PERFORMANCE ANALYSIS OF SERIES COMPENSATED THREE PHASE SELF EXCITED INDUCTION GENERATOR

A DISSERTATION
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IN
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(Power Apparatus and Systems)

By

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Dedicated to
My Wife
Poonam

CERTIFICATE

Certified that the thesis entitled **"Performance Analysis of Series Compensated Three Phase Self – Excited Induction Generator"**, which is being submitted by **Mr. Chandra Prakash Upadhayay** in partial fulfillment for the award of degree of **"Master of Engineering" in Electrical Engineering (Power Apparatus and Systems)**, Department of Electrical Engineering is a record of the students own work carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted for the award of any other degree.

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ABSTRACT

The thesis presents the investigation of phenomenon of capacitor self excitation in three phase cage rotor induction generator. Detailed analytical model has been analyzed using appropriate equivalent circuit. Parameter estimation through experimentation including saturation characteristics of induction generator has been carried out. Performance evaluation of the test machine for given combination of speed, load and capacitors has been carried out. Predicted and experimental results are compared for performance improvement. Thesis presents very important results when SEIG is feeding the R –L load. Various performance parameters has been identified to revolve out a suitable practical system.

The analysis is also extended to transient modeling dq- model equations. Different analytical methods uses as Neuton – Rapshon and Runge – Kutta methods used. Detailed experiments under different heads such as: –

- Initiation of voltage build up.
- Load perturbation under balanced and unbalanced loading conditions has been carried out.

The thesis can be considered to be significant and relevant effort in taking the concept of capacitor self excited Induction generator to a practicable reality for use in the field.

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3 TRANSIENT ANALYSIS OF THREE PHASE SERIES COMPENSATED SEIG

Chapter - I

INTRODUCTION

1.1 GENERAL

The demand of electrical energy has been rapidly increasing in India after independence, this is attributed to large scale use of electric energy for industrial, agricultural and traction purposes.

In our country, the major sources of electrical energy are fossil fuels and water. The present contribution of power generation by different sources are as under.

Thermal Plants	61.0%
Hydro Plants	25.50%
Gas Plants	9.50%
Nuclear Plants	2.50%
Diesel Plants	0.50%
Wind	0.65%
Solar	0.35%

Since, electrical energy does not occur naturally in applicable form and it cannot be stored in usefully large quantities. Therefore, it must be generated continuously to meet the power demand at all times. An efficient and convenient way to generate electric power is by conversion of mechanical power into electrical form through rotating devices called a generator.

Fast depletion of conventional sources of energy have drawn the attention of scientists and engineers towards the use of non conventional energy sources like wind, solar, small hydro, biomass, tidal etc. Induction generators are found to be suitable for generating electricity from renewable energy sources because of its distinct advantages, like robust construction, low cost, no synchronization, no hunting and inherent short circuit protection etc.

A Self – excited induction generator (SEIG) on operates the principle of capacitor self excitation of induction machine. An appropriate capacitor bank is connected across the terminals of an externally driven induction generator, a voltage is developed across its terminals. The residual magnetism in the rotor initiates voltage build up which is augmented by the capacitor current to cause a continuous rise in the voltage. A steady state voltage results due to the magnetic saturation, which balances the capacitor and SEIG voltage.

Since more than a centaury, when Thomas Elva Edison developed an electric generator, engineers continually strived and successfully reduced the size and revised upwards the efficiencies of electric machines by use of improved material and optimal designing it.

1.2 DEVELOPMENTS IN SIEG

Induction generators have same construction as squirrel cage induction motor, in fact all the induction motors can be operated very effectively as induction generators by driving them at a speed greater than synchronous speed. Obviously, the self excited induction generators are used to derive the electrical loads of static as well dynamic nature.

In induction generator application, however the machine is not started as a motor, and hence does not require a high starting torque. Induction generators are generally designed with lower resistance values to provide a lower slip and high efficiency.

In India most of SEIG are available up to 200 kW range, which are used in costal areas where wind energy is available. The maximum capacity of SEIG available in the world in 10MW in USA but that creates a vibrating problem up to 1 km periphery.

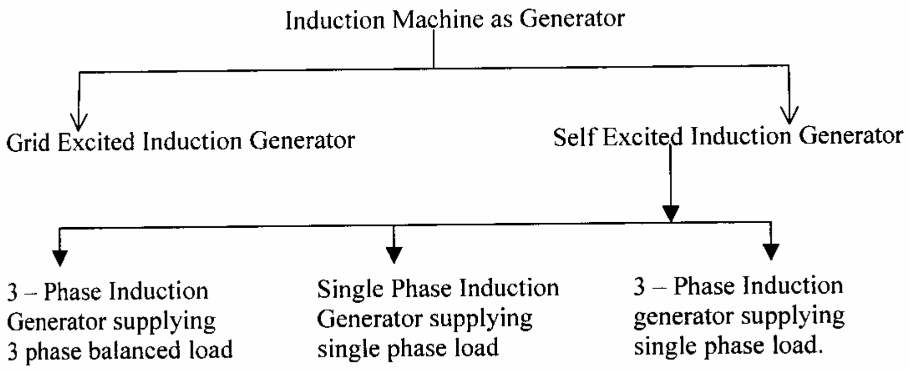
Induction generators are to be more suitable for operation by wind turbines, hydraulic turbines, and gas engines powered by natural gas or bio gas. They can range in size from a few kilo watt to 10MW or higher and are used extensively in co generation operations.

