ANALYSIS OF A STAND-ALONE INDUCTION GENERATOR WITH ROTOR FLUX ORIENTED CONTROL

A DISSERTATION

Submitted in partial fulfilment of the requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(With Specialization in Power Apparatus and Electric Drives)

By
VINOD KUMAR

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE-247 667 (INDIA)

FEBRUARY, 2000

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled "**ANALYSIS OF A STAND-ALONE INDUCTION GENERATOR WITH ROTOR FLUX ORIENTED CONTROL**" in partial fulfilment of the requirements for the award of the Degree of **Master of Engineering** in **Electrical Engineering** with specialization in **Power Apparatus and Electric Drives** submitted in the Department of Electrical Engineering, University of Roorkee, Roorkee, is an authentic record of my own work carried out from July, 1999 to February, 2000 under the supervision of **Dr.G.K.Singh**, Assistant Professor, Department of Electrical Engineering, University of Roorkee, Roorkee, U.P., India.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree.

Dated : 18 February, 2000

(VINOD KUMAR)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

(Dr. G.K. Singh)
Assistant Professor
Department of Electrical Engg.
University of Roorkee
Roorkee

ACKNOWLEDGEMENT

I would like to express my deep sense of gratitude from the apex of my heart to **Dr. G.K. Singh**, Assistant Professor, Department of Electrical Engineering, University of Roorkee, Roorkee, for his continuous and valuable guidance and providing me with necessary materials during the whole period of this work.

I am grateful to the staff members of the Department for the knowledge imparted during the course of my study at this University.

Finally, my special thanks go to those who directly or indirectly assisted me in completion of this work.

(VINOD KUMAR)

ABSTRACT

In this dissertation a detailed mathematical modelling of an induction generator in isolated mode has been presented. Reactive power requirement of generator are met by a static reactive power compensator of voltage source inverter (VSI) type, where the control of the compensator is achieved using rotor flux oriented control. Simulated results were also recorded for the induction generator with its reactive power requirements supplied through capacitor bank. The behaviour of induction generator was recorded for the following mode of operation :

Case - I : Sudden removal and reapplication after a time delay of a purely resistive load.

Case - II : Sudden removal and reapplication after a time delay of a inductive load (0.8 p.f. lagging load).

Case - III : When a capacitance of a sufficient value is connected across the terminals of a self-excited induction generator, the voltage starts building up due to the residual magnetism present in the machine. The initiation of the self-excitation process has been studied.

Case - IV : The self-excited stand alone induction generator looses excitation when a sudden short circuit (or heavy load) takes place at its terminals. This is one of the advantages of self-excited stand alone induction generators. The phenomenon has also been studied by plotting the variation of terminal voltage with respect to time.

Case - V : No load self-excitation process, step load application and speed variation in the base speed region has been studied under rotor flux orientation control.

The effect on the following parameters have been studied for above cases :

(i) Terminal voltage, i.e., the variation of terminal voltage with time.

(ii) The variation of stator and rotor current with respect to time.

(iii) The variation of load current with respect to time.

(iv) The variation of capacitor current with respect to time.

(v) The variation of shaft speed with respect to time.

NOMENCLATURE

i_{ds}, i_{qs}	=	Peak stator d- and q-axes currents (rotating reference frame)
i_{dr}, i_{qr}	=	Peak rotor d- and q-axes currents (rotating reference frame)
i_s	=	rms stator current
V_{ds}, V_{qs}	=	Peak stator d- and q-axes voltages (rotating reference frame)
V_g	=	Peak magnitude of the air-gap voltage
i_m	=	Peak magnetizing current
L_m	=	Magnetising inductance
L_r, L_s	=	Rotor and stator self inductances
L_{lr}, L_{ls}	=	Rotor and stator leakage inductances
R_s, R_r	=	Rotor and stator resistances
ω_r	=	Shaft speed (elec.rad/sec.)
ω_e	=	Electrical frequency (rad/sec.)
λ_{dr}, λ_{qr}	=	Peak rotor d- and q-axes flux linkages
λ_{ds}, λ_{qs}	=	Peak stator d- and q-axes flux linkages
N	=	Number of poles
i_{dc}, i_{qc}	=	Peak d- and q-axes capacitor currents (rotating reference frame)
i_c	=	Capacitor rms current
i_{dl}, i_{ql}	=	Peak d- and q-axes currents flowing into the load circuit (rotating reference frame)
C	=	Self excitation capacitance

R, L	=	Load resistance and inductance respectively.
H	=	Value of hysteresis band
i_a, i_b, i_c	=	Phase currents
V_{an}, V_{bn}, V_{cn}	=	Inverter phase voltages
$V_{dc}, V_{dc}*$	=	Inverter side d.c. voltage and reference voltage
I_{dc}	=	Total d.c. current
S_a, S_b, S_c	=	Inverter switches
i_{la}, i_{lb}, i_{lc}	=	Load phase currents
i_d*, i_q*	=	d- and q-axes reference currents
K_d, K_q, T_d, T_q	=	Parameters of the PI controllers in d- and -q branches
ψ_r, ψ_r*	=	Rotor and rotor reference flux respectively
i_a*, i_b*, i_c*	=	Phase current references
ϕ_{re}	=	Rotor Flux angular position

General

B, J	=	Net friction and inertia of the rotating parts of the system
T_m	=	Mechanical torque
p	=	Differential operator d/dt

CONTENT

LIST OF FIGURES

CHAPTER - 1

INTRODUCTION

1.1 PRELIMINARY REMARKS

A squirrel cage induction machine is utilized as a generator either through regeneration or through self-excitation. A squirrel cage induction machine connected to an alternating current source of appropriate voltage and frequency can operate either as a generator or as a motor. Regeneration is possible if the rotor of the induction machine is made to rotate above the synchronous speed decided by rotating magnetic field. The terminal voltage applied to the induction machine maintains excitation by producing lagging magnetizing current which in turn results in rotating magnetic flux for both motoring and generating operation.

By connecting appropriate capacitors across the stator terminals of an externally driven induction machine, an emf is produced in the machine winding due to excitation provided by the capacitors. This phenomenon is known as "Capacitor self-excitation". In order to self excite the machine, either rotor of the machine should have sufficient remnant field of proper polarity or charge on the capacitors. Induced voltage and its frequency in the winding will increase upto a level governed by magnetic saturation in the machine. The generated voltage will depend upon the speed, value of capacitance, load current and power factor of the load.

The capacitor bank provides the magnetizing VARS to induction machine as well as reactive power requirement to the external lagging power factor loads. But stand-alone induction generator requires this reactive power by means of a static reactive power compensator. The advent of power electronic converters has enabled application of inverters as static reactive power compensator for the squirrel cage induction generators.

Both current source inverters and voltage source inverters (VSI) can be used [9]. However, pulse width modulation (PWM) control of VSI enables achievement of superior dynamic response and this type of converter is now-a-days dominant in stand-alone induction generator applications. Various topologies may be used. One solution is to connect a PWM rectifier in series with the induction generator stator terminals. PWM rectifier then provides input into the second converter, a PWM VSI [13]. The output of such a system is normally constant frequency, constant voltage three-phase supply that can be delivered either to the grid or to an autonomous power system. The second method of providing reactive power for the induction generator consists of connecting a PWM VSI in parallel to the stator terminals of the machine. Control of the PWM VSI can be realised in a number of different ways. A relatively simple solution corresponds to v/f control in motoring and relies on utilisation of one of the PWM techniques, such as sinusoidal PWM. The second possibility consists of application of vector control techniques, that offer significant advantages with respect to the dynamics of the system. When vector control is applied, PWM VSI static reactive power compensator is current controlled [13].

1.2 APPLICATIONS

The self-excited stand-alone induction generator could not find many practical applications due to its inability to control the terminal voltage and frequency under varying load conditions. But by applying the rotor flux oriented control technique the terminal voltage may be kept constant under all operating conditions [13].

In recent years, owing to the increased emphasis on renewable energy resources development of suitable isolated power generators driven by the energy such as wind, small hydrofalls, biogas etc. have assumed greater significance. Due to its reduced unit cost, brushless rotor construction, absence of a separate source for excitation, ruggedness, the ease of maintenance, a capacitor self-excited induction generator has emerged as a suitable candidate for isolated power sources. Besides applications as generators, the principle of self excitation can also be used for dynamic braking of three phase induction motors. The terminal capacitors for such machines must have a certain minimum value so that self-excitation may take place. This value is affected by the machine parameters, its speed and load conditions.

The self-excited induction generator can provide reliable and relatively inexpensive means to generate electricity compared to synchronous generators for the applications where small frequency variations are allowed. The utility of self-excited induction generator is tremendously increasing because of its various advantages over the conventional synchronous generators as a source of power in isolated and remote areas. In isolated systems, the excitation can be obtained from a suitable value capacitor bank connected across armature terminals and hence, a separate d.c. source is not required for excitation by induction generators as it is required by synchronous generators. On external short circuits too, the excitation of induction generator collapses giving automatic protection to it [16].

1.2 MERITS AND DEMERITS

Induction generators can be used as an isolated or stand by power source driven by either constant speed prime movers such as diesel engines, hydro turbines or variable speed prime movers like wind turbines etc. A distinct advantage of such generator is much lower unit cost as compared to the conventional synchronous generator.

Another advantage is due to the characteristics of such a generator in case of a short circuit on the line. The drop of the voltage that accompanies a short circuit automatically reduces the excitation and so limits the short circuit current. In case of a very sudden short circuit, the initial rush of current is proportionately just as great as in the case of a synchronous generator, and for much the same reason, namely, that the energy stored in the magnetic field can be instantly be dissipated, but unlike a synchronous generator, there can be no sustained short circuit current under such conditions because of the removal of the excitation [16].

The disadvantages of the induction generators are its poor inherent frequency, and low power factor. The induction generators have also moderate efficiency. Dangerous voltages may occur with induction generators working over long transmission lines, if synchronous machines at the far end become disconnected and the line capacitance excites the induction machine. This phenomenon is known as "accidental self-excitation". But this would be rare since they may not be used with long lines.

CHAPTER - 2

LITERATURE REVIEW

As the time is changing rapidly and energy demands are increasing day by day, the utilization of non-conventional sources of energy has become essential. In this regard, it has been proposed to use the self excited induction generator where non-conventional sources of energy are abundantly available.

- Elder, Boys and Woodward [1] describe the use of self-excited induction generator as low cost stand-alone generators, including the problem of guaranting excitation and its behaviour under balanced and unbalanced conditions.
- John R. Parson [2] describe the suitability of induction generator for many industrial co-generation applications. The application of 3000 kw induction generator is compared to that of comparably sized synchronous machine considering their relative costs, equipments, protective relaying, maintenance and operating procedure.
- Singh S.P., Bhim Singh and Jain M.P. [3] dealt with the performance characteristics of a cage induction machine operating as a self-excited induction induction generator (SEIG) in stand-alone mode. A static capacitor bank was used to self excite the machine and to maintain its terminal voltage constant. The lagging reactive power requirements of self-excited induction generator was obtained for different values of load. Effect of speed on excitation requirement of cage machine was also studied. An algorithm was developed to achieve these

characteristics using "Newton-Raphson method" and steady state equivalent circuit of the machine.

- J.A.A. Melkebeedk [4] describes the application of saturated model for the stability behaviour of voltage fed induction motor and self-excited induction generator. The necessity of improved model has also been pointed out due to the unrealistic predictions of classical model. The small signal stability and dynamic response for six modes of induction generator operation including both voltage and current inverter system have been examined and compared by J.A.A. Mekebeck [5]. He has introduced an improved small signal model, considering main flux saturation to study the stability properties of all six modes. The capacitive self excited case is shown to require special treatment because of the phase freedom inherent in this mode.
- The problem of voltage and frequency variations is inherent in self-excited induction generators. To eliminate this problem an alternative solution was given by J. Arrillaga and Watson [6] by using self-excited-induction generator with controlled rectifier unit. The paper describes the operation of such system for variable d.c. load at constant voltage feeding a controllable power into an existing a.c. network through a d.c. transmission link. The operation of self-excited induction generator at variable speed prime mover i.e. wind mill is described by H.R. Bolton and Nicodemou [7]. They showed how self excited induction generator can be used for wind-mill applications. The idea opted by J. Arrillaga and Watson has been extended by Watson, Arrillaga and Densem [8] to use three

phase squirrel cage induction motor with self excitation for wind power sources at variable speed and to generate optimum power by delay angle control of rectifier.

- D.W. Navotony, Gritter and Studtmann [9] have discussed the excitation in inverter drive induction machines. They describe that the electrical output of the system is governed by the slip and system performance is controlled by magnetization characteristic, stator and rotor resistances of the machine.
- K.E. Hallenius, P. Vas and J.E. Brown [10] illustrated the application of the equations of a saturated smooth air gap machine to the analysis of the transient performance of a self-excited asynchronous generator.
- Natarajan K. [11] dealt with dynamic modelling of self-excited induction generator connected to a supply system through a d.c. link (converter-line commutated inverter) and digital control design for regulating the power transfer through the link. A non-linear model was developed by using the d-q model of induction generator and interfacing to it the models of the subsystems viz. Capacitors, converter, d.c. link and inverter appropriately. The objective of the modelling excluded the self excitation process of the induction generator and is aimed only at the behaviour after self excitation (small signal behaviour).
- Grantham, C., Sutanto, D., and Mismail, B. [12] dealt with the steady state and transient analysis of self-excited induction generators. They described a method for accurately predicting the minimum value of capacitance necessary to initiate self-excitation with a stand-alone induction generator. Final steady-state self-excitation voltages and frequencies were also calculated for loaded and unloaded operations, taking into account the rotor parameter variations with frequency. It

was shown that the calculated and measured results are in strong agreement, and for the loaded generator they agree considerably more so than when constant rotor parameters are used. The theory was also applied to include the transient built-up of voltage during the initiation stage of self excitation, and the perturbations of the terminal voltage and the stator current which result from load changes.

- Y.W. Lio, E. Levi [13] has suggested that for the proper operation of the generator with variable rotor flux reference requires applications of a saturation adaptive rotor flux estimator. Excellent tracking of rotor flux reference is achieved under all operating conditions, including operation with speeds higher than rated.
- E. Levi [14] has suggested that main flux saturation in induction machine plays an important role. The current state space model of a saturated induction machine has gained popularity recently an excellent tool for transient and steady state time domain analysis of induction machine drive.
- Thomas A. Lipo [15] has suggested a new method for the transient analysis of induction machines with saturating leakage reactances.

From the review of literature it is observed that little effort has been made till now regarding the generalised approach to analyse the transient performance of self-excited induction generator for the lagging loads (reactive loads). Here the transient analysis has been carried out for resistive & reactive loads and the stand-alone induction generator system with static reactive power compensator that is controlled by using rotor flux oriented control principles.

ORGANISATION OF THE THESIS

Starting with a brief introduction of the self-excited induction generator in the first chapter, the second chapter deals with an exhaustive literature review. The literature has been reviewed in a chronological order, dealing with the transient analysis. The transient performance equations of a self-excited induction generator and modelling of induction generator, load, inverter, hysteresis current controller and vector controller have been given in chapter three.

These equations have been derived for a rotating frame reference and can be converted to the stationary frame reference. An algorithm for solving the differential equations of the induction generator has been described in chapter four. Runga-Kutta method is used to solve these equations. A software has been developed for implementing the rotor flux oriented control technique for "stand-alone induction generator". The software has been developed for both the capacitor self-excitation process and loading phenomenon (resistive as well as inductive load) without controlling the flux and voltage and with rotor flux orientation control principle. The control of induction generator is considered only in the base speed region. The rotor flux orientation scheme makes it possible to achieve high dynamic response. The flowcharts for the different computer programs have been discussed. Results and discussions are given in chapter five. The main conclusion and the suggestions are described in the chapter six. The machine parameters have been put in appendix B.

