equations.

03. Solution Procedure

The analysis is broken up into

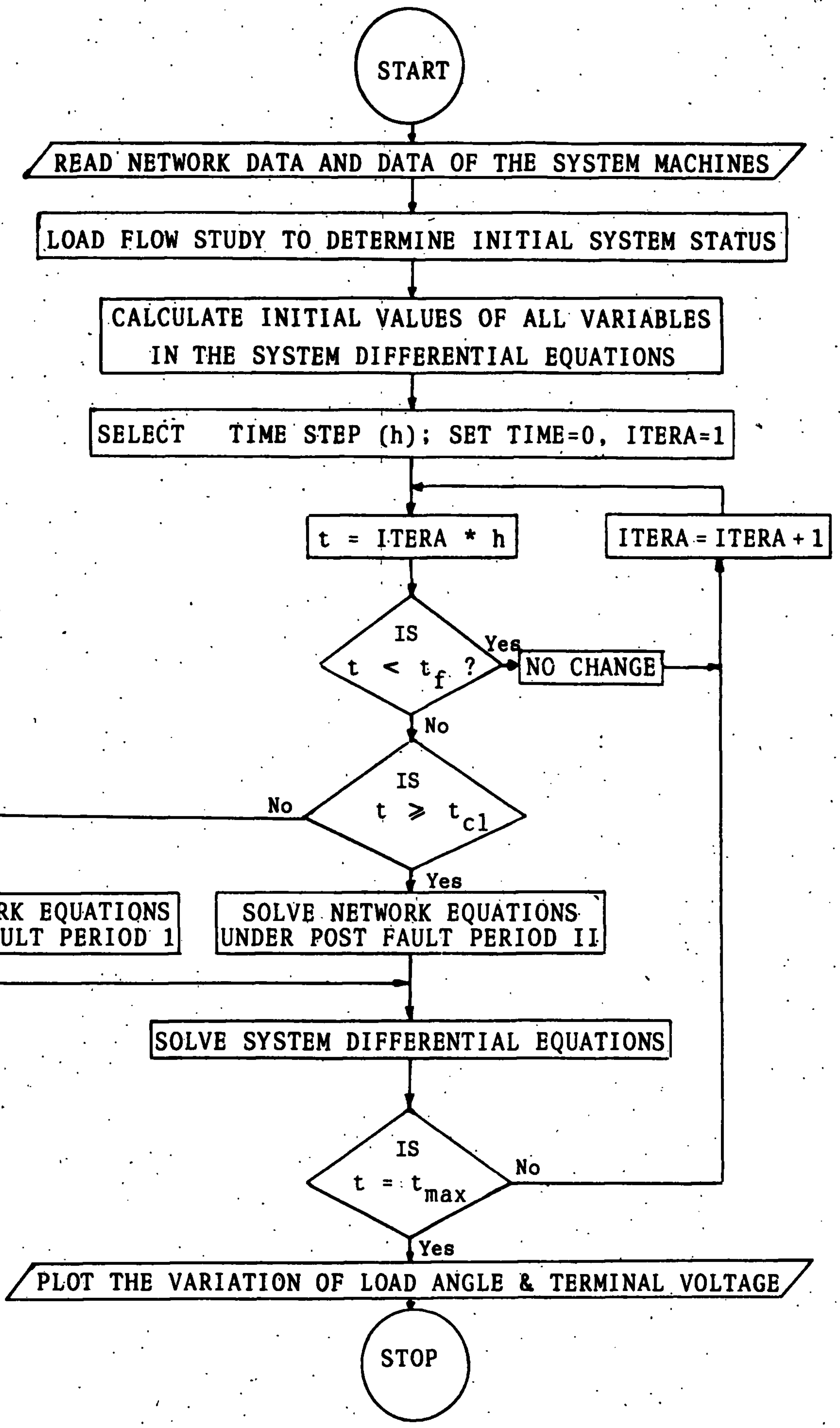