Co-generation is the sequential production of two forms of energy, usually steam for process operation and electricity for plant use and for sale to other utilities. The major problem with SEIG being experienced is its poor voltage and frequency regulation with continuously variable loads. Several methods for voltage and frequency regulation of SEIG Such as switched capacitor scheme, load controller, static VAR compensator (SVC) and static compensator (SATCOM) have been already reported in the literature []. A switched capacitor scheme provides variable VAR to SEIG with variation in load. However, due to step variation in capacitors it is able to provide the regulation in discrete steps. A load controller ensures single point operator of SEIG by balancing the real power generated by SEIG and power consumed in main consumer load through a controlled dummy load. Static reactive power compensators such as SVC and STATECOM regulates the voltage of SEIG by providing continuously variable reactive power, but they require complex and costly control circuits. However, as these compensator provides highly improved performance characteristics of SEIG with varying loads, their advantages for voltage regulation of SEIG out weight the higher cost.

1.3 TYPES OF INDUCTION GENERATORS

Induction generators are increasingly being preferred over conventional alternator (Synchronous generators) in power generation using renewable energy sources due to its lesser overall maintenance, operational simplicity, and lower unit cost.

Following classification presents brief overview of application of induction machine as generator.



1.3.1 GRID EXCITED INDUCTION GENERATOR

When an induction machine is connected to conventional utilities supply and its rotor is driven at above synchronous speed, so that the slip becomes negative $n_r > n_s$, a torque is supplied to the rotor rather than by rotor and the machine acts as generator, supplying power to the AC networks. However it still takes its magnetizing current from the supply in order to create the rotating magnetic field, just as it was a motor. The full load power output achieved at a slip of similar value but negative to the full load motoring slip.

$$S = \frac{N_s - N_r}{N_s} \tag{1.1}$$

Where S is negative as $N_r > N_s$. Here, S is slip, N_s is Synchronous speed, and N_r is the speed or rotor

With large number of wind energy conversion systems established in recent years in our country, the utility grid is facing a severe problem of poor power factor at low wind speed. This is major draw back of such induction generators as it demands. Significant amount of reactive power from the grid, hence the power factor is low at light load condition i.e. at reduced wind speed. Generally, there are two methods used to improve the power factor of grid connected induction generator

(i) Fixed capacitor method

(ii) A.C. Voltage controllers.

1.3.2 SELF EXCITED INDUCTION GENERATOR

The build up of voltage in an induction generator, that is isolated from other power sources, requires the use of capacitors in parallel with stator windings. The capacitors provide the magnetizing current, that is necessary for the build up of a rotating field. Induction generators that do not depend on the power system to establish rotating magnetic field are called self excited induction generators (SEIG). The block diagram of SEIG is shown in Fig. 1.1. An externally driven 3 – phase induction motor will generate EMF in its windings if a 3 – phase capacitor bank of sufficient magnitude is connected across its terminals. The EMF so generated keeps on rising till it gets arrested due to magnetic saturation in the machine. This voltage continues to exist as long the appropriate values of speed and capacitance are maintained. The phenomenon is termed as 'capacitor self excitation of an induction motor', as the capacitor provide the excitation (VAR) requirements of the machine. A capacitor self excited induction generator offers certain advantages over the conventional synchronous generators as source of isolated power supply such as reduced unit cost, brush less rotor (squirrel cage construction), absence of separate D.C. source and ease of maintenance.

The conventional induction generator can be used only in the presence of a gird where as the capacitor excited generator can be used in isolated areas, where the grid is not available. Recently isolated small hydro stations have been thought of as viable supplement to the growing energy requirements in many countries including India. In such cases capacitor excited single unit induction generator would be ideal to fulfill the local needs of energy.

For self excitation of induction generator, magnetizing current is needed which is obtained from capacitors. Therefore in order to obtain the required operating voltage at desired frequency the amount of capacitance must be chosen carefully. For self excitation sufficient ruminant magnetism must be present in the rotor. Ruminant magnetism is the initial magnetism present in the rotor steel, it is generally sufficient to produce a small voltage, at predefined speed (for desired frequency) without connected any capacitance across it: however the ruminant magnetism can be increased by connecting a D.C. supply for a few second across any two terminals of the machine terminal before running the machine up to the rated speed.

1.4 PHENOEMNON OF SELF EXCITATION

A simple way to understand the basic operation of a self excited induction generator (stand alone induction generator) is to represent the machine by its magnetizing reactance. The simplified equivalent circuit is show in Fig. 1.2. It is accurate method of representation for the purpose of determining capacitor requirements. When the shaft rotates, current begins to flow due to remnant magnetism present in the rotor. The capacitor current I_c will be equal to the magnetizing current I_m and the machine and capacitors will act as resonant circuit at an angular frequency ω, fixed by the shaft speed of the machine, provided that sufficient capacitance is present in it, the current will rapidly increase until stable operation is reached, when the impendence of the capacitor equal to the magnetizing impedance as given by equation (1.2)

$$\frac{1}{\omega C} = \omega.Lm \qquad (1.2)$$

Stable operation occurs because the magnetizing inductance is a non – linear function of magnetizing current, due to magnetic saturation of the rotor and stator steel. Provided that sufficient capacitance is connected, the voltage against the stator current characteristic is shown in Fig. 1.3. This is the operating point of induction generator. Increasing the capacitance will increase the operating voltage, but since more current flows into the machine additional power will be lost as heat dissipation in the stator winding. The purpose of series compensation is to regulate the terminal voltage with load and to improve the loading capability of the generator.