CHAPTER - 3

TRANSIENT PERFORMANCE EQUATIONS OF A SELF-EXCITED INDUCTION GENERATOR

3.1 INDUCTION GENERATOR MODEL

The transient equations are written based on two axis or d-q axis theory. In this method, the time varying parameters are eliminated and the variables and parameters are expressed in mutually decoupled direct and quadrature axes. The d-q transient equations of an induction generator can be expressed either in stationary or in rotating frame. The synchronously rotating frame equations can be given as -

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -(R_s + pL_s) & -\omega_e L_s & -pL_m & -\omega_e L_m \\ \omega_e L_s & -(R_s + pL_s) & \omega_e L_m & -pL_m \\ -pL_m & -(\omega_e - \omega_r)L_m & -(R_r + pL_r) & -(\omega_e - \omega_r)L_r \\ (\omega_e - \omega_r)L_m & -pL_m & (\omega_e - \omega_r)L_r & -(R_r + pL_r) \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (3.1)$$

If it is assumed that the d-axis is aligned with the stator terminal voltage phasor, then-

$V_{qs} = 0$

Now from equation (3.1) -

$$\left.\begin{aligned}
&(R_s + pL_s)\, i_{qs} + \omega_e L_s i_{ds} + pL_m i_{qr} + \omega_e L_m i_{dr} = -V_{qs} \\
&\omega_e L_s i_{qs} - (R_s + pL_s)\, i_{ds} + \omega_e L_m i_{qr} - pL_m i_{dr} = V_{ds} \\
&pL_m i_{qs} + (\omega_e - \omega_r) L_m i_{ds} + (R_r + pL_r)\, i_{qr} + (\omega_e - \omega_r) L_r i_{dr} = 0 \\
&(\omega_e - \omega_r) pL_m i_{qs} - pL_m i_{ds} + (\omega_e - \omega_r) L_r i_{qr} - (R_r + pL_r)\, i_{dr} = 0
\end{aligned}\right\} \qquad (3.2)$$

Let,

$$P\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} = \begin{bmatrix} X \\ Y \\ Z \\ K \end{bmatrix} \qquad (3.3)$$

Then

$$\left.\begin{aligned}
&L_s X + L_m Z = -V_{qs} - R_s i_{qs} - \omega_e L_s i_{ds} - \omega_e L_m i_{dr} \\
&L_s Y + L_m K = -V_{ds} + \omega_e L_s i_{qs} - R_s i_{ds} + \omega_e L_m i_{qr} \\
&L_m X + L_r Z = -(\omega_e - \omega_r) L_m i_{ds} - R_r i_{qr} - (\omega_e - \omega_r) L_r i_{dr} \\
&L_m Y + L_r K = (\omega_e - \omega_r) L_m i_{qs} + (\omega_e - \omega_r) L_r i_{qr} - R_r i_{dr}
\end{aligned}\right\} \qquad (3.4)$$

Writing equation (3.4) in a matrix form, we have -

$$\begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ K \end{bmatrix} = \begin{bmatrix} -V_{qs} - R_s i_{qs} - \omega_e \lambda_{ds} \\ -V_{ds} - R_s i_{ds} + \omega_e \lambda_{qs} \\ -(\omega_e - \omega_r)\lambda_{dr} - R_r i_{qr} \\ (\omega_e - \omega_r)\lambda_{qr} - R_r i_{dr}) \end{bmatrix} \qquad (3.5)$$

where,

$$\left.\begin{aligned}\lambda_{ds} &= L_s i_{ds} + L_m i_{dr}\\ \lambda_{qs} &= L_s i_{qs} + L_m i_{qr}\\ \lambda_{dr} &= L_m i_{ds} + L_r i_{dr}\\ \lambda_{qr} &= L_m i_{qs} + L_r i_{qr}\end{aligned}\right\} \tag{3.6}$$

The inverse of the inductance matrix given in equation (3.5) is -

$$\frac{1}{D}\begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix}$$

where,

$$D = L_s L_r - L_m^2$$

$$\begin{bmatrix} X \\ Y \\ Z \\ K \end{bmatrix} = \frac{1}{D}\begin{bmatrix} L_r & 0 & -L_m & 0 \\ 0 & L_r & 0 & -L_m \\ -L_m & 0 & L_s & 0 \\ 0 & -L_m & 0 & L_s \end{bmatrix}\begin{bmatrix} -V_{qs} - R_s i_{qs} - \omega_e \lambda_{ds} \\ -V_{ds} - R_s i_{ds} + \omega_e \lambda_{qs} \\ -(\omega_e - \omega_r)\lambda_{dr} - R_r i_{qr} \\ (\omega_e - \omega_r)\lambda_{qr} - R_r i_{dr} \end{bmatrix}$$

$$= \frac{1}{D}\begin{bmatrix} -L_r(V_{qs} + R_s i_{qs} + \omega_e \lambda_{ds}) + L_m(\omega_e - \omega_r)\lambda_{dr} + L_m R_r i_{qr} \\ L_r(-V_{ds} - R_s i_{ds} + \omega_e \lambda_{qs}) - L_m(\omega_e - \omega_r)\lambda_{qr} + L_m R_r i_{dr} \\ L_m(V_{qs} + R_s i_{qs} + \omega_e \lambda_{ds}) - L_s(\omega_e - \omega_r)\lambda_{dr} - L_s L_r i_{qr} \\ L_m(V_{ds} + R_s i_{ds} - \omega_e \lambda_{qs}) + L_s(\omega_e - \omega_r)\lambda_{qr} - L_s L_r i_{dr} \end{bmatrix}$$

Putting the values of X, Y, Z and K from equation (3.3) and solving -

$$pi_{qs} = \frac{1}{D}[-L_r R_s i_{qs} - L_r \omega_e (L_s i_{ds} + L_m i_{dr}) + L_m(\omega_e - \omega_r) \times$$

$$\times (L_m i_{ds} + L_r i_{dr}) - L_r V_{qs} + L_m R_r i_{qr}]$$

$$pi_{qs} = -K_1 R_s i_{qs} - (\omega_e + K_2 L_m \omega_r)\, i_{ds} + K_2 R_r i_{qr} - K_1 L_m \omega_r i_{dr} - K_1 V_{qs} \tag{3.7}$$

$$pi_{ds} = \frac{1}{D}[-L_r V_{ds} - L_r R_s i_{ds} + L_r \omega_e (L_s i_{qs} + L_m i_{qr})$$

$$- L_m(\omega_e - \omega_r)(L_m i_{qs} + L_r i_{qr}) + L_m R_r i_{dr}]$$

$$pi_{ds} = (\omega_e + K_2 L_m \omega_r) i_{qs} - K_1 R_s i_{ds} + K_1 L_m \omega_r i_{qr} + K_2 R_r i_{dr} - K_1 V_{ds} \tag{3.8}$$

$$pi_{qr} = \frac{1}{D}[L_m R_s i_{qs} + L_m \omega_e (L_s i_{ds} + L_m i_{dr}) - L_s(\omega_e - \omega_r) \text{ x}$$

$$\text{x } (L_m i_{ds} + L_r i_{dr}) - L_s R_r i_{qr} + L_m V_{qs}]$$

$$pi_{qr} = K_2 R_s i_{qs} + L_s K_2 \omega_r i_{ds} - [(R_r + L_m K_2 R_r)/L_r]\, i_{qr}$$

$$+ (L_s K_1 \omega_r - \omega_e)\, i_{dr} + K_2 V_{qs} \tag{3.9}$$

$$pi_{dr} = \frac{1}{D}[L_m V_{ds} + L_m R_s i_{ds} - L_m \omega_e (L_s i_{qs} + L_m i_{qr})$$

$$+ L_s(\omega_e - \omega_r)(L_m i_{qs} + L_r i_{qr}) - L_s R_r i_{dr}]$$

$$pi_{dr} = -L_s K_2 \omega_r i_{qs} + K_2 R_s i_{ds} - (L_s K_1 \omega_r - \omega_e)\, i_{qr}$$

$$-[(R_r + L_m K_2 R_r)/L_r]\, i_{dr} + K_2 V_{ds} \tag{3.10}$$

where,

$$\left.\begin{aligned} K_1 &= L_r/(L_s L_r - L_m^2) \\ \textit{and} \quad K_2 &= L_m/(L_s L_r - L_m^2) \end{aligned}\right\} \tag{3.11}$$

The expression for torque equation is -

$$T_e = \left(\frac{3}{2}\right) \cdot \left(\frac{P}{2}\right) . L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) + \left(\frac{2}{P}\right) . Jp\omega_r$$

$$T_e = T_m - \left(\frac{2B}{P}\right) . \omega_r$$

$$P\omega_r = -(B/J)\omega_r + (3N^2L_m/8J)\,(i_{qs}i_{dr} - i_{ds}i_{qr}) + (N/2\ J).T_m \tag{3.12}$$

The self excited induction generator in the stationary reference frame is shown in Fig.(3.1). The d-q equivalent circuits at synchronously rotating reference frame is shown in Fig.(3.2). In self excited induction generators, the magnitude of the generated air gap voltage in the steady state is given by -

$$V_g = \omega_e\, L_m\, |i_m|$$

where,

$$|i_m| = \sqrt{(i_{qs} + i_{qr})^2 + (i_{ds} + i_{dr})^2} \tag{3.13}$$

Here L_m, the magnetizing inductance, is not a constant but a function of the magnetizing current i_m given as

$$L_m = f(|i_m|)$$

The current flow directions in the exciting capacitors and the load resistors are shown in Fig.(3.3)

where,

R = load resistance

C = exciting capacitor

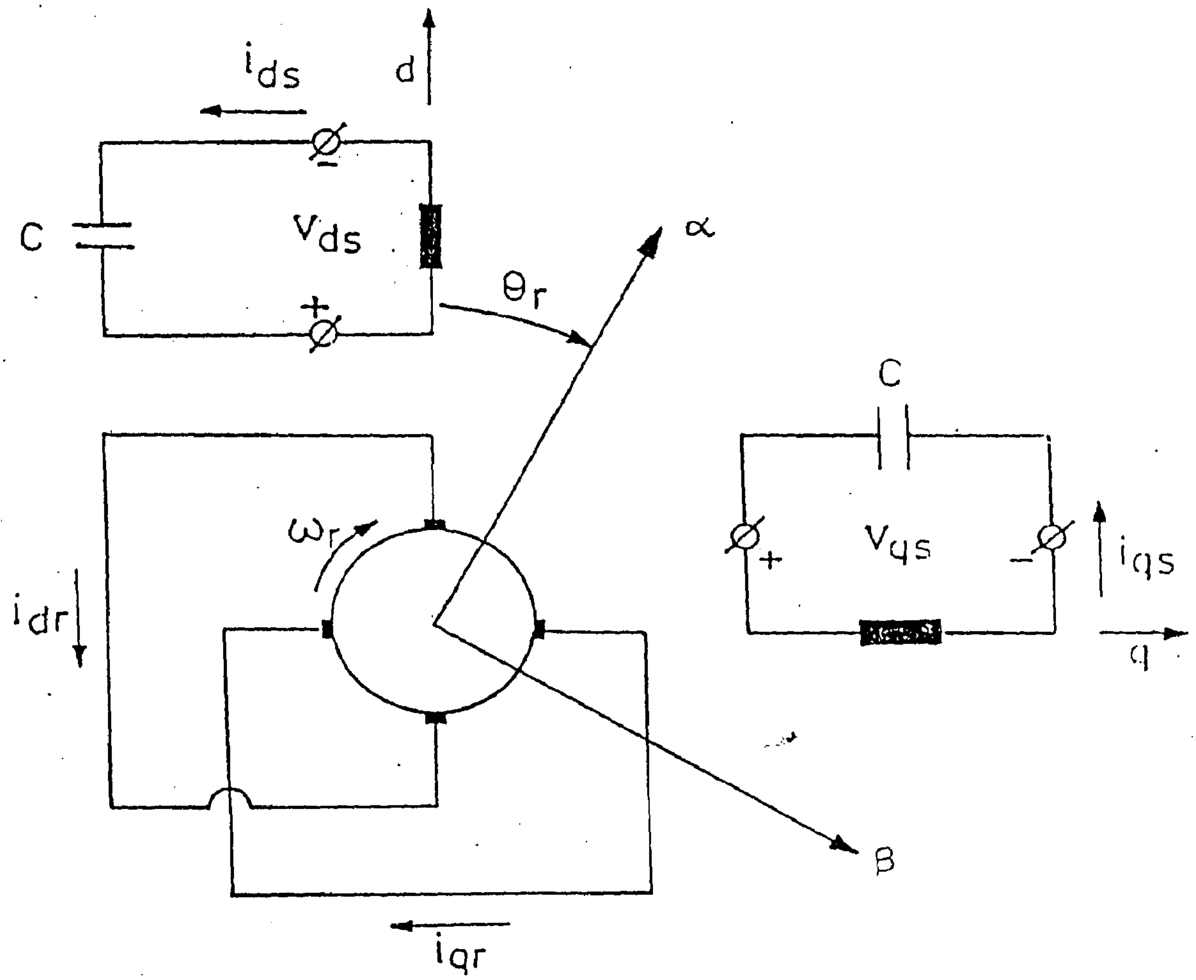


Fig.3.1 : The self-excited generator in the stationary reference frame

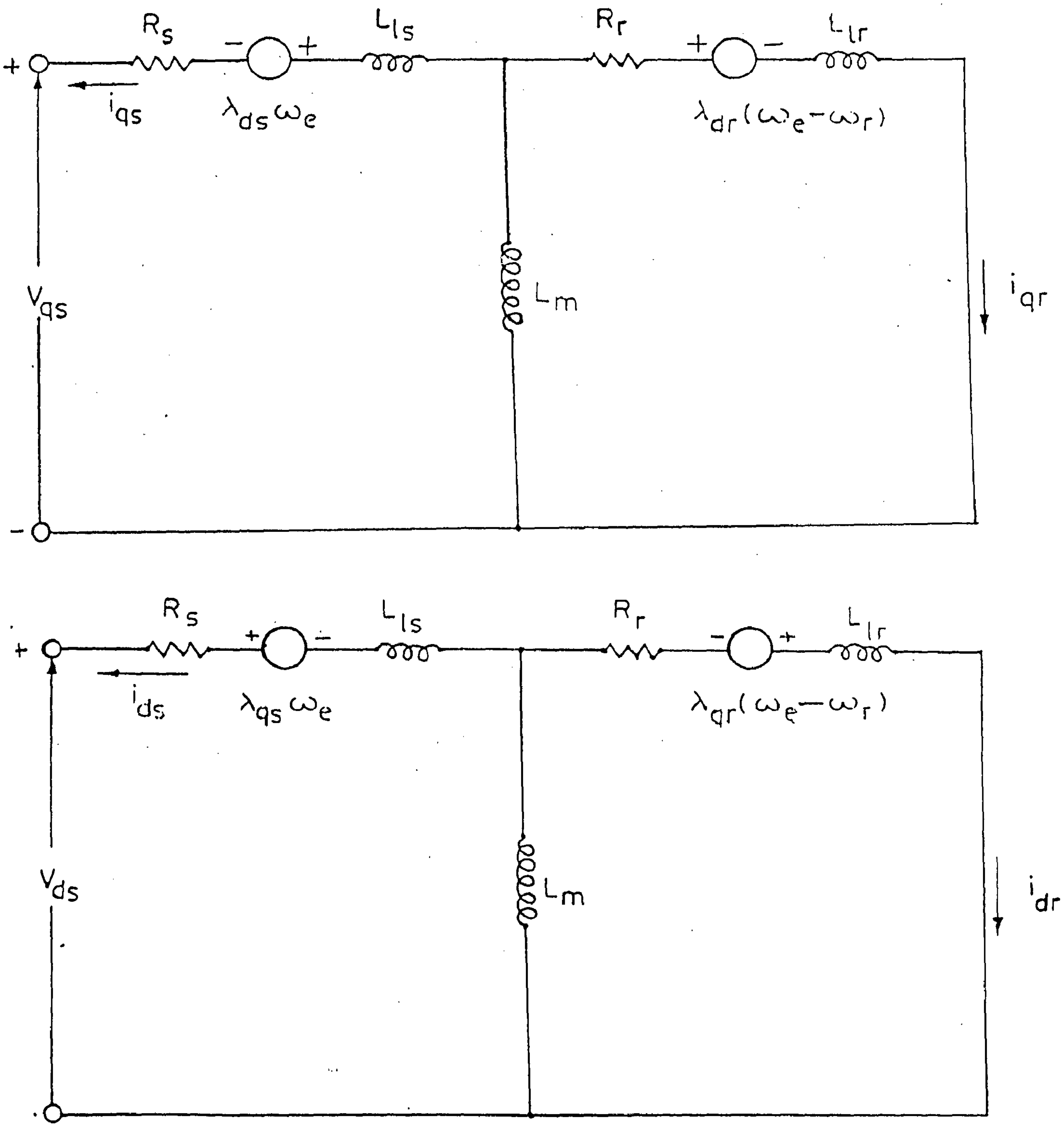


Fig.3.2 : Equivalent circuit of induction generator in d-q reference frame

The self-exciting capacitor introduces the following state equations -

$$\left.\begin{aligned} pV_{ds} &= (i_{dc}/C) + \omega_e V_{qs} \\ pV_{qs} &= (i_{qc}/C) - \omega_e V_{ds} \end{aligned}\right\} \tag{3.14}$$

where the capacitor currents i_{dc} and i_{qc} flow as shown in Fig.(3.3). If V_{qs}=0, the above equations reduces to -

$$\left.\begin{aligned} pV_{ds} &= i_{dc}/C \\ \omega_e &= i_{qc}/(CV_{ds}) \end{aligned}\right\} \tag{3.15}$$

When vector control is applied, PWM-VSI static reactive power compensator is current controlled, with current control being executed either in stationary reference frame or in rotational reference frame.

Three phase load is assumed to be either purely resistive or combined resistive inductive. The reactive power compensator is required to provide reactive power for the generator and for the load when it is of resistance inductive nature. Power circuit of the compensator versus the well-known six switch three phase topology (parallel connection) of a controllable semi-conductor and an anti-parallel diode as shown in fig.(3.4). Inverter firing signals are obtained from a closed loop current control algorithm. Firing signals are created on the basis of the errors between phase current reference and measured stator-phase current of the generator. The capacitor at the inverter d.c. side is of relatively high capacitance. It is assumed that capacitor is precharged to an appropriate voltage. The resistor connected in parallel to the d.c. side capacitor, is a fictitious element that does not

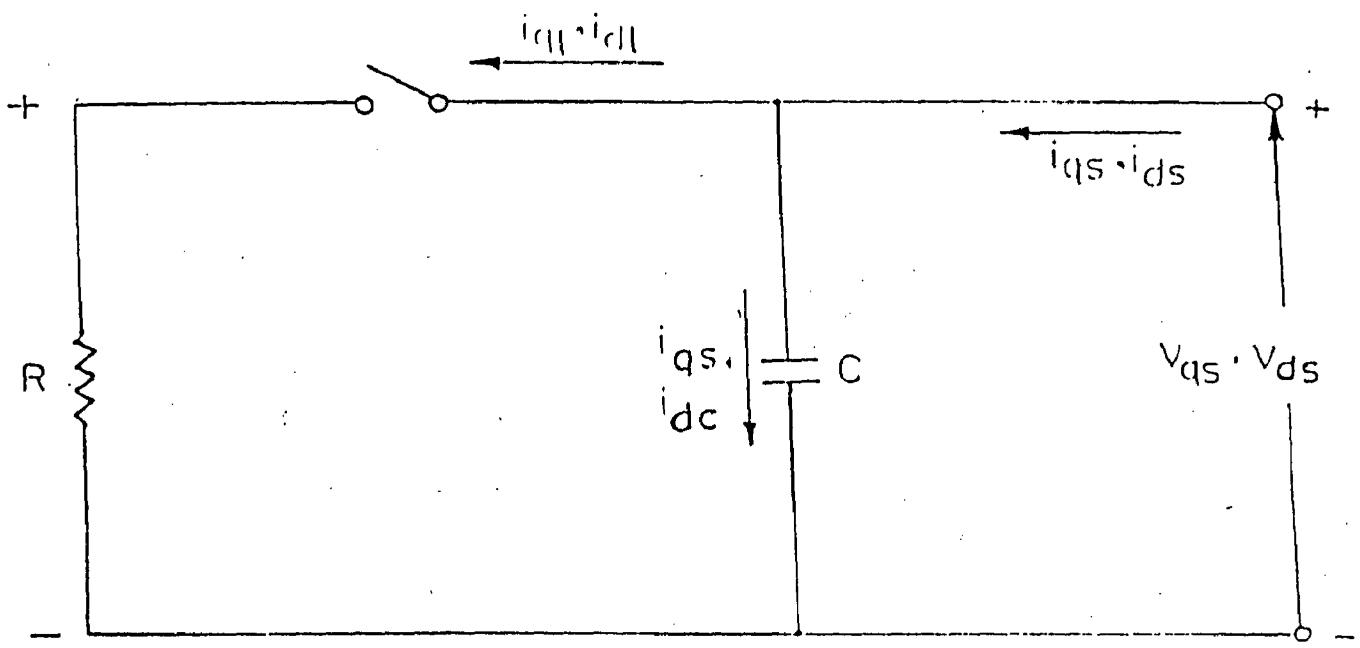


Fig.3.3 : Current flow directions in the exciting capacitor

exist in reality. The resistor is used to represent losses that take place in the inverter and in the real d.c. circuit. Control of the PWM-VSI static reactive power compensator is depicted in fig.(3.5).