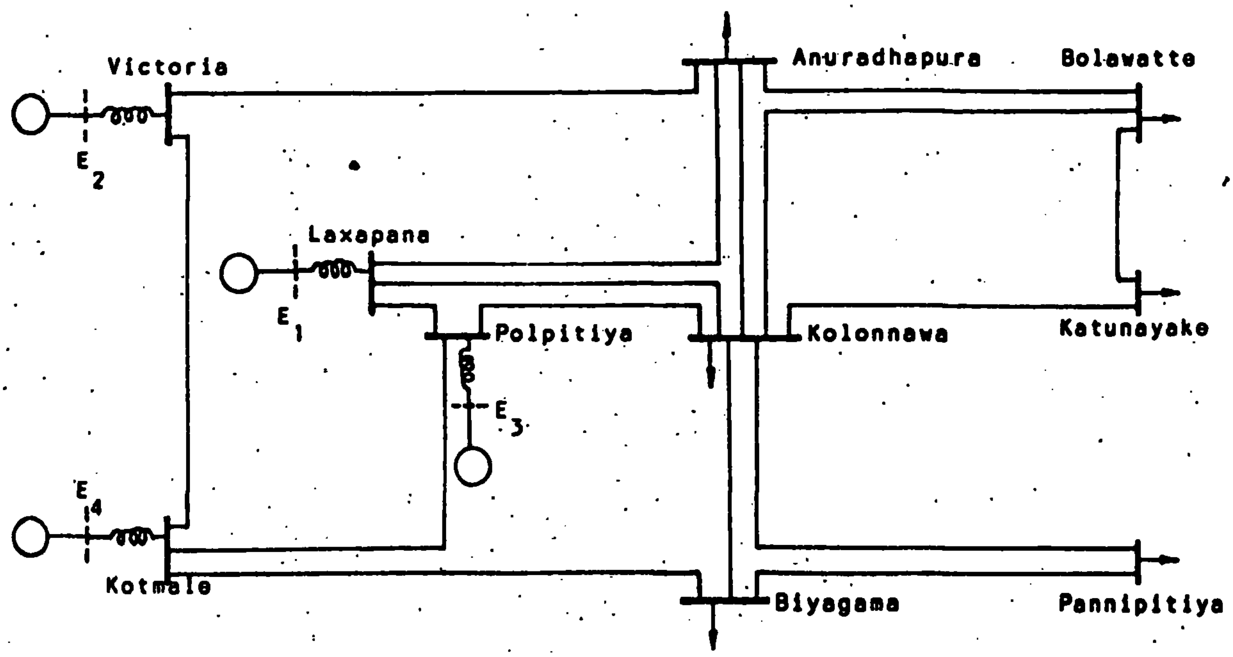
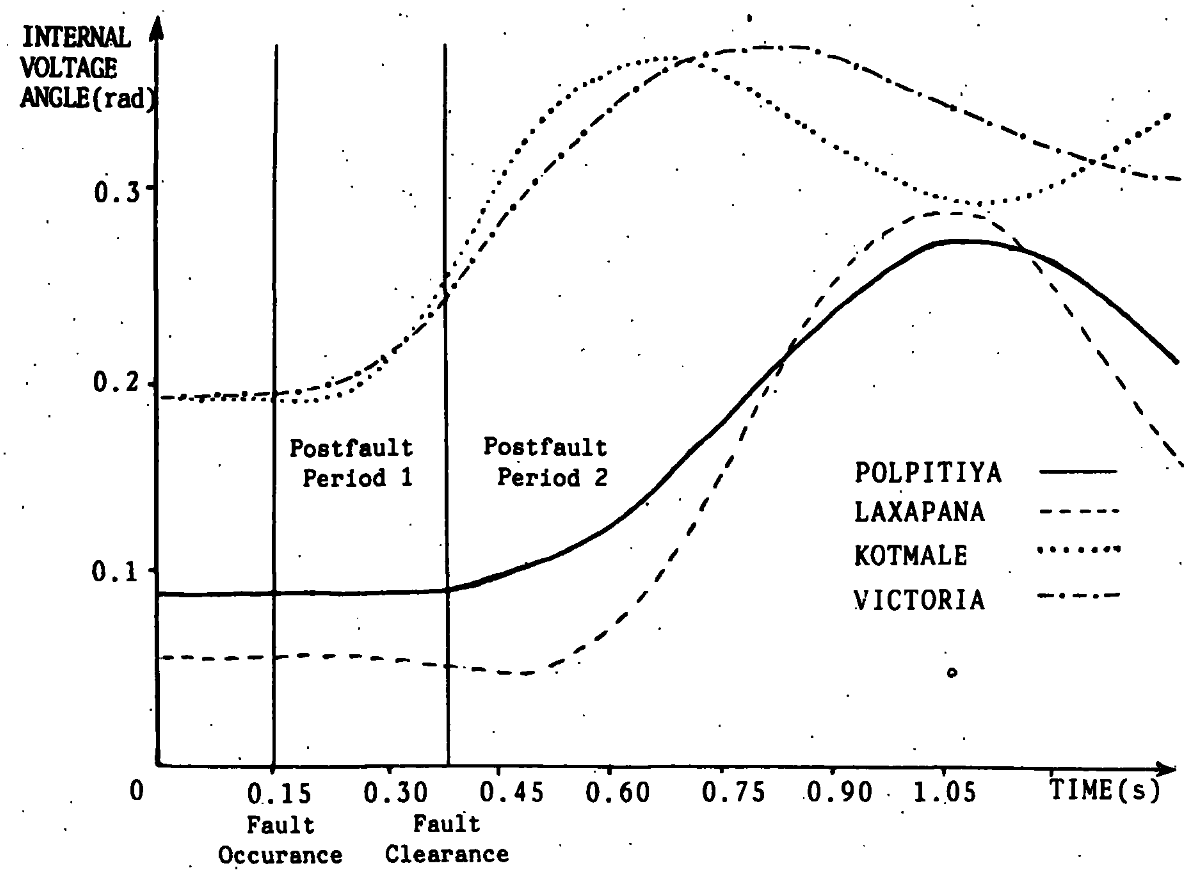