When the SEIG is operating under no load condition, there will not be any current through the series capacitor (C_{se}) and only shunt capacitor (C_{sh}) will be effective in the circuit. Therefore, effect of C_{sh} is reflected on the no load performance of the SEIG. But When loaded, both shunt and series capacitors will be effective. Hence, proper value of these elements can be chosen by first studying the variation of no load terminal voltage with C_{sh}. Having chosen a suitable value for C_{sh} from the curve, the influence of C_{se} can be studied by observing the effect of C_{se} on voltage regulation of the SEIG. Appropriate value of C_{se} can be selected from the range of values thus obtained depending upon the desired regulation and other operating constraints. Following section illustrates the procedure.

1.5 SERIES COMPENSTATED SEIG

1.5.1 SHORT SHUNT SEIG

In short shunt SEIG configuration, the stator terminals of the induction generator is first connected in parallel with the shunt excitation capacitance (C_{sh}) as shown in Fig. 1.5 by single line diagram, and then connected to the induction motor load via short shunt capacitance (C_{short}) The Schematic diagram is shown in Fig. 1.6 since the poor voltage regulation is main draw back of SEIG even at regulated speed. Short shunt SEIG provides additional VAR with load and hence better voltage regulation of the SEIG. It is self voltage regulating scheme. It is also demonstrated experimentally that it is possible to have almost of a flat load characteristic with a particular combination of capacitors connected under short shunt configuration as shown in Fig. 1.4. This eliminates any other voltage regulator since the scheme has inherent self regulating feature. For betterment of this scheme we have to select the appropriate pair of capacitors. An ideal combination of shunt and series capacitor is the one for which the load voltage can be maintained with in acceptable limits from no load to full load.

1.5.2 LONG SHUNT SEIG

In long shunt configuration the stator terminal of the induction generator is connected to the parallel connection of C_{sh} and load via long shunt capacitance (C_{Long}), as shown by single line diagram in Fig. 1.7. This configuration of SEIG also employed for simplifying the need of complex voltage regulators. It is also another way of improving voltage regulation of SEIG. This configuration can be employed to maintain the load voltage under varying load. A schematic diagram of long shunt SEIG is shown in Fig. 1.8.

1.6 CONCLUSION

In this chapter the importance, scope, applications and operation of different types of induction generators haven been described. Effect of series compensation in short shunt and long – shunt configuration are discussed in view of improving the voltage regulation and steady – state performance of the SEIG.