When the reactive power compensation, to the induction generator, is given through static reactive power compensator, i.e., through inverter, the co-ordinate transformations between generator phase to neutral voltage, determined by the inverter, and d-q axis voltages and between the generator d-q axis currents and phase currents are given with

$$\left.\begin{aligned} V_{ds} &= \left(\frac{2}{3}\right)\left[V_{an}\cos 2\pi 50t + V_{bn}\cos(2\pi 50t - 2\pi/3) + V_{cn}\cos(2\pi 50t - 4\pi/3)\right] \\ V_{qs} &= \left(-\frac{2}{3}\right)\left[V_{an}\sin 2\pi 50t + V_{bn}\sin(2\pi 50t - 2\pi/3) + V_{cn}\sin(2\pi 50t - 4\pi/3)\right] \end{aligned}\right\} \tag{3.16}$$

$$\left.\begin{aligned} i_a &= i_{ds}\cos 2\pi 50t - i_{qs}\sin 2\pi 50t \\ i_b &= i_{ds}\cos(2\pi 50t - 2\pi/3) - i_{qs}\sin(2\pi 50t - 2\pi/3) \\ i_c &= i_{ds}\cos(2\pi 50t - 4\pi/3) - i_{qs}\sin(2\pi 50t - 4\pi/3) \end{aligned}\right\} \tag{3.17}$$

where selection $\omega_e = 2\pi 50$ is accounted for, indices a,b,c identify the three phases, and index 'n' stands for neutral point of the star connected generator's stator winding.

3.2 LOAD MODEL

The load current is given by -

$$i_l = \sqrt{(i_{ql})^2 + (i_{dl})^2}$$

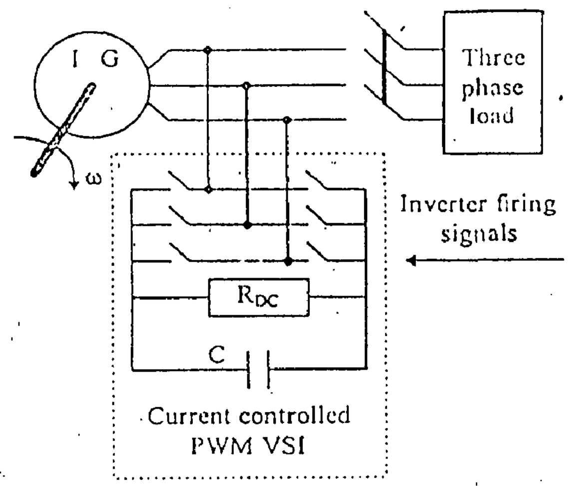


Fig.3.4 : Induction generator self-excitation scheme based on PWM VSI

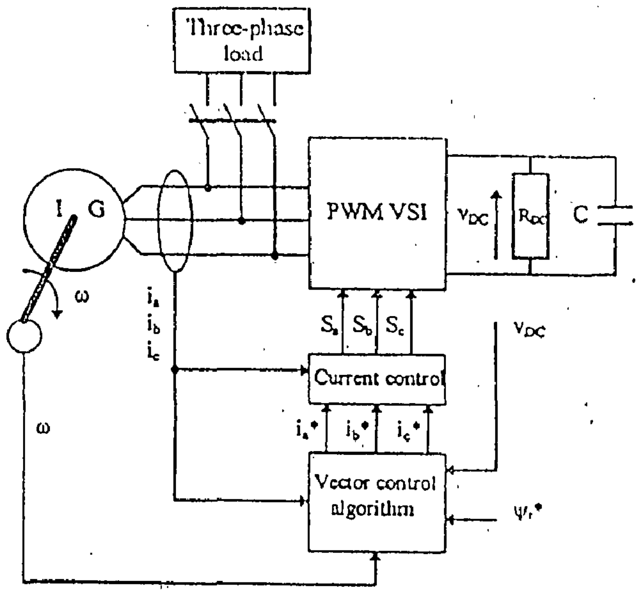


Fig.3.5 : Configuration of the vector control scheme for an induction generator with current controlled PWM VSI based reactive power compensator

If a resistive load of "R" ohms is connected across the terminals of the generator as shown in Fig.(3.3)

$$\left.\begin{aligned} i_{dl} &= V_{ds}/R \\ i_{ql} &= V_{qs}/R \end{aligned}\right\} \tag{3.18}$$

Applying KCL at the capacitor terminals, we gets -

$$\left.\begin{aligned} i_{qc} &= i_{qs} - i_{ql} \\ i_{dc} &= i_{ds} - i_{dl} \end{aligned}\right\} \tag{3.19}$$

Using equations (3.19) in (3.14) and using equations (3.18), the variables i_{qc} and i_{dc} can be eliminated from the equations (3.14) giving

$$pV_{ds} = (i_{ds} - i_{dl})/C + \omega_e V_{qs}$$

or

$$\left.\begin{aligned} pV_{ds} &= i_{ds}/C - V_{ds}/RC + \omega_e V_{qs} \\ pV_{qs} &= i_{qs}/C - V_{qs}/RC - \omega_e V_{ds} \end{aligned}\right\} \tag{3.20}$$

If instead of a resistive load, a reactive load (R-L load) is applied, equations (3.16) are modified as -

$$\left.\begin{aligned} pi_{ql} &= -\left(\frac{R}{L}\right) i_{ql} - \omega_e i_{dl} + \left(\frac{1}{L}\right) V_{qs} \\ pi_{dl} &= -\left(\frac{R}{L}\right) i_{dl} + \omega_e i_{ql} + \left(\frac{1}{L}\right) V_{ds} \end{aligned}\right\} \tag{3.21}$$

3.3 MODEL OF THE D.C. SIDE OF THE INVERTER

Using the notation and current flow directions of Fig.(3.6) for the inverter d.c. side, change of d.c. voltage is governed with-

$$dV_{dc}/dt = -(i_{dc} + V_{dc}/R_{dc})/C \tag{3.22}$$

Total d.c. current i_{dc} can be expressed using inverter switching function as (index 'e' identifies compensator phase currents)

$$i_{dc} = S_a i_{ea} + S_b i_{eb} + S_c i_{ec} \tag{3.23}$$

Any of the three switching functions takes the value of 1 if upper switch in the given inverter leg is on an lower switch is off, and value '0' if lower switch in the same inverter leg is on, while upper switch is off. Correlation between generator currents, compensator currents and load currents is, from Fig.(3.6), (Load currents are identified with index L) given with-

$$\left.\begin{aligned} i_{ea} &= i_a + i_{la} \\ i_{eb} &= i_b + i_{lb} \\ i_{ec} &= i_c + i_{lc} \end{aligned}\right\} \tag{3.24}$$

The rotating frame model though requires multiple transformations has the advantage that with sinusoidal excitation the variables appear as dc quantities in steady-state condition. The equation (3.1) can be converted to that in stationary reference frame (Stanley equation) by substituting ω_e=0. In stationary reference frame representation, the variables appear as sine waves in steady state condition.

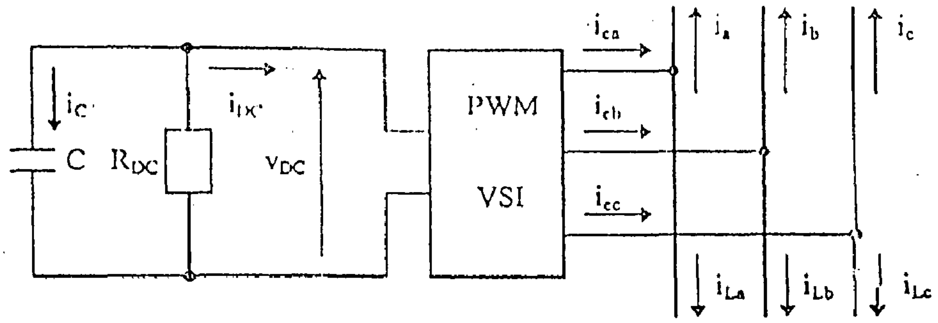


Fig.3.6 : Current flow directions in the system

3.4 MODEL OF HYSTERESIS CURRENT CONTROLLER

The current obtained from the vector controller serve as references for the current hysteresis controlled PWM VSI. The basic circuit of a 3-ϕ VSI is shown in Fig.(3.7). The three pairs of power transistors (denoted by S_a-S'_a, S_b-S'_b and S_c-S'_c) provide eight conduction modes according to the switching of transistors that is determined from the hysteresis controllers.

Fig.(3.8) shows the control for one inverter leg. In the figure, the phase-a current reference i_a^* is subtracted from the feedback phase - a line current i_a to form the current deviation $\Delta i_a(=i_a^* - i_a)$. If Δi_a is greater (less) than the present hysteresis band `H', the inverter leg is switched in the positive (negative) direction. Otherwise, if $|\Delta i_a| < H$), the inverter leg retains its current conduction mode. The hysteresis band in effect regulates the maximum current ripple in phase - a. The operation of the other two hysteresis controllers can be similarly described.

Phase voltages created by the inverter are expressed in terms of the switching function as -

$$\left.\begin{aligned} V_{an} &= V_{dc}(2S_a/3 - S_b/3 - S_c/3) \\ V_{bn} &= V_{dc}(2S_b/3 - S_a/3 - S_c/3) \\ V_{cn} &= V_{dc}(2S_c/3 - S_b/3 - S_a/3) \end{aligned}\right\} \qquad (3.25)$$

3.5 MODEL OF VECTOR CONTROLLER

From figure (3.9) the following equations are obtained -

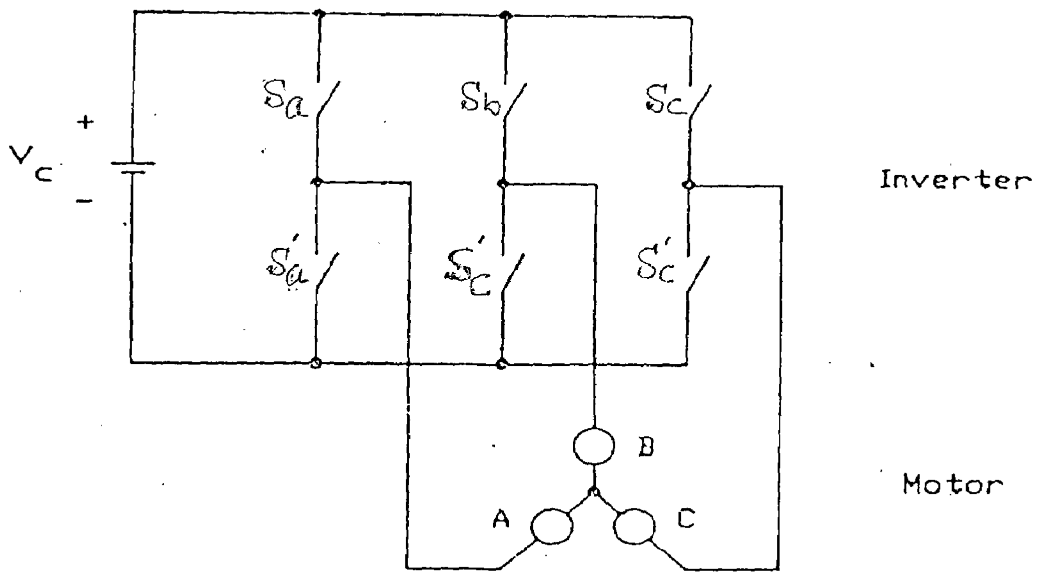


Fig.3.7 The power circuit of a voltage-source inverter.

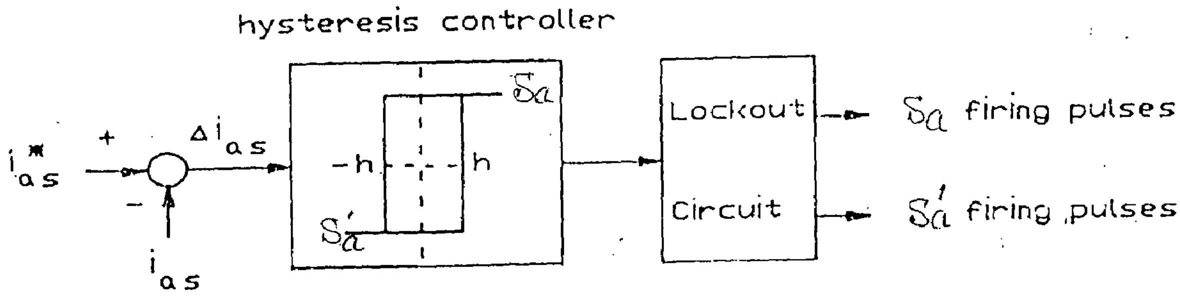


Fig.3.8 Current hystresis controller for one inverter leg.

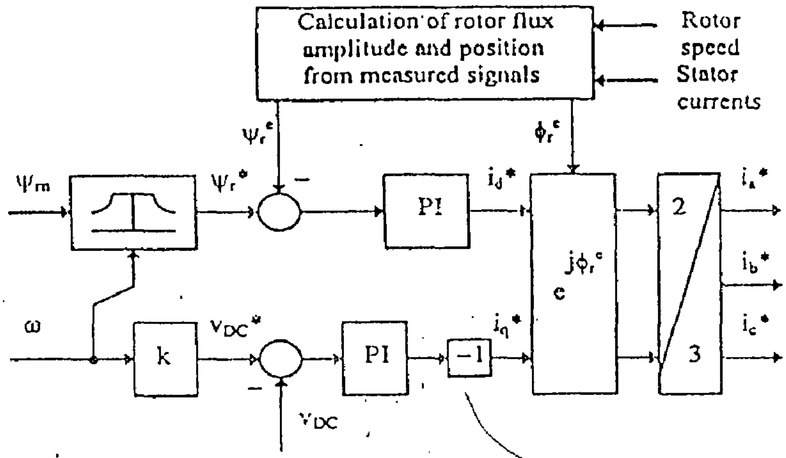


Fig.3.9 : Block diagram of vector control algorithm

$$\left.\begin{aligned} i_d^* &= K_d(\Psi_r^* - \Psi_r) + (K_d / T_d)\int(\Psi_r^* - \Psi_r)dt \\ -i_q^* &= K_q(V_{dc}^* - V_{dc}) + (K_q / T_q)\int(V_{dc}^* - V_{dc})dt \end{aligned}\right\} \qquad (3.26)$$

where K_d, K_q, T_d and T_q are parameters of the PI controllers. $V_{dc}^* = K\omega_r$ and $\psi_r^* = \psi_m$ (index 'n' stands for rated values) in the base speed region, while above base speed rotor flux reference is $\psi_r^* = \psi_m\ \omega_b/\omega$. Base speed takes as equal to rated synchronous speed.

The parameters K_d, K_q, T_d and T_q for the PI controller used in above expression can be evaluated from the departitioning technique detailed in appendix (A). However for the purpose of this dissertation, a detailed literature survey was carried out to calculate the suitable value of K_d, K_q, T_d and T_q. Analytical model was tested for different value of these constant and on the basis of references reported earlier.

Phase current references are built using estimated rotor flux angular position ϕ_r, so that -

$$\left.\begin{aligned} i_a^* &= i_{ds}^* \cos\phi_r^e - i_{qs}^* \sin\phi_r^e \\ i_b^* &= i_{ds}^* \cos(\phi_r^e - 2\pi/3) - i_{qs}^* \sin(\phi_r^e - 2\pi/3) \\ i_c^* &= i_{ds}^* \cos(\phi_r^e - 4\pi/3) - i_{qs}^* \sin(\phi_r^e - 4\pi/3) \end{aligned}\right\} \qquad (3.27)$$

It has to be noted that the model of the induction generator is formed in the reference frame that rotates at 2π50 rad/sec., while control system operates in the rotor flux oriented reference frame.

CHAPTER - 4

TRANSIENT ANALYSIS - ALGORITHMS, FLOWCHARTS AND COMPUTER SIMULATION

4.1 COMPUTER SIMULATION

4.1.1 Case 1 : Resistive Load

The instantaneous values of d- and q-axes stator, rotor and load currents can be found out by solving the differential equations which results from equations (3.1). A step by step numerical solution method is used for this purpose. Of all the numerical methods available, the Runga-Kutta method has been chosen. Because of non-linear nature of L_m, this has to be taken into account from the L_m V_s i_m curve in each iteration.

Algorithm

The program first reads the initial steady-state values of the direct and quadrature axes stator currents i_{qso}, i_{dso}, rotor currents i_{qro}, i_{qro}, stator terminal voltages V_{dso}, V_{qso}, shaft speed in electrical rad/sec, ω_{ro}, and the magnetizing inductance L_{mo}. The program also reads the machine parameters like the stator and rotor resistances and leakage reactances, moment of inertia, friction coefficient, mechanical torque, number of poles, electrical speed in rad/sec., etc. Now set the initial time `t_o', final time 't_f ' and the step size 'h'. The stator and the rotor self inductances L_s and L_r respectively are found from the relations :

$$\left.\begin{aligned} L_s &= L_{ls} + L_{mo} \\ L_r &= L_{lr} + L_{mo} \end{aligned}\right\} \tag{4.1}$$

where, L_{ls} and L_{lr} are the stator and rotor leakage inductances.

The constant K_1 and K_2 are found using equations (3.11). Then by using Runga-Kutta method, the differential equations are solved.

For a resistive load, only seven differential equations are used, two for stator currents; two for rotor current, two for stator terminal voltage and one torque equation. The equations are solved in a stationary reference frame, so put ω_e=0.

Initially let the machine was operating at steady-state condition at a load resistance of 'R' ohms. Now at time t=0, the load circuit is opened. This is done by putting the value of 'R' to be infinity (theoretically a very large value), then the differential equations are solved using Runga-Kutta method to get the values of i_{qs}, i_{ds}, i_{qr}, i_{dr}, V_{ds}, V_{qs}, ω_r etc. at time $t_1 = t_0+h$.

Knowing d-q axes currents the magnitude of magnetizing current i_m is calculated as -

$$i_m = \sqrt{(i_{qs} + i_{qr})^2 + (i_{ds} + i_{dr})^2} \tag{4.2}$$

The magnetizing inductance L_m can then be evaluated from L_m Vs i_m curve. The following relations may be used for calculating the magnitudes of the variables.

$$\left.\begin{aligned} |i_s| &= \sqrt{(i_{qs}^s)^2 + (i_{ds}^s)^2} \\ |i_r| &= \sqrt{(i_{qr}^s)^2 + (i_{dr}^s)^2} \\ |i_l| &= \sqrt{(i_{ql}^s)^2 + (i_{dl}^s)^2} \\ |i_c| &= \sqrt{(i_{qc}^s)^2 + (i_{dc}^s)^2} \\ |V_t| &= \sqrt{(V_{qs}^s)^2 + (V_{ds}^s)^2} \end{aligned}\right\} \qquad (4.3)$$

where i_s, i_r, i_l, i_c and V_t are the peak values of any instant of time.