Figure 3.1 Solution Algorithm

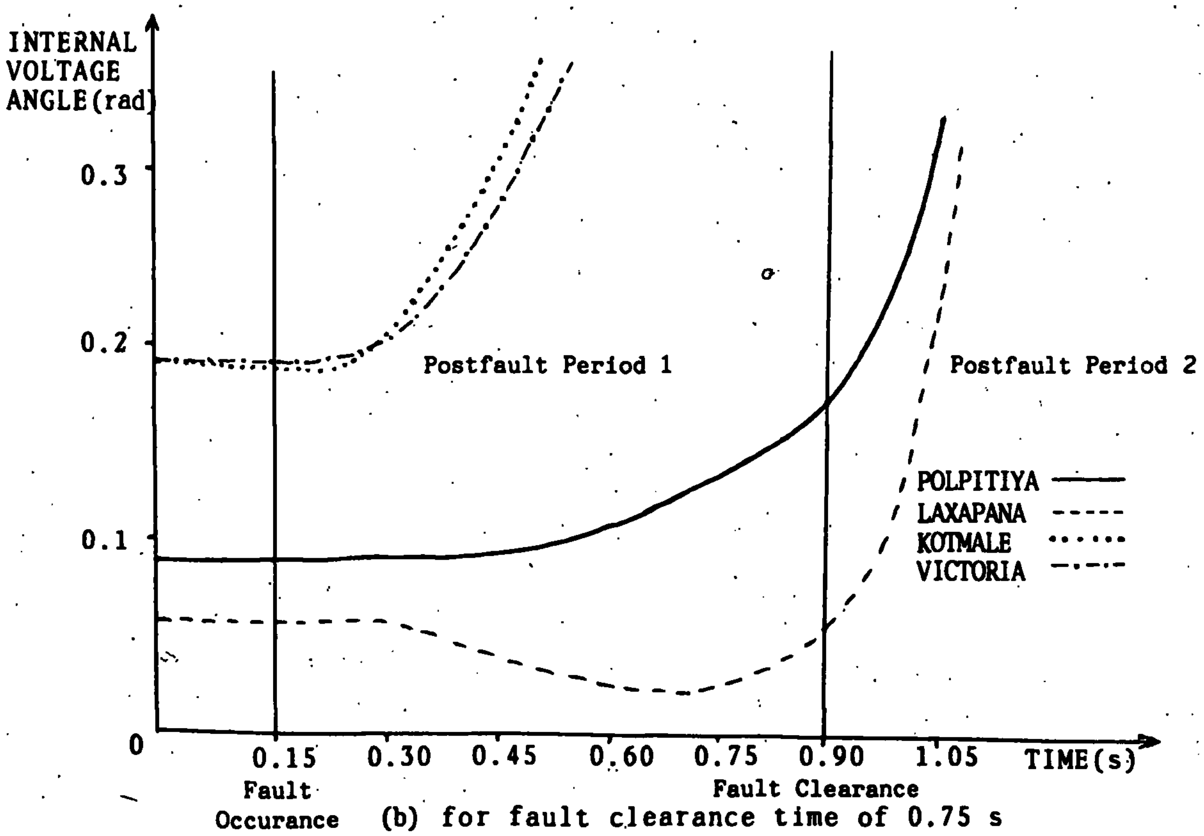


10 BUSBARS, 16 TRANSMISSION LINES, 4 GENERATOR BUSBARS.

Figure 4.1 Simplified Sri Lanka Power System



(a) for fault clearance time of 0.25 s



(b) for fault clearance time of 0.75 s

Figure 4.2 Plot of Internal Voltage Vs Angle

GENERATOR	X_d'(p.u)	M-CONSTANT (p.u MW/rad S^{-2})
LAXAPANA	0.1517	0.1537
POLPITIYA	0.2271	0.0847
VICTORIA	0.1055	0.3309
KOTMALE	0.1417	0.2358

TABLE 1. Generator Parameters

BUS 1	BUS 2	RESISTANCE (p.u)	REACTANCE (p.u)
LAXA	POLP	0.0080	0.0189
LAXA	KOLO	0.0170	0.0400
LAXA	ANUR	0.0033	0.0075
POLP	KOLO	0.0580	0.1020
POLP	KOTM	0.0357	0.0821
KOLO	ANUR	0.1560	0.3410
KOLO	BOLA	0.0570	0.1300
KOLO	KATU	0.0322	0.0565
KOLO	PANN	0.0045	0.0105
KOLO	BIYA	0.0045	0.0105
ANUR	BOLA	0.3470	0.8000
ANUR	VICT	0.0088	0.0694
KATU	BOLA	0.0295	0.0489
PANN	BIYA	0.0028	0.0141
BIYA	KOTM	0.0068	0.0427
KOTM	VICT	0.0031	0.0194

TABLE 2. Transmission Line Parameters

BUS NAME	BUS TYPE	ACTIVE POWER (p.u)	REACTIVE POWER (p.u)	VOLTAGE MAGNITUDE (p.u)