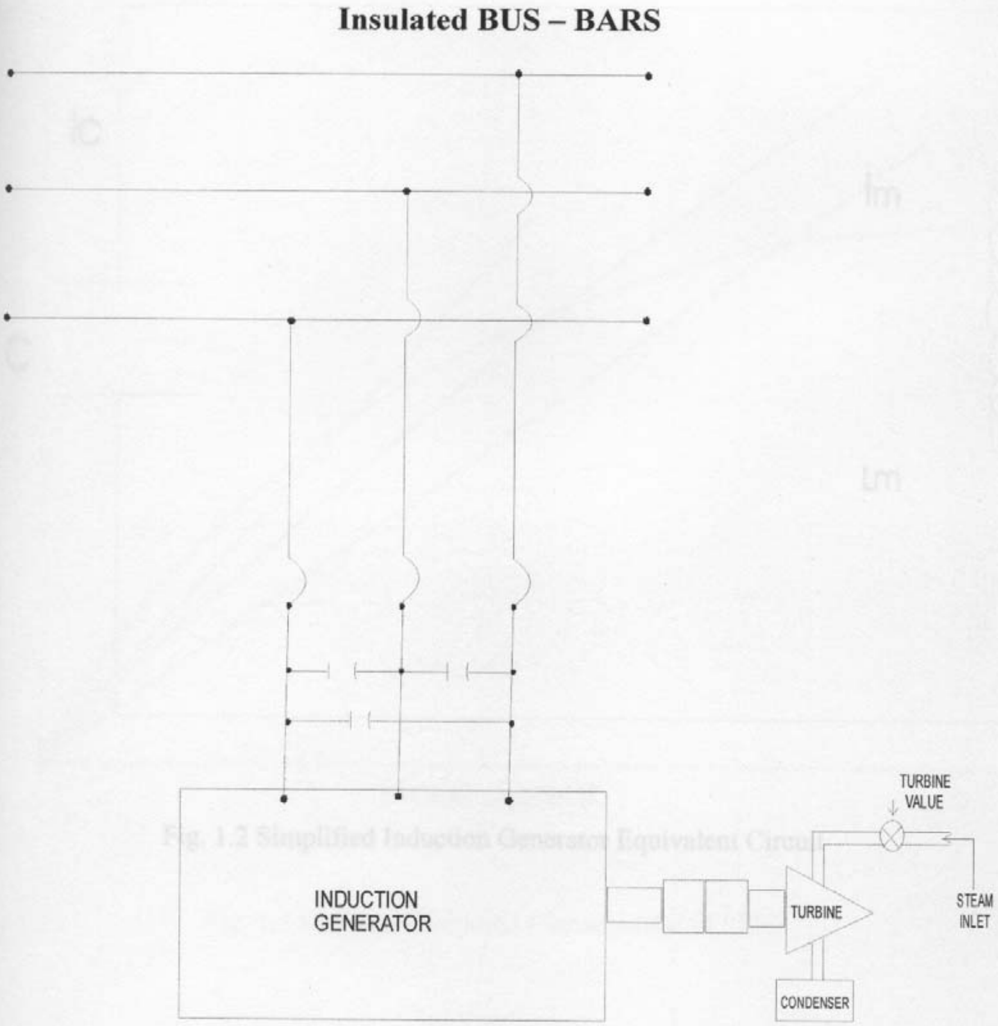


Fig. 1.1 Block Diagram of Induction Generator

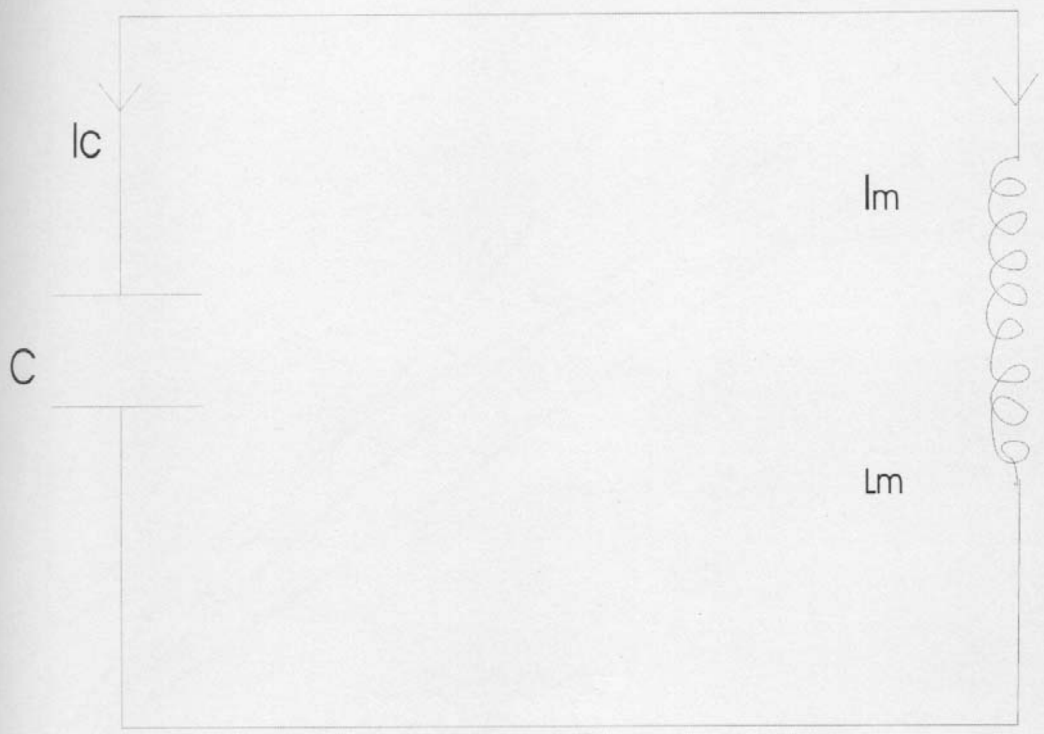


Fig. 1.2 Simplified Induction Generator Equivalent Circuit