Now from the modified values of i_{qs}, i_{ds}, i_{qr} and i_{dr} the new value of i_m and hence L_m is found out as discussed before.

With these modified values of L_m and currents and voltages the above iteration is repeated. The iterations are continued for 0.5 sec. At t=0.5 sec., the load is again applied and the above process is repeated to get the new values of the variables at next interval. This is done till final time 't_f' is achieved. The flowcharts for solving the differential equations using Runga-Kutta method and for finding the transient performance of the induction generator are given in Figs.(4.2) and (4.1) respectively. Flowchart of Fig.(4.2) gives an algorithm for solving the differential equation using Runga-Kutta method. The following first order differential equation has been considered -

$$x(t) = f(x(t),\ u(t); \quad x(t_o) = x_o$$

4.1.2 Case - 2 : Inductive Load

The algorithm for finding the transient behaviour of the machine is same as that for a resistive load. Here two more differential equations of the load circuit are included thereby increasing the number of differential equations to be nine. They are solved simultaneously using Runga-Kutta method.

Algorithm

Here at t=0, the switch of the load circuit is opened by putting the value of the load resistance to be very high. During the period the load circuit is opened, put the value of the load current to be zero. Now knowing the initial conditions from the previous step the differential equations are solved simultaneously to get new values of the stator, rotor and load currents along d- and q-axes in stationary reference frame. The new value of the terminal voltage is also obtained along d- and q- axes from these improved values of the stator and the rotor currents, the magnetizing current i_m is found using equation (3.13) and corresponding to this value of i_m, the magnetizing inductance L_m is found out from L_m V_s i_m curve. Now considering this new value of L_m and the improved values of the stator and rotor currents as the initial operating point, the differential equations are again solved. The iteration is repeated for 0.5 sec. when the load is reapplied. With the applied load, the differential equations are again solved for finding the values of the different currents and voltages. The process is repeated till final time t_f reaches when transients in the currents and the voltages has died out.

4.1.3 Case - 3 : The Initial Self Excitation Process

With the machine driven at synchronous speed a three phases capacitor bank is switched on to the terminals. The capacitors, connected in delta, were chosen. Their value was 12 μF per equivalent star phase. Due to residual magnetism present in the machine, the voltage starts building up. The value of the capacitor used is more than the minimum value to cause self-excitation.

Algorithm

The program first reads the initial values of the stator and the rotor currents and the stator terminal voltage. The residual magnetism voltage is taken 30 volts. This voltage is assumed to be aligned along the d- axis. Using initial values of stator and rotor currents, the magnetizing current i_m and hence the magnetizing inductance L_m is found out. The machine is run at synchronous speed. At t=0, the capacitor bank is switched on and the calculations for the variables are carried out by solving the differential equations. Here only six differential equations are to be solved, two for stator current, two for rotor current and two for the stator terminal voltage. At time $t=t_1$, we get the new values of i_{qs}, i_{ds}, i_{dr}, i_{qr}, V_{ds} and V_{qs}. With these new values of currents, i_m is found out. The differential equations are again solved using these modified values of currents, voltages and magnetizing inductance L_m. The above iteration is repeated till the terminal voltage becomes constant.

4.1.4 Case - 4 : Fall of Terminal Voltage When a Heavy Load is Applied at the Terminals of the Generator

As discussed earlier in chapter 1, an induction generator loses excitation when a heavy load is applied or a short circuit takes place at the terminals of the machine. Due to lose of excitation the output voltage drops thus limiting the short circuit current.

Algorithm

Initially let the machine was running at steady-state condition for a fixed value of capacitor connected across the stator terminals. At time t=0, a heavy load (R =30Ω) is applied at the terminals of the machine. Now the differential equations for the stator current, rotor current, terminal voltage and shaft speed are solved simultaneously using Runga-Kutta method. Thus the output voltage is found out at next interval. The iteration is repeated till the terminal voltage becomes zero.

The fall of the terminal voltage depends upon the time-constant of the RC circuit, where -

C = exciting capacitor

And R = load resistor.

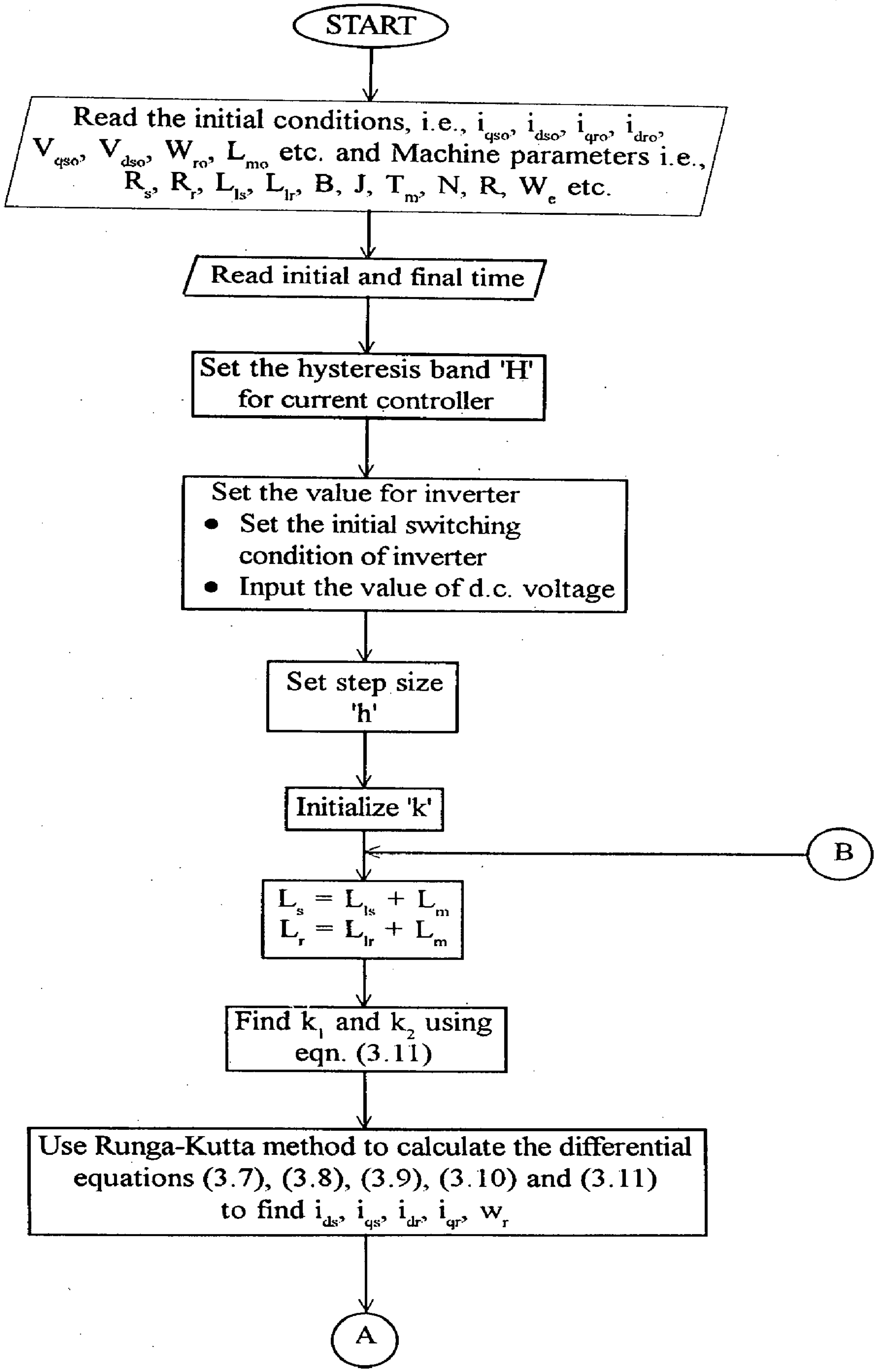
4.1.5 Case - 5 : Self-Excitation, Step Load Application and Variable Speed Operation under Rotor Flux Oriented Control

The algorithm for finding the transient behaviour of the machine is same as earlier. Here only five differential equations are used for resistive load and seven for inductive load. They are solved simultaneously using Runga-Kutta method.

Algorithm

The program first reads the initial steady-state values of the direct and quadrature axes stator currents, rotor currents, stator terminal voltages, shaft speed and the magnetizing inductance. The program also reads the machine parameters. Here after calculating L_s and L_r, the differential equations are calculated using Runga-Kutta method and then inverter phase voltages are calculated. Now in close loop operation vector controller and Hysteresis controllers are used.

The equations are solved in the reference frame that rotates at $2\pi 50$ rad/sec. The generator is assumed to run initially at constant speed $2\pi 50$ rad/sec. electrical. Self excitation is started at t=0 second, by connecting the compensator to induction generator terminals under no-load conditions. Capacitor at the d.c. side of the inverter is selected as 12μF and it is assumed that the capacitor is precharged to a voltage of V (t=0)=600 V. At time instant t=0.5 second pure resistive load of 250Ω per phase is applied in a stepwise manner, the differential equations are again solved for finding the values of the different currents and voltages. The process is repeated till final time t_f reaches.


START
Read the initial conditions, i.e., i_{qso}, i_{dso}, i_{qro}, i_{dro}, V_{qso}, V_{dso}, W_{ro}, L_{mo} etc. and Machine parameters i.e., R_s, R_r, L_{ls}, L_{lr}, B, J, T_m, N, R, W_e etc.
Read initial and final time
Set the hysteresis band 'H' for current controller
Set the value for inverter
• Set the initial switching condition of inverter
• Input the value of d.c. voltage
Set step size 'h'
Initialize 'k'
B
$L_s = L_{ls} + L_m$
$L_r = L_{lr} + L_m$
Find k_1 and k_2 using eqn. (3.11)
Use Runga-Kutta method to calculate the differential equations (3.7), (3.8), (3.9), (3.10) and (3.11) to find i_{ds}, i_{qs}, i_{dr}, i_{qr}, w_r
A

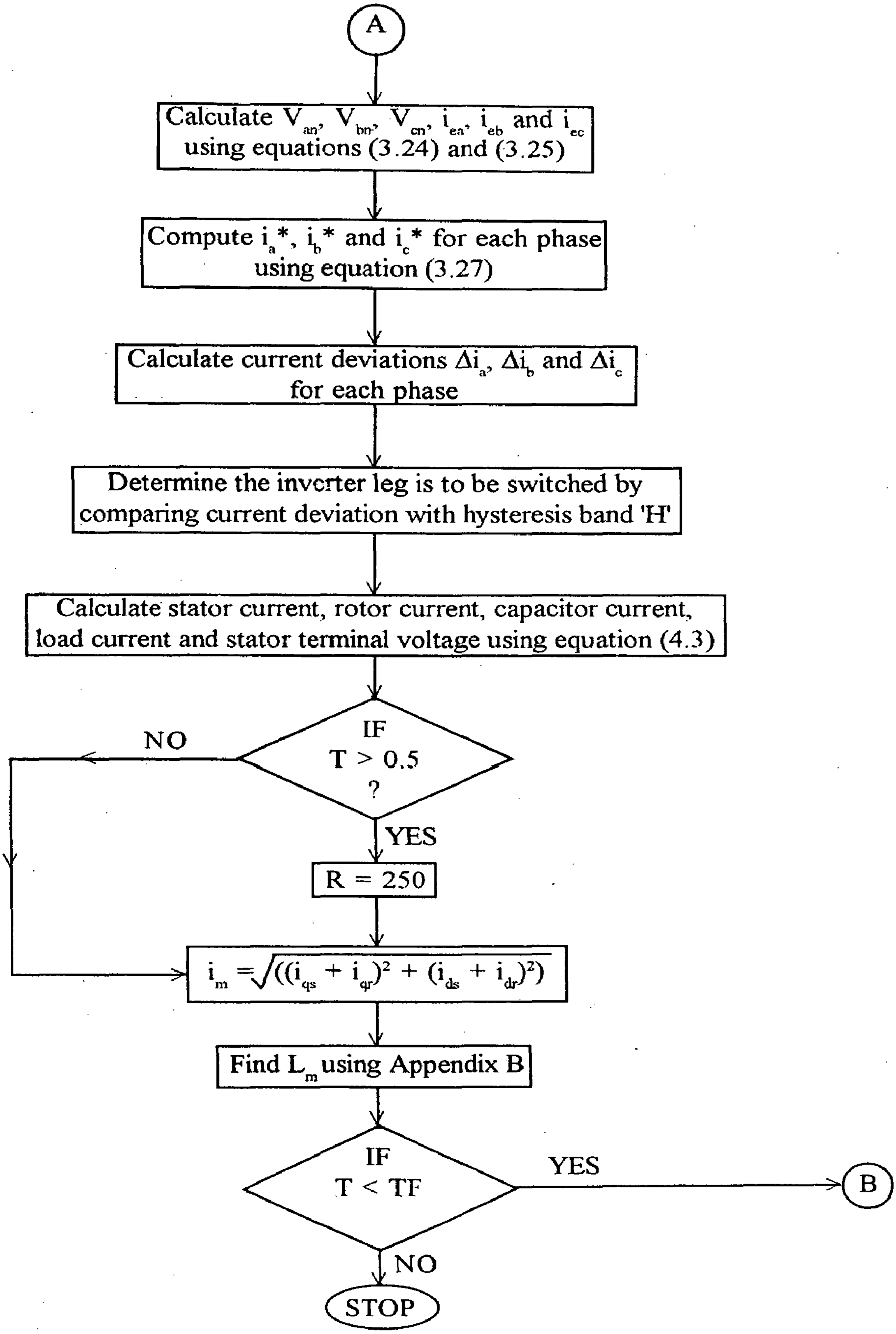


Fig.4.1 : Flowchart for the calculations of the self-excited induction generator

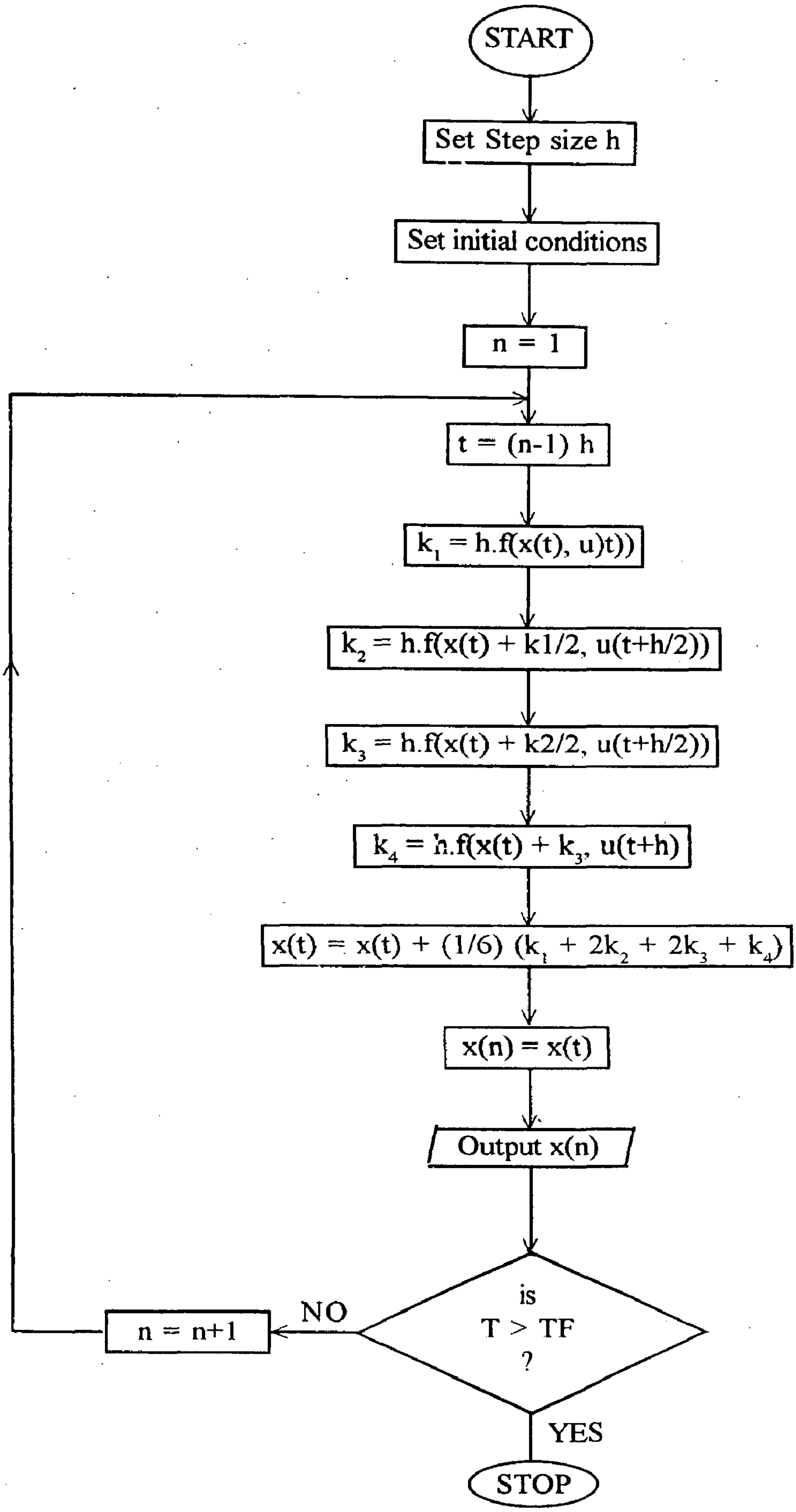


Fig.4.2 : Flowchart for the solution of differential equations by Runga-Kutta method (an algorithm)

CHAPTER - 5

RESULTS AND DISCUSSION

The transient performance of a 5 h.p. induction machine as self-excited stand-alone induction generator has been computed for different cases. The computation has been done by using the analytical techniques of which the flowcharts are given in previous chapter. A step by step numerical solution method is used for solving the differential equations. Fourth-order Runga-Kutta method is used for this purpose due to its high accuracy. The following cases has been studied:

(i) Sudden removal and re-application after a time delay of a purely resistive load.