LAXA	SLACK			1.001
POLP	GENERATOR	0.25		1.000
KOLO	LOAD	-0.70	-0.20	
ANUR	LOAD	-0.45	-0.10	
KATU	LOAD	-0.43	-0.16	
BOLA	LOAD	-0.34	-0.11	
PANN	LOAD	-0.36	-0.08	
BIYA	LOAD	-0.65	-0.21	
KOTM	GENERATOR	1.10		1.040
VICT	GENERATOR	1.30		1.046

TABLE 3. Bus Data used for the Load Flow Study

BUS NAME	ACTIVE POWER (P.u)	REACTIVE POWER (p.u)	VOLTAGE MAGNITUDE (p.u)	VOLTAGE ANGLE (Degree)
LAXA	0.3319	-0.5567	1.00100	0.00000
POLP	0.2502	-0.6611	1.00000	0.44039
KOTM	1.1000	1.0539	1.04000	1.57208
VICT	1.3000	0.8651	1.04600	2.20973
KOLO	-0.7000	-0.2000	0.99351	-1.74553
ANUR	-0.4500	-0.1000	1.00480	-0.06699
KATU	-0.0430	-0.1600	0.96749	-3.02293
BOLA	-0.3400	-0.1100	0.96642	-3.15898
PANN	-0.3600	-0.0800	0.99514	-1.78097
BIYA	-0.6500	-0.2100	0.99859	-1.53374

TABLE 4. Solution of the initial Load Flow Study

3 time zones; the pre-fault; post fault I; and post fault II; The network performance equations have to be suitably modified under each time zone to simulate the unfaulted, faulted and fault eliminated Power System respectively.