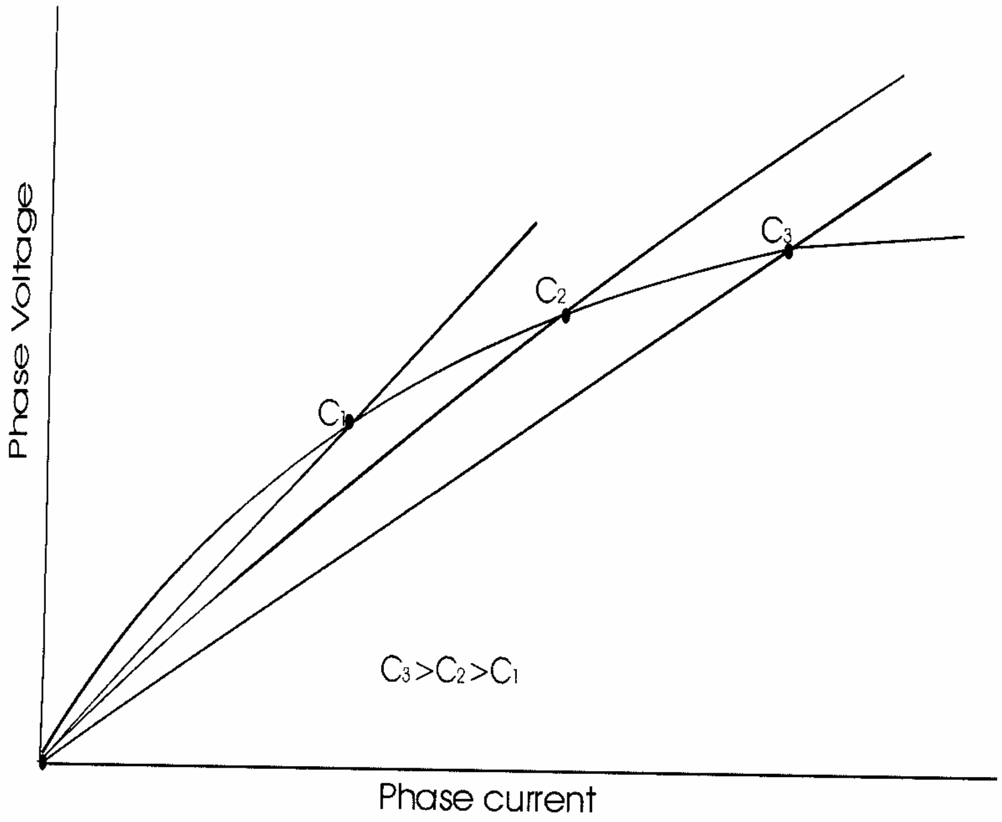


Fig. 1.3 No Load Excitation Characteristic of SEIG

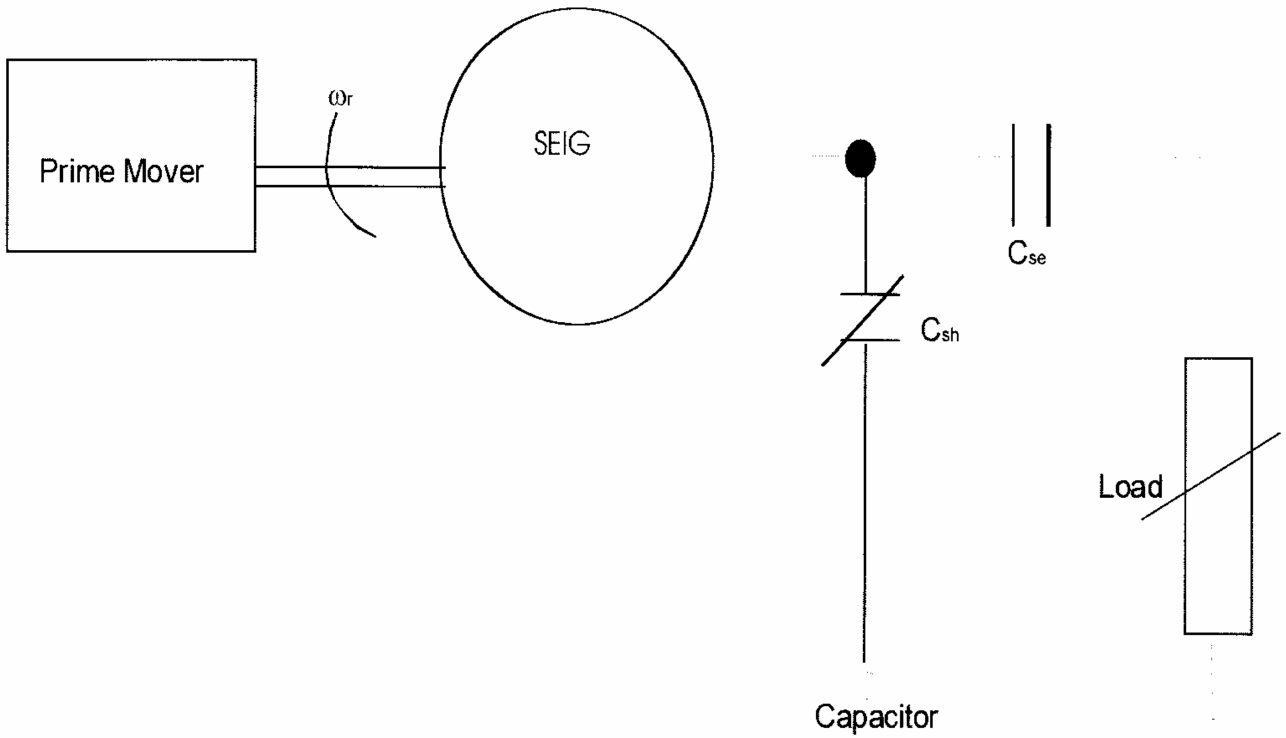


Fig. 1.4 Schematic Diagram of Self Excited Induction Generator System with Series Capacitor