(ii) Sudden removal and re-application after a time delay of an inductive load.

(iii) The initial self excitation process of terminal voltage, stator and rotor currents.

(iv) The fall of output voltage when a heavy load is applied at the terminals of the generator.

(v) Self-excitation process, step load application and variable speed operation under rotor flux orientation control.

5.1 RESISTIVE LOAD

Initially the induction generator was running at rated speed at a load of 250Ω and terminal capacitor of 12μF. For this condition, a stator current of 2.3841 amp (peak) was flowing in the generator. Now at time t=0, the load circuit is opened. The variation of the stator current after opening the load circuit is calculated and is shown in Fig.(5.1). From the figure, we observe that as the load circuit is opened, the stator current starts going down.

As the mechanical torque applied to the machine remains constant, the speed goes on rising till at 0.5 sec., the load is again applied. Due to increase in shaft speed of the machine, the generated air-gap voltage of the machine increases and hence the stator and also the rotor current rise continuously. The variation of rotor current is shown in Fig.(5.2). Now as soon as the load is again applied, the speed starts coming back to its original value and so the stator and the rotor currents.

The stator current settles at 2.38356 amp after 6 seconds which is very near to its value which was initially flowing in the machine. The rotor current before removal of the load was 1.8357 amp and it settles down at 1.8375 amp after dieing out of the transients after 6 sec. Thus it comes back to its initial value.

The shaft speed also settles back to its original value after 6 sec. The variation of shaft speed is shown in fig.(5.3). Initially the machine was running at 314.159 elec.rad/sec. During the period there is no load on the machine, the speed rises two about 349 elec.rad/sec. When the load is again applied, the speed starts decreasing. But before settling to its rated value of 314.159 elec.rad/sec., the speed goes below this rated value (about 311 elec.rad/sec.). This is due to moment of inertia of the machine. The speed again rises and then settles at its rated value.

The variation of stator terminal voltage is shown in Fig.(5.4). The terminal voltage is dependent upon the air gap voltage which in turn is related with the shaft speed. Hence the stator terminal voltage changes according to the shaft speed. The load current and the capacitor current depends upon the stator terminal voltage. Their variations are shown in figs.(5.5 and 5.6). The load current remains zero during the period there is no load in the circuit. As soon as the load is applied, the load current rises and starts decreasing according to shaft speed. The load current settles down when the speed becomes constant.

5.2 INDUCTIVE LOAD

Initially the induction generator was running at rated speed for a terminal capacitor of 12μF and a load resistance of 250Ω and reactance of 375Ω. At time t=0, the load circuit was opened by putting a large value of load resistance R. After 0.5 seconds, the load was restored. For these disturbances, the variation of the stator and rotor currents, shaft speed, stator terminal voltage, capacitor current and load current were studied and given in Figs.(5.7), (5.8), (5.9), (5.10), (5.11) and (5.12) respectively.

From the stator current variation, it is found that when the load current becomes zero at time t=0, the stator current starts rising. From the figures it is observed that the variables settles to its initial steady-state values after the transients have died out.

5.3 THE INITIAL SELF EXCITATION PROCESS

When a terminal capacitor of sufficient value is connected across the terminals of an induction machine, the voltage starts building up due to residual magnetism present in the machine. This terminal voltage depends upon the speed of the machine.

The build up of the output voltage during initial self-excitation process is shown in Fig.(5.13). From the figure it is evident that the voltage rises and becomes constant at 545.53 volts for a terminal capacitance of 12μF after 6 seconds. For the sake of clarify the curve is drawn only for 3.5 seconds where the voltage has almost become constant. Figs.(5.14) and (5.15) shows the variations of the stator current and the rotor current during the self excitation process. From these curves it is observed that these currents become stable after 4-seconds.

5.4 FALL OF OUTPUT VOLTAGE WHEN A HEAVY LOAD IS APPLIED AT ITS TERMINALS

This phenomenon takes place due to lose of excitation and as explained in chapter-3, this is one of the advantages of self excited induction generators. The fall of terminal voltage is shown in Fig.(5.16). It is observed that the voltage becomes zero after 0.4 seconds only.

5.5 SELF EXCITATION PROCESS, STEP LOAD APPLICATION AND VARIABLE SPEED OPERATION UNDER ROTOR FLUX ORIENTED CONTROL

The generator is assumed to run initially at constant speed. Self-excitation is started at t=0 seconds by connecting the compensator to induction generator terminals under no-load conditions. Capacitor across the d.c. side of the inverter is 12μF and it is charged to a sufficient value for the self excitation of the generator to a voltage of 600V at t=0 seconds. Now at t=0.5 seconds we applies the resistive load of 250Ω in stepwise manner. At t=1.4 seconds, a linear decrease in speed is initiated, speed is reduced, from 349 elect-rad/second to 311 electrical rad/sec. rather than settling to its rated value of 314.159 electrical rad/sec. The speed again rises and then settles at its rated value. Rotor flux reference is constant and equal to rated throughout. Figs.(5.17), (5.18), (5.19), (5.20), (5.21) and (5.22) shows the variation of stator terminal voltage, stator current, rotor current, load current, capacitor current and shaft-speed respectively.

When self-excitation is initiated, capacitor d.c. voltage initially experiences a large reduction with respect to the pre-charged voltage value. However, it quickly recovers, and the process of excitation is completed within few hundreds of milli seconds, cause transients in d.c. voltage that die out rapidly, and d.c. voltage becomes equal in steady-state to the reference value and so for the stator terminal voltage also reaches its steady-state position after 0.05 seconds and at the same time stator current also becomes constant. after 0.05 seconds. Initially, when there is no load, the rotor current is very little and after 0.5 seconds when load is applied, rotor current goes upto 2.6 amp.