The solution algorithm is presented in the form of a flow chart in Figure (3.1). There are four mian functional blocks that could be identified, namely

1. Performing a prefault load flow study to identify all nodal voltages.
2. Calculation of internal emfs of all synchronous machines determination of load admittance and calculation of the initial state vector.
3. Obtaining an iterative solution of the network performance equations using the Gauss-Seidel iterative scheme.
4. Solving the set of differential equations for each synchronous machine using the second order Runge-Kutta method to obtain the state vector corresponding to the next time step.

The procedure is repeated for each time step until the state trajectories of all machines are obtained throughout the transient period.

04. Case Study

The case under review is the simplified 4 generator power system of Sri Lanka given in Figure (4.1). Some of the major generating stations and load centers connected to the National Grid have been included in the network with the interconnections based on the existing transmission structure. Bus bars with comparatively small loads have been disregarded altogether while some have been eliminated by using star-delta transformation to arrive at a simplified final network for the study. All line parameters and generator parameters are based on values specified by the CEB. Wherever sufficient data is not available, realistic assumptions have been made. This is specifically so in the formation of machine control loops.

When a generating station consists of more than one synchronous machine, assuming them to be identical and operating in parallel, an equivalent machine with a modified M-constant (see Appendix 2) and transient reactance is formulated to simplify calculations. The values so obtained are given in Table 1.

Table 2 provides the total line resistance and reactance of the 16 interconnecting transmission lines. Capacitive and conductive effects of the lines have been neglected for simplicty.

The selection of Generator, Load and slack bus bars in the pre-fault load flow study, with the respective powers and voltage magnitudes are given in Table 3. The results of the load flow study are given in Table 4. These results are used to calculate the initial state vectors of the synchronous machines and to determine the static load admittances which are to be substituted during the transient analysis.

The stability of the system is then disturbed by simulating a 3 phase-short-circuit fault at the Kolonnawa bus bar. The ensuing internal voltage angle variations of the four generators are shown in Figures (4.2 a & b). Diagrams (a) and (b) represent the angle variations for two fault clearance times, 0.25s and 0.75s after fault occurrence respectively. The step length has been taken as 0.05s.

05. Conclusion

A 'transiently stable' power system should ride through the fault and emerge fully synchronised. With reference to Fig. (4.2 a), it is seen that there is only an oscillation of voltage angles of individual machines in the transient state. At no point in time do the machines pull out of synchronism or in other words, at no point in time does pole slipping of generators occur. Once oscillations are damped out, the system regains its stable equilibrium.

In contrast Fig. (4.2 b) which is a plot of the same voltage angle variations of the generators under the same faulted conditions but for a longer fault clearance time of 0.75s shows an uninhibited rise in the quantities with time. This causes the generators to go out of synchronism and points to a transiently unstable state.

The study establishes the fact that speedy fault removal improves transient stability. Critical clearing time for the fault, could be obtained by successive analysis with varying clearance times.

From Figure (4.2 ~~a & b) it is seen~~ that in both transiently stable and unstable cases, generators at Laxapana, Polpitiya and Victoria, Kotmale show coherence in their voltage angle variations. Such generator pools are called coherent groups of generators and are formed due to proximity of machines with similar ratings and characteristics. The existence of coherent groups of generators in a power system is made use of to improve its tranient stability. In an unstable condition, these coherent groups of generators may be isolated within suitable constraints, and kept operating separately until such time that they could be resynchronised and the system brought back to its steady state operating made. For instance, in the case of the system shown in Fig. (4.1), generator groups 1, 3 and 2, 4 could be completely isolated by tripping the seven transmission lines, namely,

1.	Victoria	-	Anuradhapura
2.	Kotmale	-	Polpitiya
3.	Polpitiya	-	Kolonnawa
4.	Kolonnawa	-	Anuradhapura
5.	Kolonnawa	-	Bolawatte
6.	Laxapana	-	Kolonnawa
7.	Kolonnawa	-	Katunayake

According to this scheme loads at Anuradhapura, Bolawatte an Katunayake are supplied by Laxapana and Polpitiya generators while loads at Kolonnawa, Biyagama and Pannipitiya are supplied by Victoria and Kotmale generators.