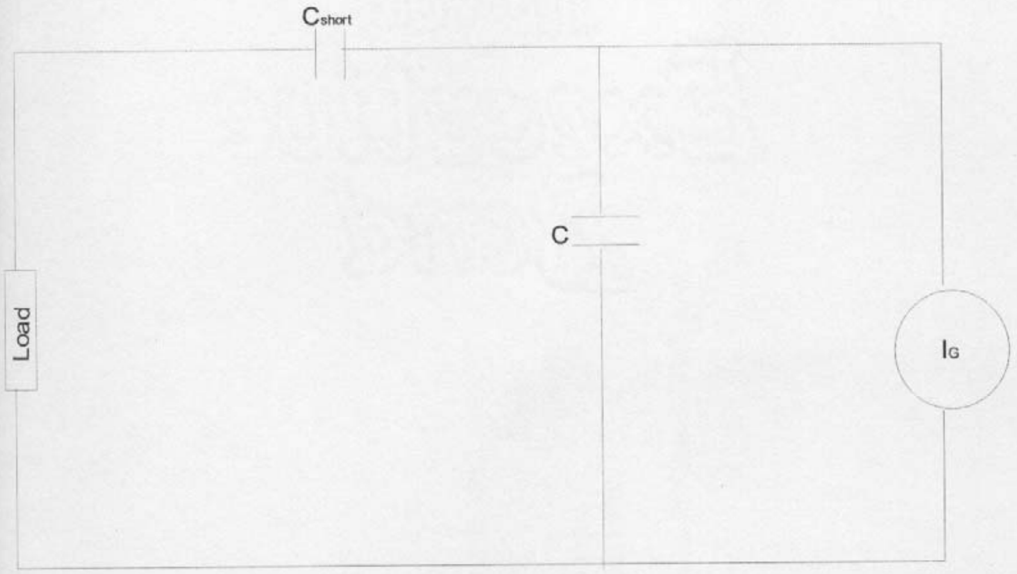


Fig.1.5 Single Line Diagram of Short Shunt SEIG

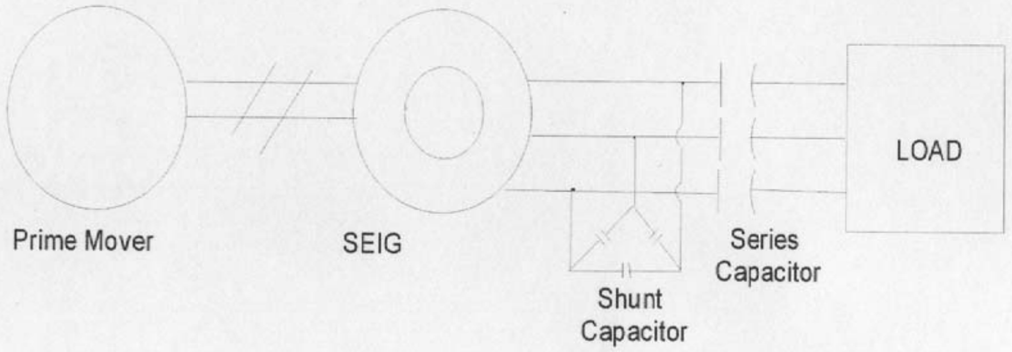


Fig. 1.6 Schematic Diagram of Three Phase Short Shunt SEIG System

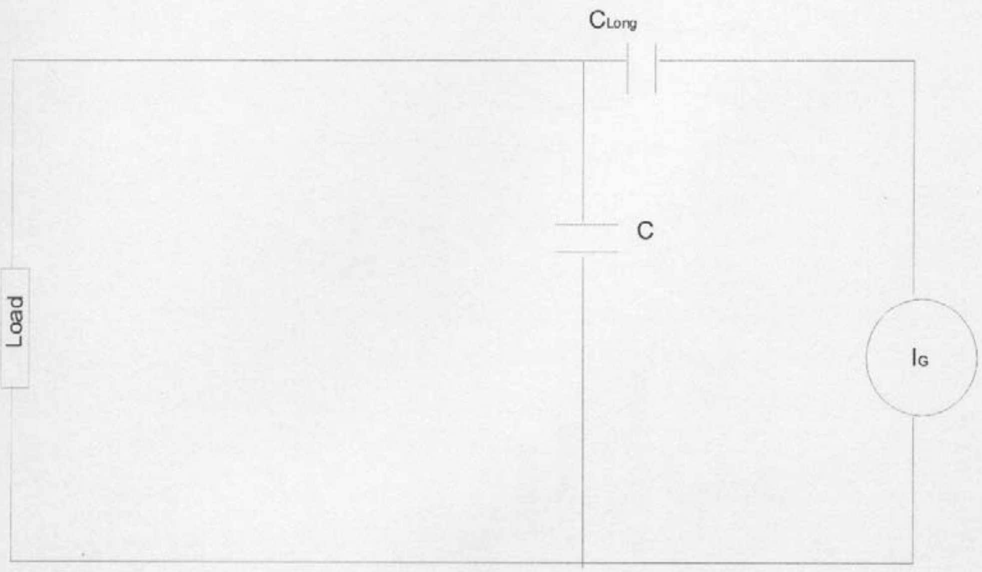


Fig. 1.7 Single Line Diagram of Long Shunt SEIG Configuration

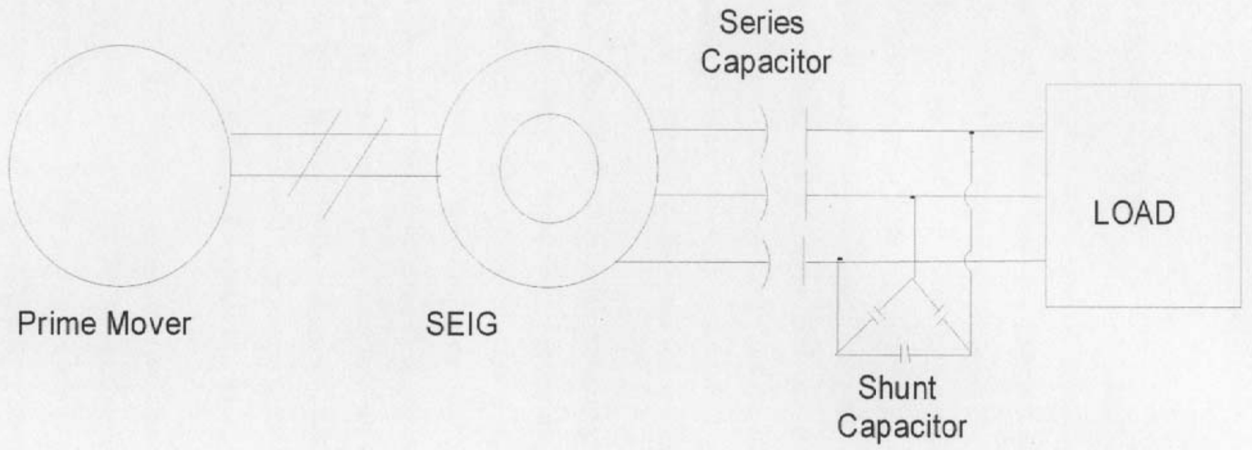


Fig. 1.8 Schematic Diagram of Three Phase Long Shunt SEIG System

Chapter – II

STEADY STATE ANALYSIS OF THREE PHASE SERIES COMPENSATED SEIG

2.1 INTRODUCTION

The rapid depletion and enhanced cost of conventional fuels have given an impetus to the self–excited induction generator as an alternative power generating source, converting power from non–conventional sources like wind, biogas, mini and micro hydro units etc. However, except for the case of portable power supply units, it is unlikely that a single generator could meet the power demand, also utilization of full potential of energy may require of many such units in parallel. When induction generators are connected to power gird controlled by large rating synchronous generators, it draws the required VAR from the bus voltage and frequency of which are determined by dynamics of the synchronous generators. Extensive studies have been carried out on the self excited induction generators in stand alone mode.