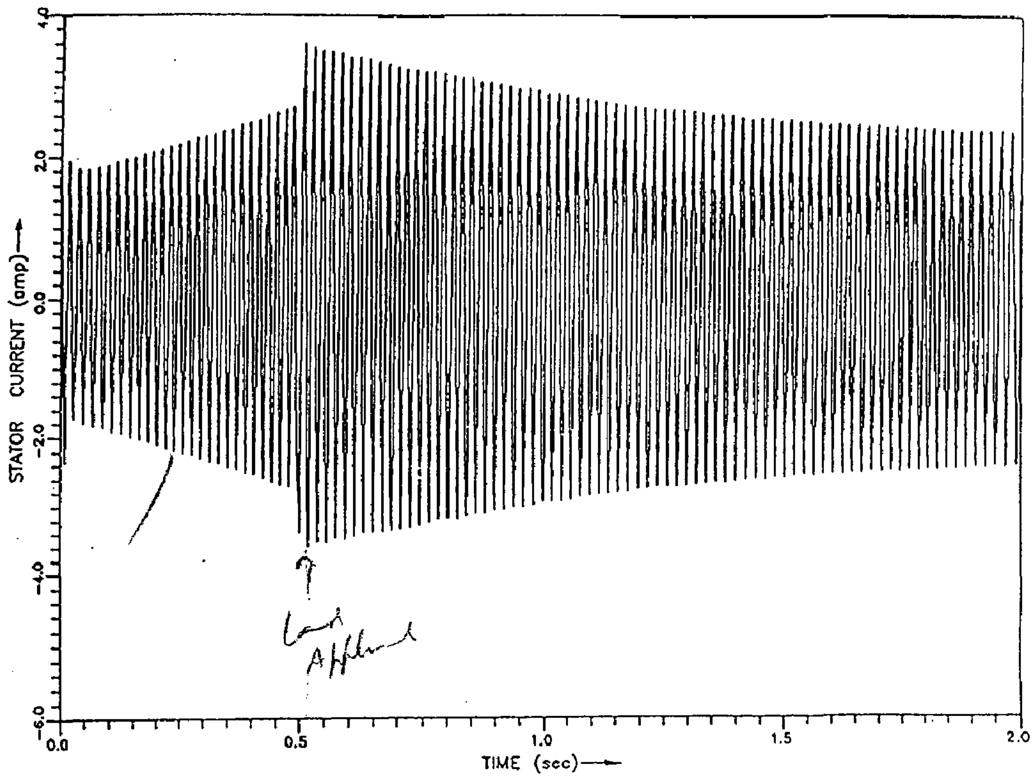


Fig.5.1 : Variation of stator current with time for a resistive load

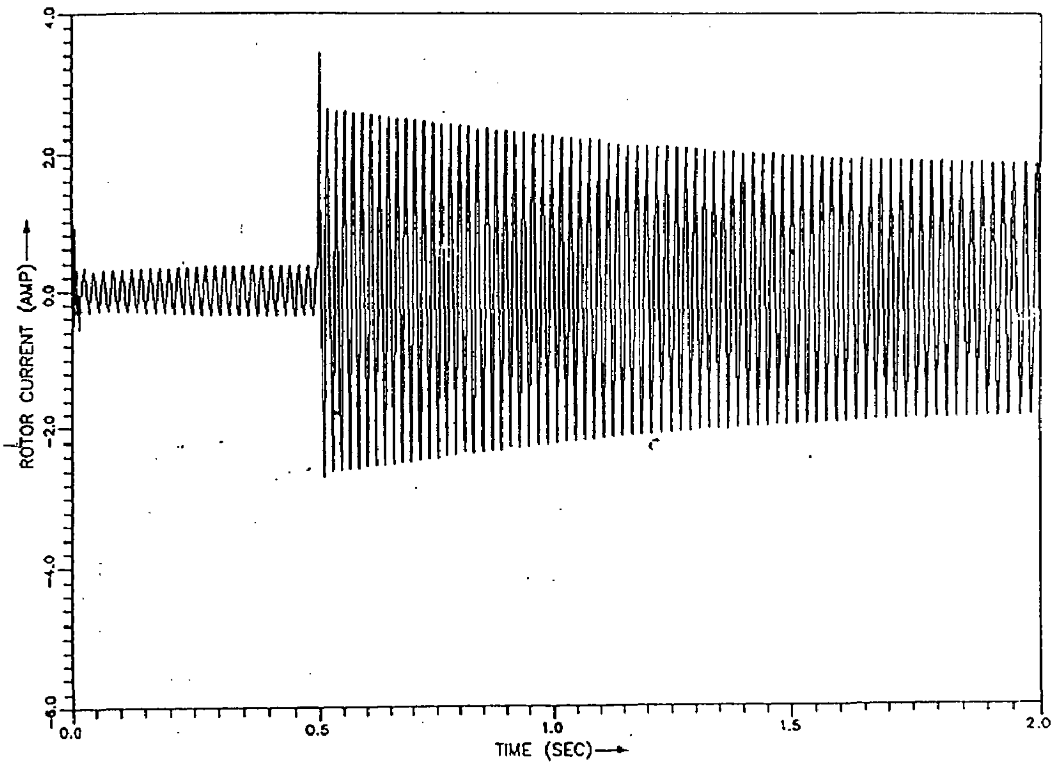


Fig.5.2 : Variation of rotor current with time for a resistive load

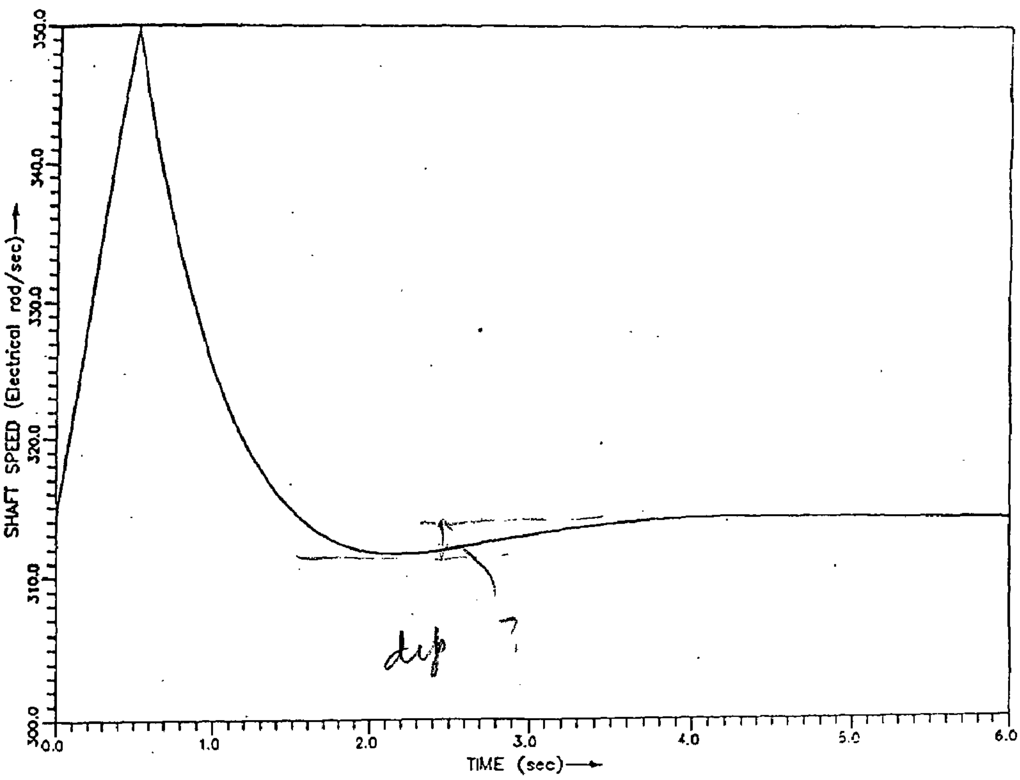


Fig.5.3 : Variation of shaft speed with time for a resistive load

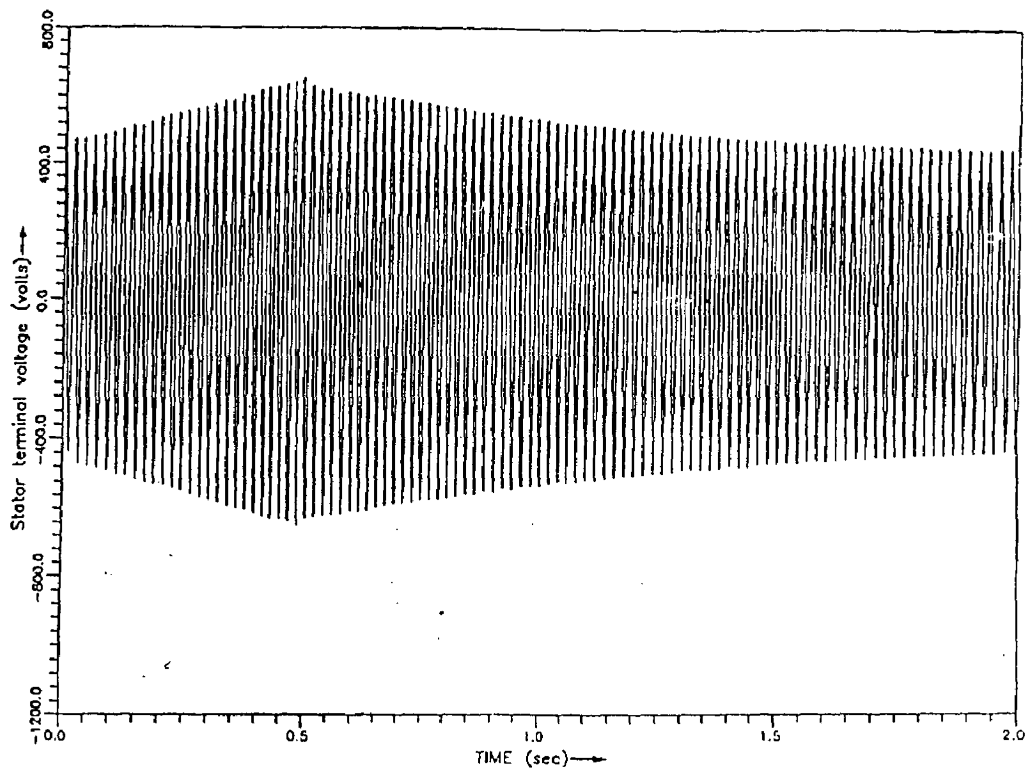


Fig.5.4 : Variation of stator terminal voltage with time for a resistive load

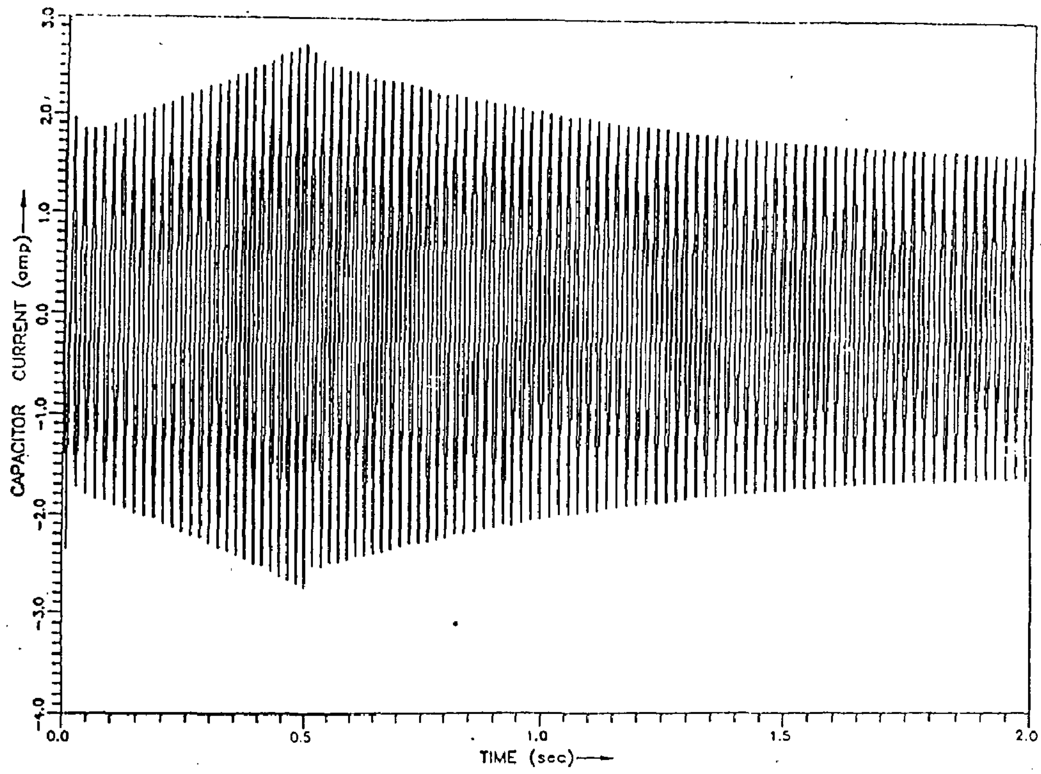


Fig.5.5 : Variation of capacitor current with time for a resistive load

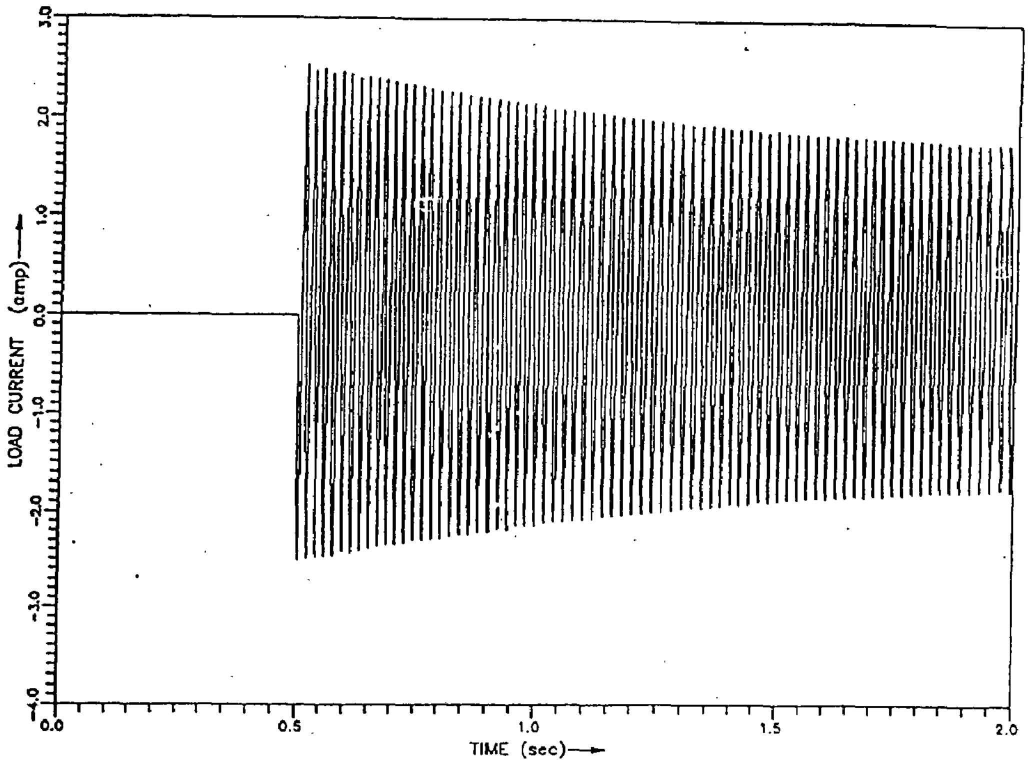


Fig.5.6 : Variation of load current with time for a resistive load

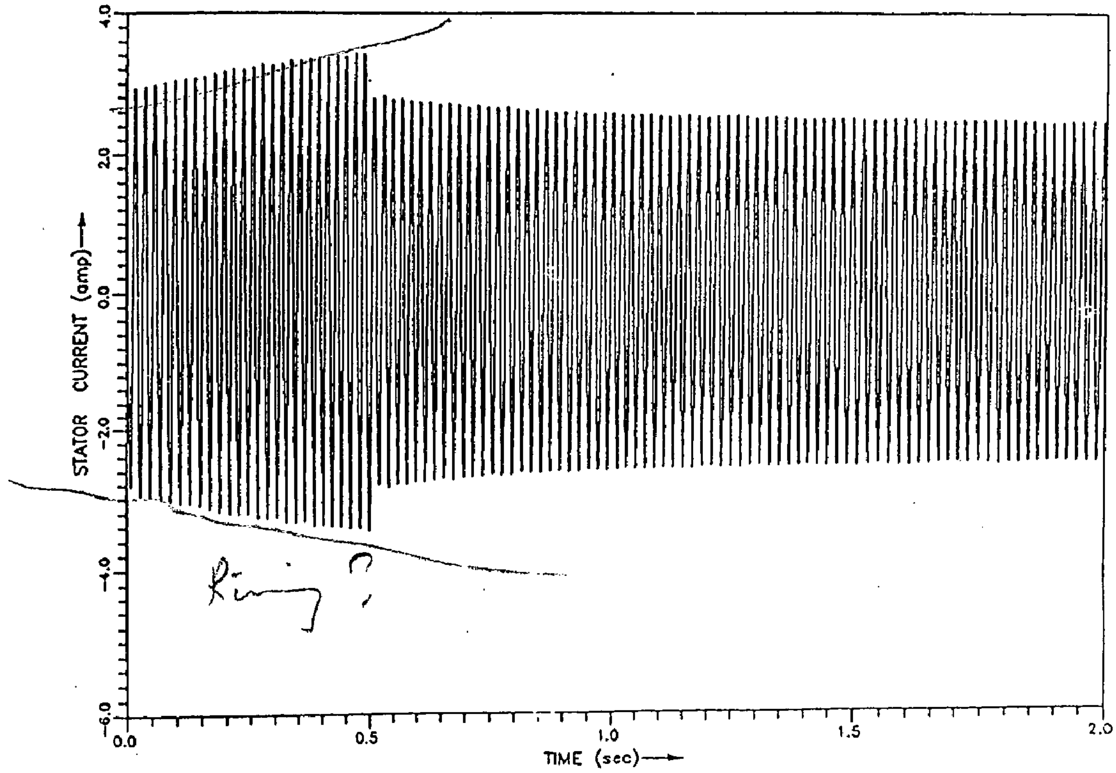


Fig.5.7 : Variation of stator current with time for an inductive load

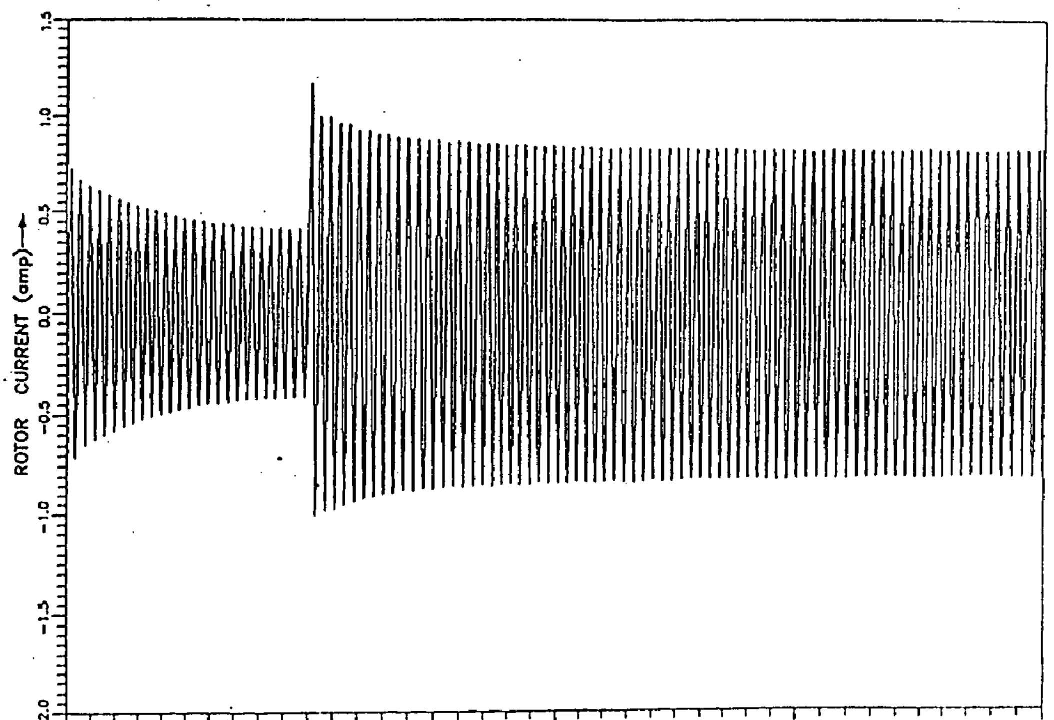


Fig.5.8 : Variation of rotor current with time for an inductive load

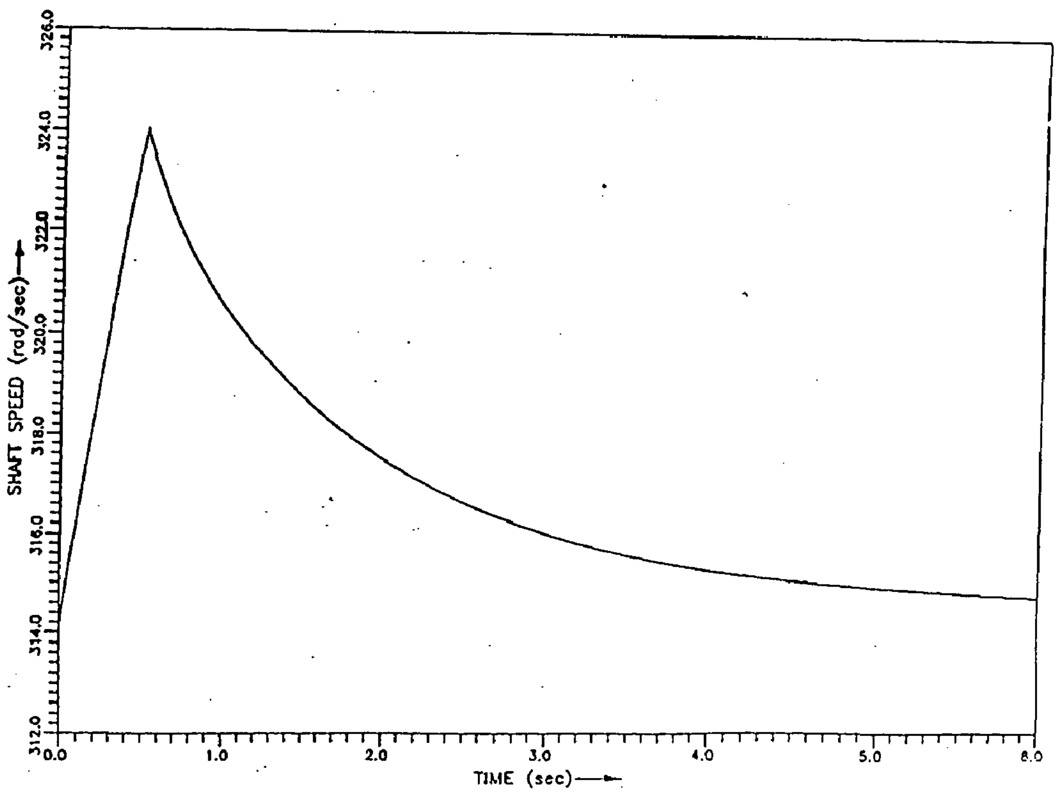


Fig.5.9 : Variation of shaft speed with time for an inductive load

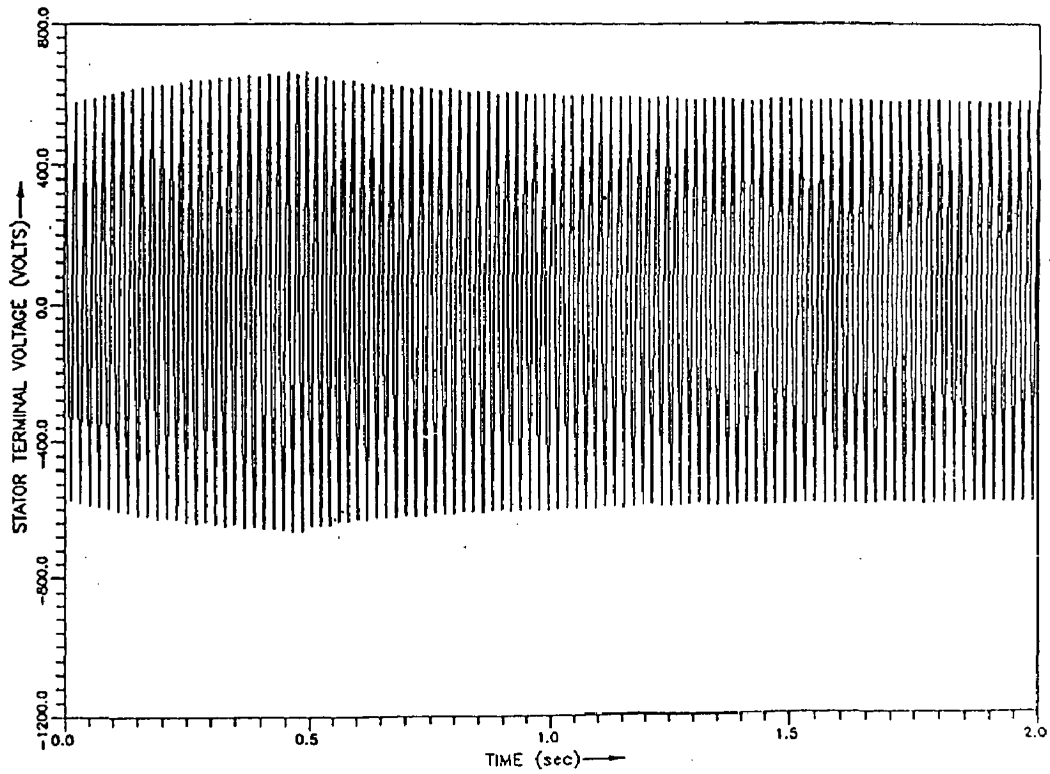


Fig.5.10 : Variation of stator terminal voltage with time for an inductive load