Although the scheme illustrates the concept of splitting of a faulted power system into coherent groups, stability of such a sequence of events has to be determined before implementation. This includes the verification of all line flows, nodal voltage fluctuations, generator rotor swings etc. to ensure that they are within specified operational limits. Such an analysis is well within the scope of the program and is being presently studied.

06. References

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APPENDIX I

Formulation of the State-space equations for the Synchronous Generator Model

ALFC Unit

With reference to Fig. (2.1), an increase in governor output command results from an increase in ΔP_{ref} and a decrease in Δf

$$\text{but } \Delta P_{ref}(S) = -K_I/S \cdot \Delta f(s) \tag{1}$$

$$\text{in the time domain } \frac{d(\Delta P_{ref})}{dt} = K_I \cdot \Delta f \tag{2}$$

but f could be attributed rotor acceleration and hence

$$\Delta f = \frac{1}{2\pi} \cdot \frac{d}{dt} \tag{3}$$

substituting $\dot{\delta} = D$

$$\frac{d \cdot (\Delta P_{ref})}{dt} = -\frac{K_I}{2\pi} \cdot D \tag{4}$$

But under pre-fault condition

$$P_{refo} = P_{Vo} = P_{To} = P_{go} \tag{5}$$

Hence

$$P_{ref} = P_{refo} + \Delta P_{ref} \tag{6}$$

and similarly,

$$\begin{aligned} P_V &= P_{Vo} + \Delta P_v \\ P_T &= P_{To} + \Delta P_T \\ P_g &= P_{go} + \Delta P_g \end{aligned} \tag{7}$$

differentiating (6),

$$\frac{d.\ P_{ref}}{dt} = \frac{d(\Delta P_{ref})}{dt} \tag{8}$$

Substituting result (8) in (4)

$$\dot{P}_{ref} = -\frac{K_I}{2\pi} \cdot D \tag{2.3}$$

The Governor and integrator output command or the input signal to the hydraulic system is

$$\Delta P_{ref}(s) - \frac{1}{R} \cdot f(s)$$

and the output signal is P_v.

$$\frac{\Delta Pv\ (s)}{\Delta P_{ref}(s) - \frac{1}{R} \cdot \Delta f(s)} = \frac{1}{1 + S\, T_H} \tag{9}$$

$$S.\Delta P_v(s) = \frac{1}{T_H} \Delta P_{ref}(s) - \Delta P_v(s) - \frac{1}{R} \Delta f(s) \tag{10}$$

by using equations (3), (5), (6) and (7), equation (10) becomes,

$$\dot{P}_v = \frac{1}{T_H} [P_{ref} - P_v - \frac{1}{2\pi R} \cdot D] \tag{2.4}$$

it could be similarly proved that

$$P_T = \frac{1}{T_T} \cdot [P_V - P_T] \tag{2.5}$$

AVR Unit

With reference to Fig. (2.2), the comparator output $V_{ref}(s) - |V|$ is fed to the amplifier.

$$\frac{V_R\ (s)}{V_{ref} - |V|} = \frac{K_A}{1 + ST_A} \tag{11}$$

$$SV_R = \frac{1}{T_A} [(V_{ref}\ (s) - |V|). K_A - V_R(s)] \tag{12}$$

in the time domain equation 12 becomes,

$$\dot{V}_R = \frac{1}{T_A} [(V_{ref} - |V|).\ K_A - V_R] \tag{2.6}$$

Similarly considering the exciter and generator field transfer function it could be proved that,