When an induction machine is connected to A.C. supply, magnetizing current flows from the supply and creates a rotating magnetic field in the machine. The rotating field cuts the short circuited rotor bars, inducing current in them. This induced current produces MMF, which is rotated at synchronous speed with respect to the stator. The interaction of the rotor field and resultant field creates torque. This torque drags the rotor round with the field, but a slightly lower speed, the small difference in speed arises because without it no current would be induced in the rotor and therefore, no torque would be produced to turn it. When a load is applied to the motor the speed difference will increase as a result, greater torque must be produced.

If the A.C. supply connected induction machine is driven at above synchronous speed, so that the slip becomes negative, a torque is supplied to rotor rather than by the rotor and the machines acts as generator, supplying power to the network. However it will takes magnetizing currents from the supply in order to create the rotating field, just as though it was a motor. The full load power output is achieved at slip similar value but negative sign to the full load motoring slip.

The magnetizing current of an induction machine can be supplied, in total or in part by capacitors. In fact, the capacitors are often fitted to large induction machines and supply connected induction generator to reduce the reactive current drawn from the supply, especially where the power supply company imposes charges for poor power factor.

The only external sources of magnetizing current in SEIG or stand alone generator are capacitors. Hence, in order to obtain the required operating voltage at desired frequency, the rating of capacitors must by chosen carefully. The sufficient remnant magnetism must be present in the rotor for build up of a voltage.

In case if there is not sufficient remnant magnetism in the rotor to excite the induction generator at rated frequency, one of the following methods are adoped for satisfactory generation.

- Increase the prime mover speed for short time as per mechanical design of the rotor.
- Increase the value of connected capacitance across the terminal for a short duration.
- Connect a D.C. supply for few second across any of the two windings of the induction generator.

Induction generators are increasingly being preferred over conventional alternators in isolated system due to its overall maintenance and operational simplicity, lower unit cost and ready availability in lower rating. The possible applications of interest are the small rural power sources for developing countries, using prime movers such as hydro turbines, wind turbines, diesel/kerosene/biogas engine etc.

Over the years, the scientist have been engaged in investigation related to analysis, design and control aspect of SEIG with a view to evolve viable standby\autonomous power generation unit by oil engines, michrohydro turbines and wind turbines. Lower unit cost, brushless rotor construction, absence of separate DC source, better stability and self protection under fault conditions are the major reason for preferring SEIG over conventional alternator in such generating units but poor voltage regulation of SEIG even at regulated speed has been a major drawback in it's application.

In rural and remote areas the population is sparsely distributed and the electric load for the purpose of lighting, heating, water pump etc are usually of single phase types. In such cases the single phase power supply is preferred to three phase.

In order to make the distribution system simple and cost effective, hydro electric generator with capacity less than 20 kW are located in remote areas may served with only a single phase line, the induction generator used for power generation from renewable sources of energy, would be relatively small rating, size and cost (less than 20 kW). However, single phase induction generators are not easily available in teagral kW ratings. Moreover, three phase induction generators have higher efficiency and less cost, than an equivalent sized single phase generator. Due to these reason it would be desirable to use a three phase induction generator, as a three phase SEIG for a single phase power generation, but the use of three phase SEIG for supplying single phase load is an extreme case of unbalance operation causes additional losses in the equipment due to flow of negative sequence component of current. Therefore the load that can be pulled on an unbalanced three phase SEIG must be evaluated for a constant load, as the current is reduced in one phase, the current in other phase increase. Under this condition a three phase induction generator would have to be de – rated in order to keep the temperature of the generator with in allowable limits. The vibration problem also appears during unbalance operation of the machines therefore it is considered desirable to balance the SEIG system supplying the single phase load.

Several voltage regulating schemes have been tried to achieve this aim. These schemes mostly utilize switch capacitor or variable inductor or saturable core reactor based close loop schemes using relay/contactors or semiconductor switches, but complex system configuration, intricate control circuit design and operational problem like harmonics and switching transients, associated with voltage regulator vitiate the very advantage of recommending induction generators for autonomous power generation.

Inclusion of additional series capacitance to provide additional VAR with load is one of attractive options to improve the voltage regulation of SEIG. It is also demonstrated experimentally that it is possible to have almost a flat load characteristic with a particular combination of capacitors connected under short circuit configuration.

2.2 CIRCUIT CONFIGURATION AND EQUIVALENT CIRCUIT

The and equivalent circuit diagram for steady state performance has shown in Fig. 2.1 (a) and Fig. 2.1 (b) shows the single line diagram of SEIG feeding inductive load. An equivalent circuit diagram of SEIG with series capacitor in short – shunt configuration is shown in Fig. 2.2 (a). Fig. 2.2 (b) shows the equivalent circuit of long–shunt SEIG. Fig. 2.2 (c) shows the long shunt SEIG single line diagram.

2.3 STEADY STATE MODELING EQUATIONS

To represent the steady state model of SEIG following relations have been developed.

2.3.1 STEADY STATE VOLTAGE VS SPEED RELATIONSHIP (NO LOAD)

In order to obtain the voltage Vs speed relation at no load, the simplified equivalent circuit of induction generator shown in Fig. 2.3 is used.