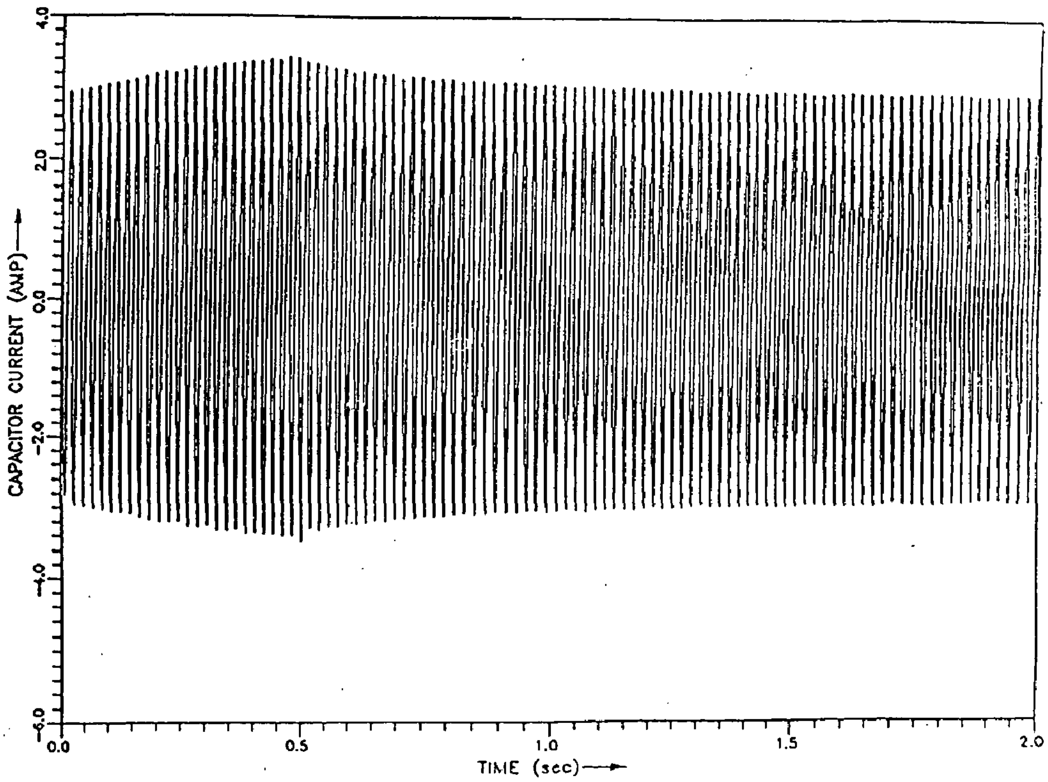


Fig.5.11 : Variation of capacitor current with time for an inductive load

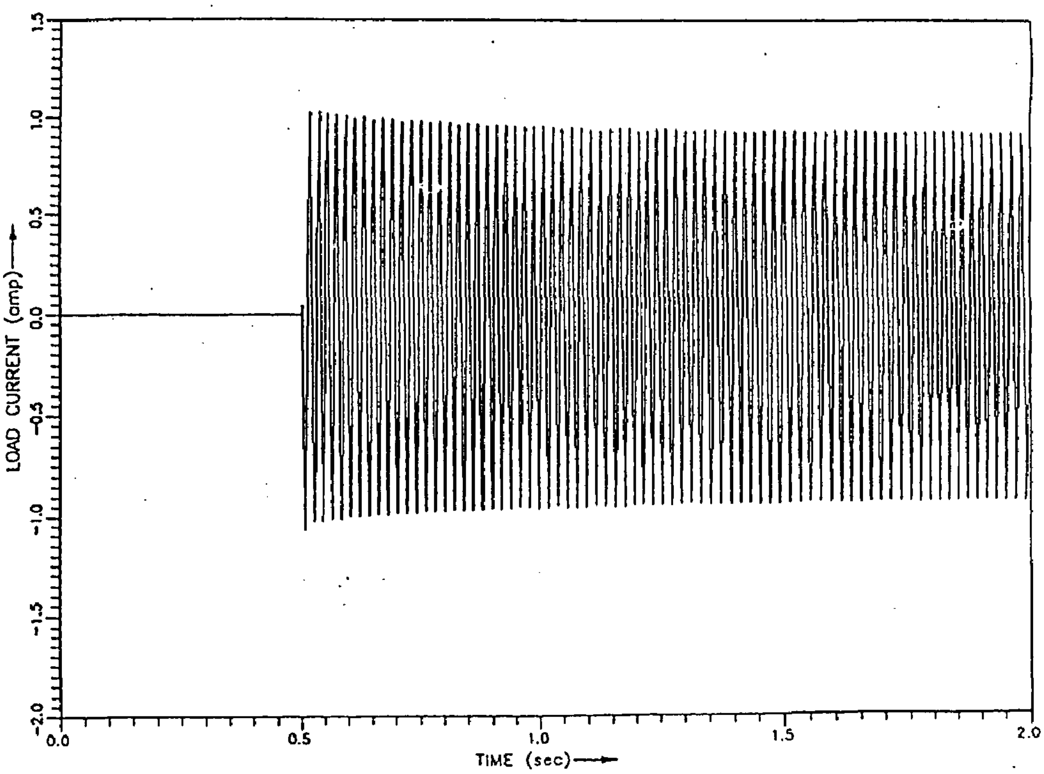


Fig.5.12 : Variation of load current with time for an inductive load

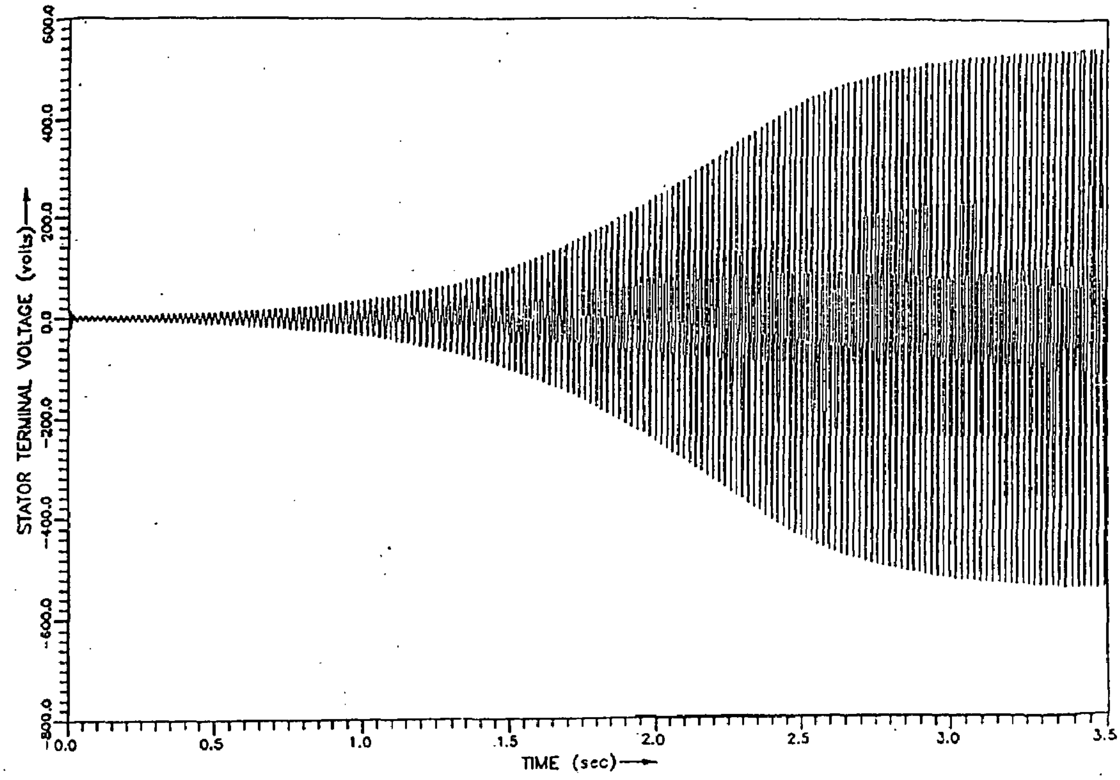


Fig.5.13 : Variation of output voltage with time during initiation of self-excitation

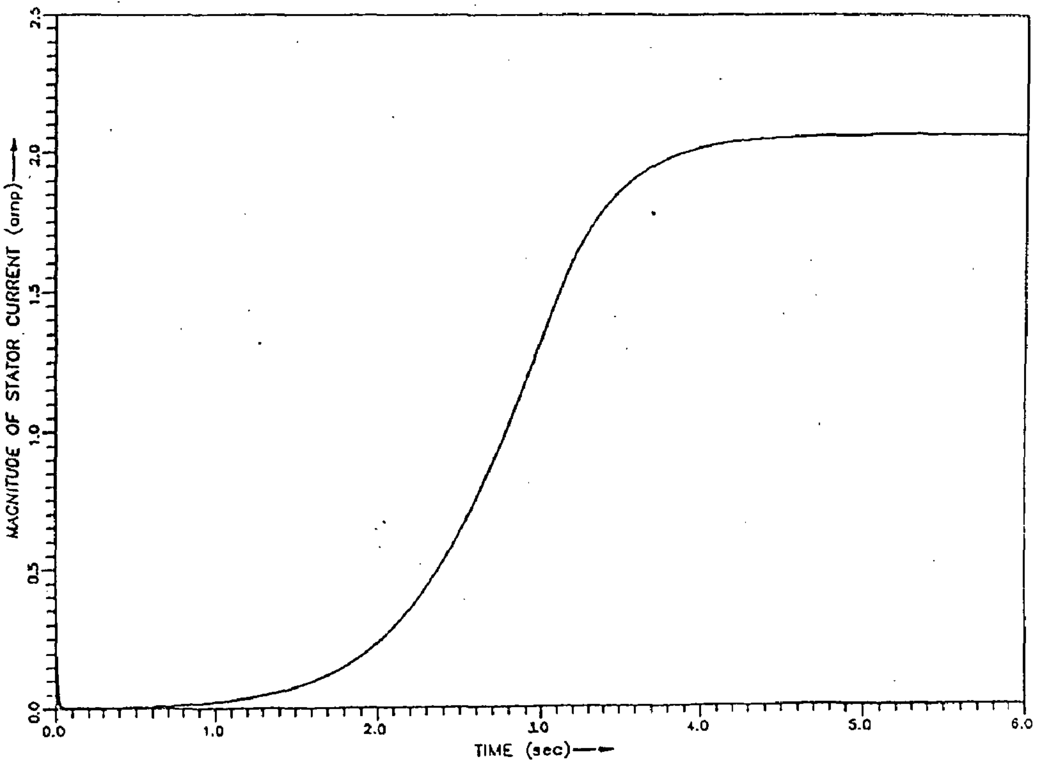


Fig.5.14 : Variation of stator current during initiation of self-excitation

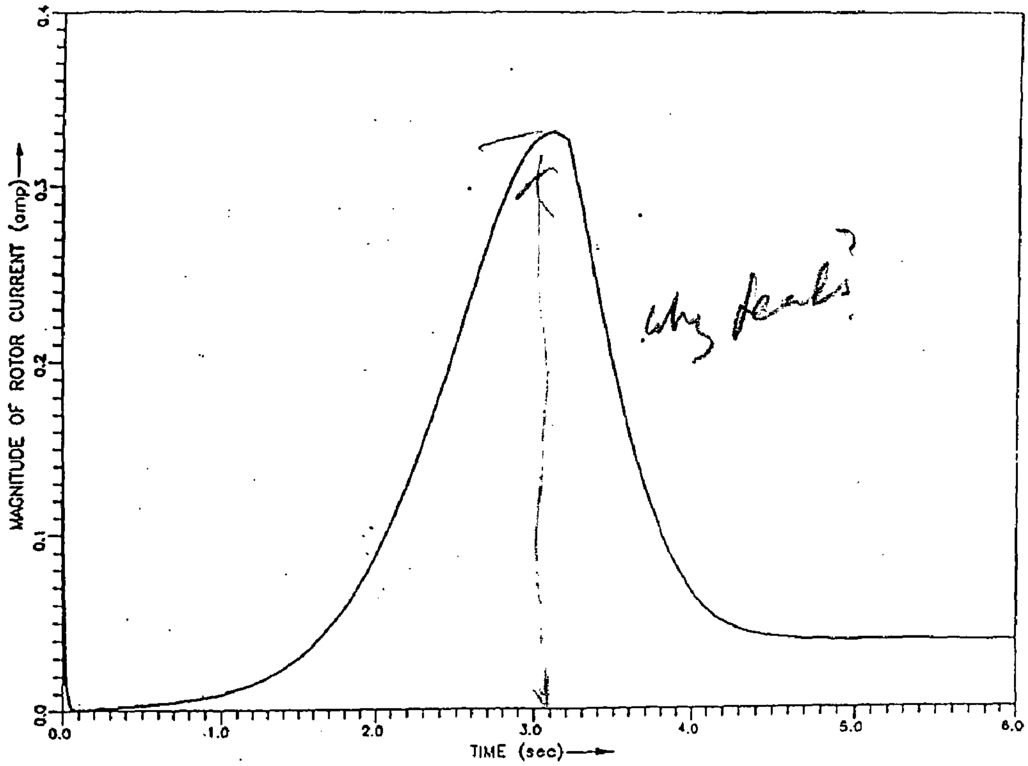


Fig.5.15 : Variation of rotor current during initiation of self-excitation

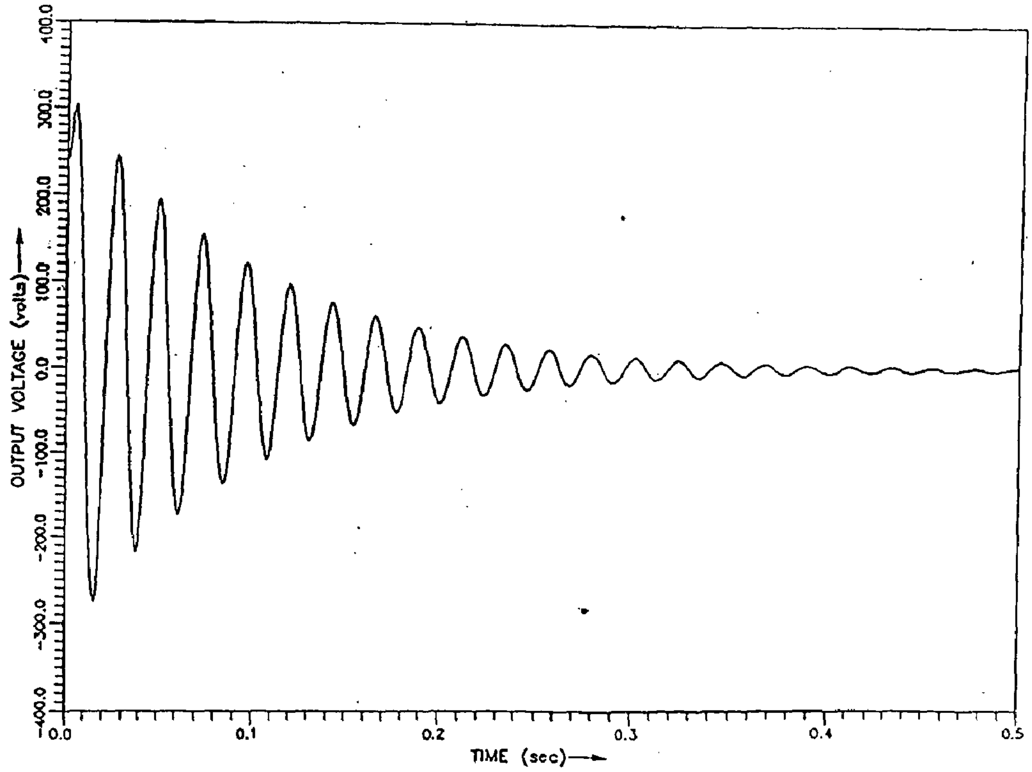


Fig.5.16 : Fall of stator terminal voltage with time when a heavy load is applied at the stator terminals

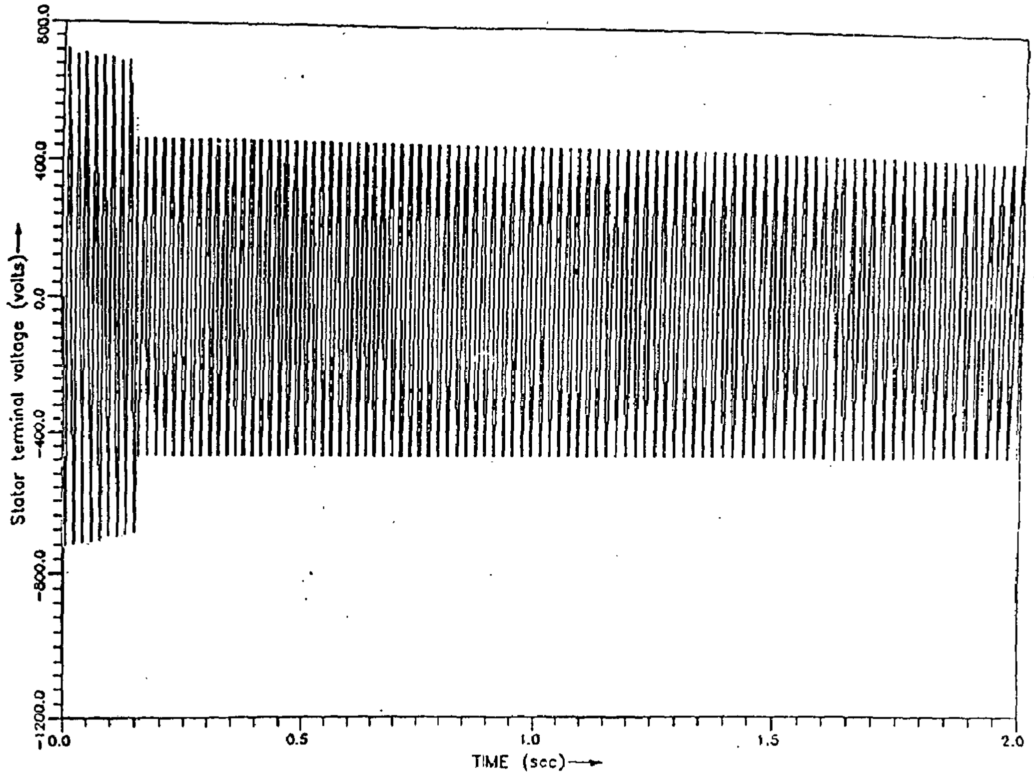


Fig.5.17 : Variation of stator terminal voltage with time under rotor flux orientation control

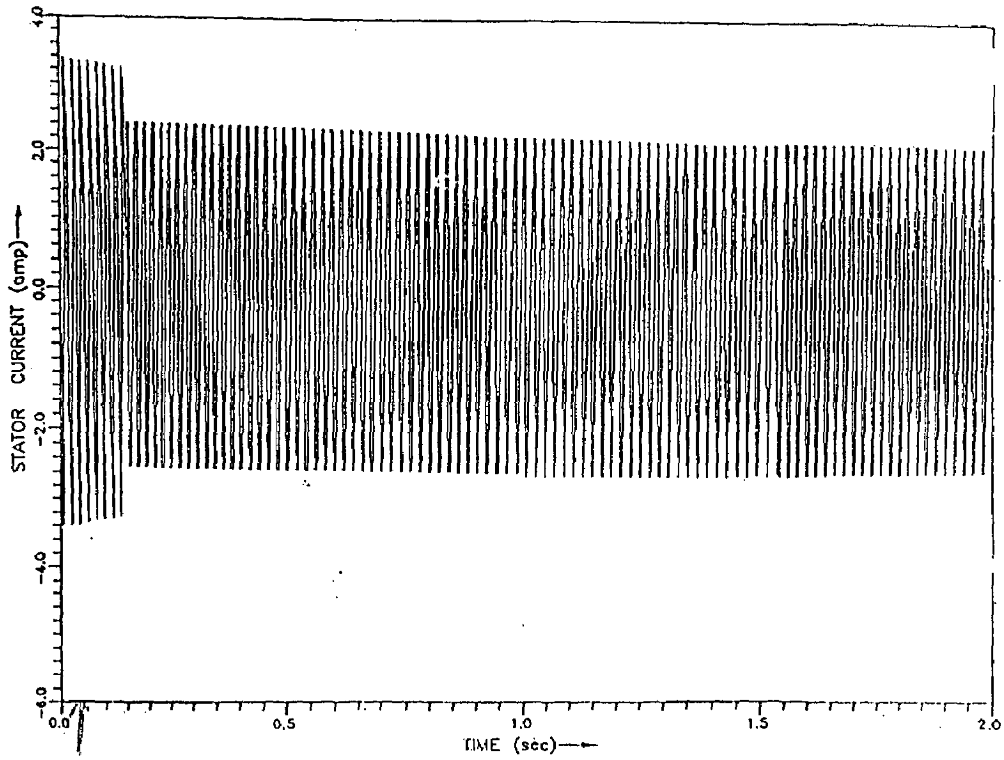


Fig.5.18 : Variation of stator current with time under rotor flux orientation control

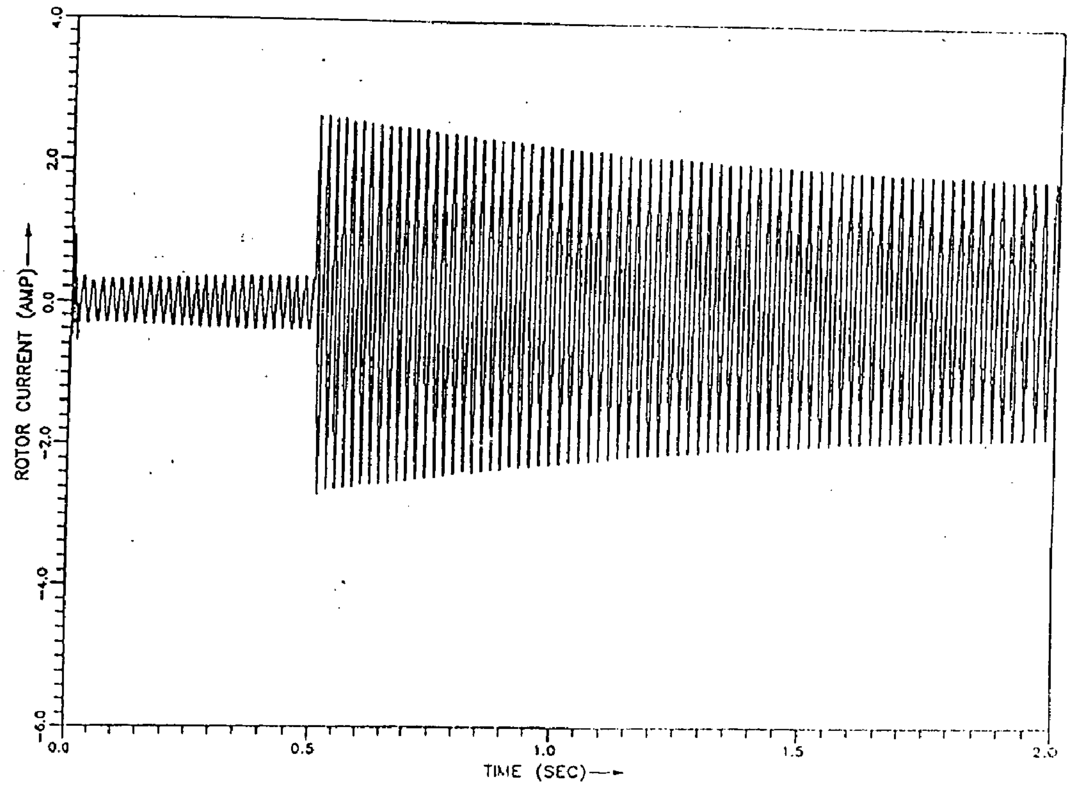


Fig.5.19 : Variation of rotor current with time under rotor flux orientation control