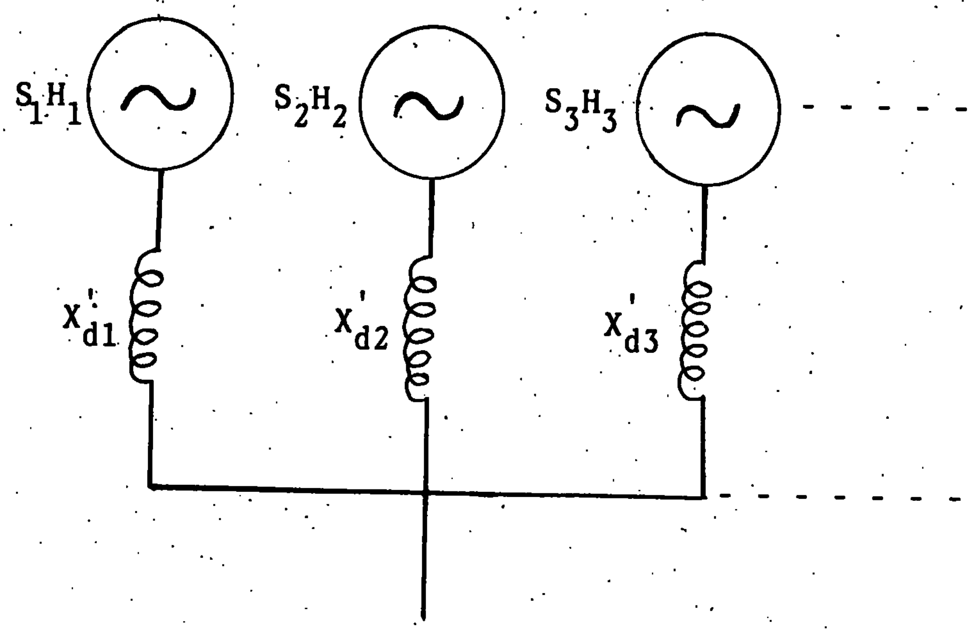
$$\dot{V}_F = \frac{1}{\quad} [(V_R - A.(e^{BV_F} - 1).K_E - V_F] \tag{2.7}$$

and $$\dot{E} = \frac{1}{} [V_F . K_F - E] \qquad (2.8)$$

Equation (2.3) to (2.8) characterising the ALFC and the AVR control loops together with equations (2.1) and (2.2) forming the swing equation, make up the eight first order differential equations of the synchronous machine state-space model. It is presented in the standard format $\dot{X} = F(X)$

APPENDIX II

Calculation of Equivalent M-constant



Assume the general case of n generators connected onto a single bus bar.

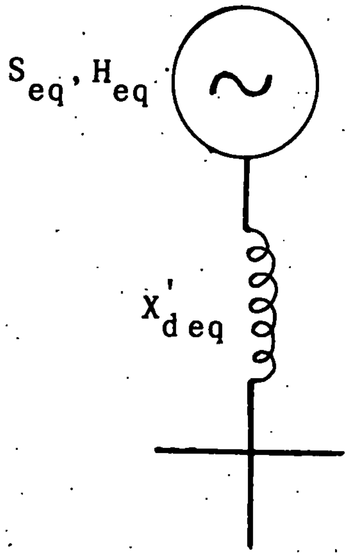
Total rotor energy $= \sum_{i=1}^{n} S_i H_i$

If the equivalent machine has a H-constant given by Heq on a base of Seq.

$$Heq. \ Seq = \sum_{i=1}^{n} H_i S_i = \tfrac{1}{2} M_{eq} \cdot 2\pi f$$

$$Meq = \frac{\sum_{i=1}^{n} H_i S_i}{\pi f} \quad \text{MJs/elect. rad.}$$

$$H_{eq} = \frac{\sum_{i=1}^{n} H_i S_i}{Seq \, \pi \, f} \quad \text{p.u. MWs}$$



Calculation of equivalent transient Reactance

Assuming the voltage back to transient reactance to be the same for all generators, the model in Fig. (II) could be simplified to

where $$\frac{1}{X_{d'eq}} = \sum_{i=1}^{n} \frac{1}{X_{d'i}}$$