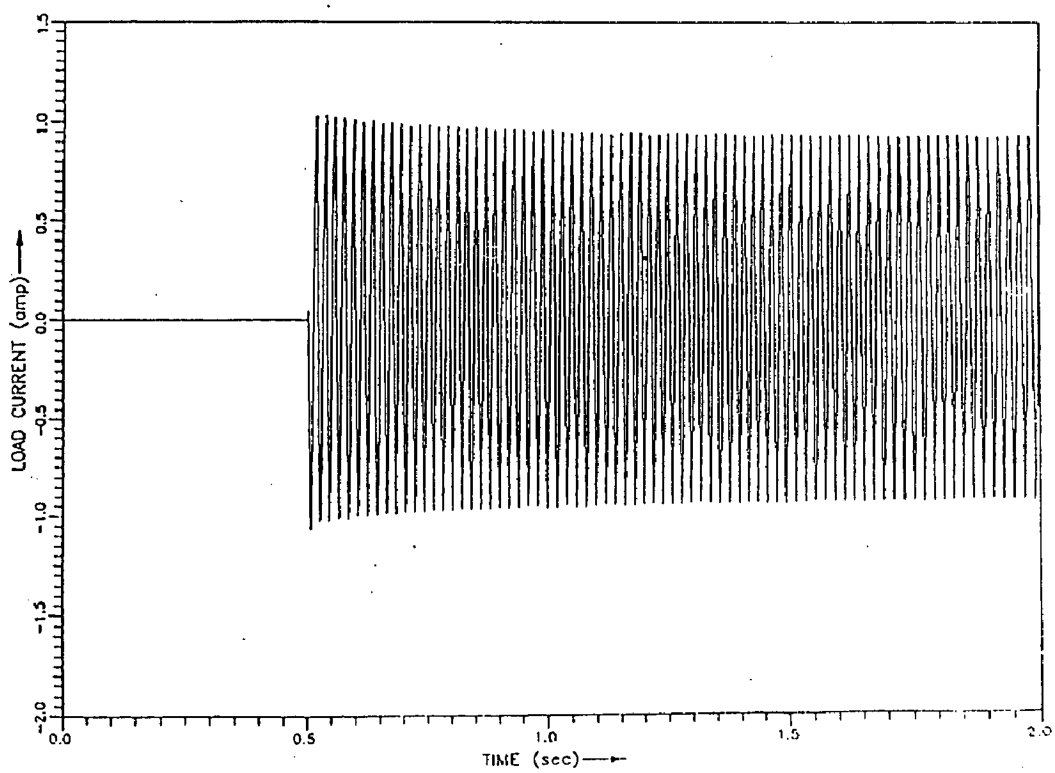


Fig.5.20 : Variation of load current with time under rotor flux orientation control

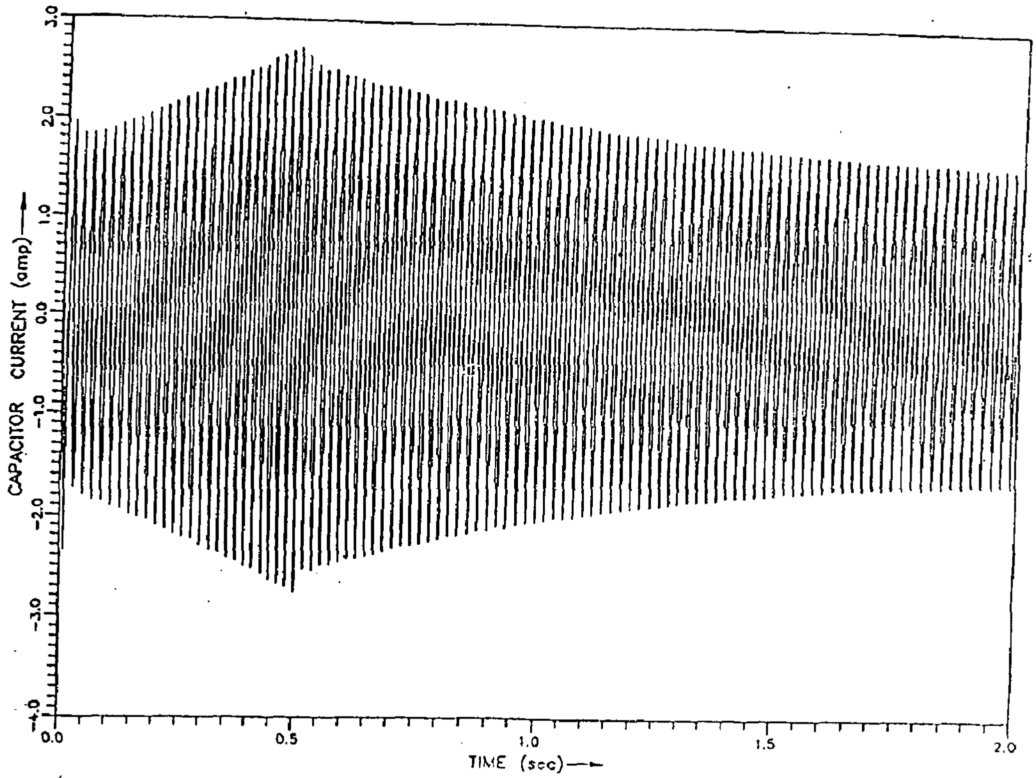


Fig.5.21 : Variation of capacitor current with time under rotor flux orientation control

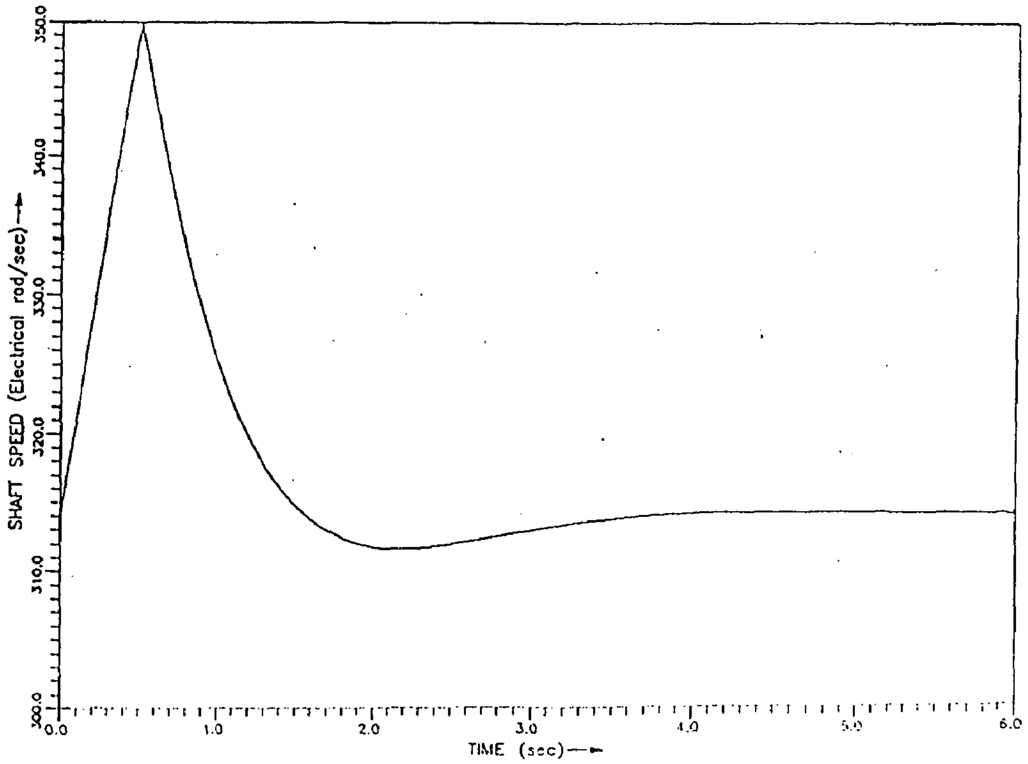


Fig.5.22 : Variation of shaft speed with time under rotor flux orientation control

CHAPTER - 6

CONCLUSION AND SCOPE FOR FUTURE WORK

In the present work, an analytical technique has been developed for the transient analysis of a capacitor self-excited stand-alone induction generator and static reactive power compensators for squirrel cage induction generators under rotor flux orientation control. Five cases have been studied as discussed before. A step by step numerical technique was used to solve the transient equations. The flowcharts and the computer program algorithm for the above cases are given. The computed results were discussed in chapter 5 while dealing with result and discussion. It was observed that in the first two cases, the machine parameters like stator current, rotor current, shaft speed etc. settled back to initial set value after dieing out of the transients thus verifying the validity of the theory developed. In other cases they attained the expected steady-state values.

The mechanical torque supplied by a prime mover to the induction generator was assumed to be constant and saturation dependent coefficients are also assumed to be constant and the transient calculations were carried out. The control of the induction generator is executed using rotor flux oriented control principles.

The present analysis was carried out both without using the effect of a voltage regulator in first four cases and in the last case the control of the voltage is carried out by using the reactive power compensator of VSI type and the control of the compensator is achieved using rotor flux oriented control principles. Here the analysis is done only for the speed variation in the base speed and field weakening region. Thus the generator is operating under variable rotor flux condition, which means that the degree of main flux saturation in the generator will vary.

SCOPE FOR FUTURE WORK

The saturation adaptive rotor flux estimator is the recent method by which the rotor flux build up is very fast and that estimator at all times correctly predicts the values of the rotor flux. This initiates a detailed and thorough studies about the various rotor flux estimator to have a optimum efficiency in terms of performance and cost.

REFERENCES

1. Elder, J.M., Boys, J.T. and Prof. Woodward, J.L., "Self-excited induction machines as low cost generator", IEE Proceedings, Part-C, Vol.131, No.2, March 1984, pp.33-41.

2. John R. Parsons, J.R., "Co-generation application of induction generator", IEEE Trans, IA, Vol.IA-20, No.3, May/June, 1984, pp.497-503.

3. Singh, S.P., Bhim Singh, Jain, M.P., "Performance characteristic and optimum utilization of a cage machine as capacitor excited induction generator", IEEE Transaction on Energy Conversion, Vol.5, No.4, Dec. 1990, pp.679-684.

4. Melkebeek, J.A.A., 'Magnetizing field saturation and dynamic behaviour of induction machines Part-2: stability limits of a voltage fed induction motor and of a self-excited induction generator", IEE Proceedings, Part-B, Vol.130, No.1, January, 1983, pp.10-17.

5. Melkebeek, J.A.A. and Novotony, D.W., "Small signal dynamic analysis of regeneration and self excitation in induction machines", Electric Machines and Power System, Vol.8, No.4-5, July-Oct., 1983, pp.259-275.

6. Prof. Arrillaga, J. and Watson, D.B., "Static power conversion from self-excited induction generator", IEE Proceedings, Vol.125, No.8, August, 1978, pp.743-746.

7. Bolton, H.R. and Nicodemou, V.C., "Operation of self-excited generator for wind mill applications", Proceedings IEE, Vol.126, No.9, September, 1979, pp.815-820.

8. Watson, D.B., Arrillaga, J. and Densem, T., "Controllable D.C. power supply from wind driven self-excited induction machines", Proceedings IEE, Vol.126, No.12, Dec., 1979, pp.1245-1298.

9. Novotony, D.W., Gritter, D.J. and Studmann, G.H., "Self-excitation in inverter driven induction machines", IEEE Trans. PAS, Vol:PAS-96, No.4, July/August, 1977, pp.1117-1125.

10. Hallenius, K.E., Vas, P., Brown, J.E., "The analysis of a saturated self-excited a synchronous generator", IEEE Transactions on Energy Conversion, 1991, Vol.EC-6, No.2, pp.336-341.

11. Natarajan, K., Shraf, A.M., Sivakumar, S., Naganathan, S., "Modelling and control design for wind energy power conversion scheme using self-excited induction generator", IEEE Transactions on Energy Conversion, Vol.EC-2, No.3, September, 1987, pp.605-512.

12. Grantham, C., Sutanto, D., Mismil, B., "Steady-state and transient analysis of self-excited induction generators", IEE Proceedings, Vol.136, Part-B, No.2, March, 1989, pp.61-68.

'3. Liao, Y.W., E. Levi, "Modelling and simulation of a stand-alone induction generator with rotor flux oriented control", Electric Power System Research I(46), 1998.

14. Levi E., "A unified approach to main flux saturation modelling in d-q axis model of induction machines, IEEE Trans. Energy Conversion, 10(3), 1995, pp.455-461.

15. Lipo, T.A. & Consoli, A., "Modelling & simulation of induction motors with saturable leakage reactance", IEEE Trans. Ind. Appl., IA-20, 1984, pp.180-189.

16. Hind Marsh, "Theory of alternating current machinery", pp.355-362.

APPENDIX - A

A.1 D-PARTITION METHOD

This method is also known as D-decomposition method. The method provides a means for determining the region of stability in the plane of a specified parameter or two parameters. In the present work the stability boundary has been plotted in the plane. Of two parameters at a time. This region of stability is also known as Vishnegradskii diagram. The V-diagram may thus be obtained by constructing the D-partition of the plane of the two real parameters, i.e., the plane section of the D-partition of the parameter space.

Let us suppose that the coefficients of the characteristic equation of the system.

$$a_o p^n + a_1 p^{n-1} + a_2 p^{n-2} + \ldots + a_n = 0$$

depend on two parameters k_1, and k_2 and let us restrict ourselves to the case when these parameters enter into the equation linearly, so that this equation can be reduced to the form -

$$k_1 S(p) + k_2 Q(p) + R(p) = 0$$

Putting further p=jω and separating real and imaginary parts, we obtain -

$$k_1 S(j\omega) + k_2 Q(j\omega) + R(j\omega) = V(\omega) + ju(\omega) = 0$$

In the general case both function u(ω) and V(ω) depend not only on ω, but also on the two parameters k_1 and k_2. In order to construct the boundary of the D-partition it is necessary to determine k_1 and k_2 for each ω, by solving simultaneously the two equations.

$$u(\omega) = 0 \qquad \text{and} \qquad v(\omega) = 0$$

If in each of them we separate the terms containing k_1 and k_2 then a set of two equations with two unknowns are obtained as follows,

$$u(\omega) = k_1 S_1(\omega) + k_2 Q_1(\omega) + R_1(\omega) = 0$$

$$v(\omega) = k_1 S_2(\omega) + k_2 Q_2(\omega) + R_2(\omega) = 0$$

Solving this set of two linear algebraic equations with respect to k_1 and k_2 for each value of ω, we can obtain,

$$k_1 = \frac{\begin{vmatrix} -R_1 & Q_1 \\ -R_2 & Q_2 \end{vmatrix}}{\begin{vmatrix} S_1 & Q_1 \\ S_2 & Q_2 \end{vmatrix}} = \frac{-R_1Q_2 + R_2Q_2}{S_1Q_2 - S_2Q_1}$$

and $k_2 = \dfrac{\begin{vmatrix} S_1 & R_1 \\ S_2 & R_2 \end{vmatrix}}{\begin{vmatrix} S_1 & Q_1 \\ S_2 & Q_2 \end{vmatrix}} = \dfrac{-S_1R_2 + S_2R_1}{S_1Q_2 - S_2Q_1}$

The equations determine one value of k_1 and k_2 for each ω only when these equations are simultaneous and independent. If for some value of ω the numerator and denominator of above equations become zero, then for this value of ω one of the equations $u(\omega)=0$ or $V(\omega)=0$ is a consequence of the other, and this value of ω not a point but a straight line in the plane of k_1 and k_2 is obtained. In this case, either of the equation $u(\omega)=0$ or $V(\omega)=0$ is the equation of straight line when this value of ω is substituted.

If the coefficient of the highest term of the characteristic equation depends on the parameters k_1 and k_2, then, by equating this coefficient to zero, the equation of another straight line corresponding to $\omega=\infty$ is obtained. These straight lines are called singular special lines.

In order to shade the boundary of the D-partition boundary one must move along the boundary in the direction of ω increasing, and shade it on the left side of those points for which $D > 0$ and on the right side for those points for which $D < 0$.

Where $D = \begin{vmatrix} S_1 & Q_1 \\ S_2 & Q_2 \end{vmatrix}$

Usually this curve is traversed twice : once when ω goes from $-\infty$ to 0, and then when it changes from 0 to ∞, but it is shaded both times on the same side, since usually the sign of D changes for $\omega > 0$ and $\omega < 0$. Near the point of intersection of the curve and the straight line (ω being same at intersection) their shaded sides must be directed towards one another.

The possible zone is determined as the inner most region in the sense of shading. To ensure that the possible stable zone is a stable zone, a point check for stability in the zone may be done by the frequency scanning technique.

A.2 FREQUENCY SCANNING TECHNIQUE

Let $D(p) = 0$

be the characteristic equation of the system, where D(p) may be a polynomial in p or may include hyperbolic functions of p. The method consists of finding a frequency ω ($p=j\omega$), where system parameters would satisfy the above equation. Frequency trajectories which are the result of plotting the imaginary part of $D(j\omega)$ against its real part as frequency is varied from zero to infinity, are drawn. The frequency trajectory along with its mirror image is shaded on the left side for $\omega = -\infty$ to $\omega = \infty$. If the origin is contained in the inner most region (in the sense of shading) the system is stable.

APPENDIX - B

The induction generator selected for simulation has specification as follows :

INDUCTION MACHINE

Supply available	-	3-ϕ a.c., 415 V, 50 Hz, Δsquirrel cage rotor
Power	-	3.7 kw
Current	-	7.1 amp.
R_s	-	4.8 Ω
R_r	-	4.8 Ω
L_{ls}	-	0.029062
L_{lr}	-	0.029062
L_m	-	0.969413
J	-	0.2068
B	-	0.011
H	-	0.5
N	-	4

PRIME MOVER (SYNCHRONOUS MOTOR)

3 - ϕ, 1500 rpm, 50 H, 5 h.p.

RELATION BETWEEN MAGNITIZING INDUCTANCE AND MAGNETIZING CURRENT

(i) $L_m = \dfrac{3.720}{i_m + 2.734}$; $(i_m < 0.903)$

(ii) $L_m = \dfrac{2.245}{i_m + 1.292}$; $(1.674 > i_m > 0.903)$

(iii) $L_m = \dfrac{1.902}{i_m + 0.837}$; $(i_m > 1.674)$