In the circuit the stator resistance, stator and rotor leakage, reactances are very small and negligible compared to $\frac{R_r}{s}$ and X_m respectively. The load current is zero. Hence the equivalent admittance looking into the circuit is zero.

$$\left[\frac{1}{R_m}+\frac{S}{R_r}\right]+j\left[\omega C-\frac{1}{\omega L_m}\right]=0 \tag{2.1}$$

Where

R_r = Rotor resistance reflected to the stator per phase

L_m = Magnetizing inductance

R_m = Core loss resistance per phase

ω = Generated frequency

C = External excitation capacitor

equating the real and imaginary parts of equation (2.1) we get

$$S = -\frac{R_r}{R_m} \tag{2.2}$$

$$\omega = \sqrt{\frac{1}{L_m \cdot C}} \tag{2.3}$$

It is clear that slip S is low since $R_m > R_r$ for a normally constructed induction generator and the excitation of the induction generator corresponds to the resonance between the capacitor and the magnetizing inductance (L_m). If ω_m is the angular speed of rotor in (rad/sec) and P is the magnetic poles of the machines the slip is given by

$$S = 1 - \frac{\omega_m}{\frac{2}{p} \cdot \omega} \tag{2.4}$$

Substituting this value in equations (2.1), (2.2) and (2.3)

The angular speed is given as a function of per phase equivalent circuit parameter by

$$\omega_m = \left[1 + \frac{R_r}{R_m}\right] \frac{2}{P} \cdot \sqrt{\frac{1}{L_m \cdot C}} \tag{2.5}$$

Considering $\frac{R_r}{R_m} = 0$, than equation (2.5) can be simplified as

$$\omega_m = \frac{2}{P} \cdot \sqrt{\frac{1}{L_m \cdot C}} \tag{2.6}$$

The magnetizing inductance L_m is a function of induced voltage. The qualitative inductance V_s voltage curve is obtained from the saturation curve of the machine Fig. 2.4(a) and Fig. 2.4(b).

For a given voltage V_1 the corresponding value of magnetizing current I_m is read and magnetizing inductance L_m is obtained from

$$L_m = \frac{X_m}{\omega} = \frac{1}{\omega}\left[\frac{V}{I_m}\right] \tag{2.7}$$

At low voltage, the inductance L_m rises as voltage increases. At higher voltages, L_m decreases due to saturation. Substituting the values of the L_m, in equation (2.6) we obtain the voltage V_s speed curve of the machine as shown in Fig 2.4 (c)

It is seen from the curve, there is a region where there are two possible values of generated voltage for each values of speed. From load's criterion, the lower voltage is observable in practical application. Applying this criterion to the equation (2.1) the steady state stability condition reduced to

$$\frac{V}{I_m} > 0 \tag{2.8}$$

Thus, if the machine is gradually accelerated, The induced voltage will rises suddenly at a speed ω_1. it should be emphasized that for increasing speeds, There is region for which and then the voltage drops to zero in a abruptly way.

The following assumption are made in the steady state analysis of capacitor self excited induction generator:

(a) All the equivalent circuit parameters except the magnetizing reactance (X_m) are assumed to be constant (only the magnetizing reactance is to be affected by saturation).

(b) Core loss in the generator is neglected.

(c) MMF space harmonics and the time harmonics in the induced voltage and current wave forms are ignored.

The steady state equivalent circuit of a capacitor self excited induction generator with a R –L load is shown in Fig 2.4 (a), where

R_s, X_{ls} = Stator resistance & leakage reactance per phase

R_r, X_{lr} = Rotor resistance and leakage reactance per phase

X_m = Magnetizing Reactance
X_c = Capacitive reactance per phase
R_L, X_L = Load resistance and reactance
Z_L = Load impedance, $R_L + jX_L$
F, V = Frequency and speed in p.u.

It will be noted that under steady state, the equivalent admittance seen from the terminal of Y_m must be purely imaginary. Expresses in terms of the appropriate circuit parameters, the admittance can be stated as a function of the frequency F, and X_m

$$Y(F) = G(F) + jB(F) \tag{2.9}$$

By letting G(F) = 0, F may be dermind and subsequent substitution of F in B(F) yield X_m. This approach, which has been suggested by the researcher, is conceptually very simple and attractive.

By considering the constant speed situation in which a capacitance higher than the critical value is connected. The real part of one of the roots of equation (2.9) will be greater than zero. The other two roots will have large negative real parts signifying current components that die down rapidly. These two root lie in second quadrants. Due to self excitation the terminal voltage V_t and the air gap voltage V_g continue to increase. Eventually the principal magnetic flux path in the machine saturates, and effective magnetizing reactance X_m decreases. A_s X_m decreases the magnitude of the real part of the root which is positive will also decreases and will ultimately reach zero for a particular value of X_m. The stator voltage continues to rise as long as the real part of the root is positive. Voltage rises ceases that the real part becomes zero, and the generator is in the steady state operating condition.

2.3.2 STEADY STATE MODEL OF SHORT SHUNT SEIG

Due to requirement of dynamic reactive power (VAR) the self excited induction generators have poor voltage regulation with varying loads even at constant speeds. Fixed and varying reactive power compensators with conventional devices such as synchronous condenser, shunt capacitor, series capacitors have inherent problems like sluggish response, undue over–voltage, switching transients, sub–synchronous resonance etc.

In short shunt SEIG configuration series capacitor supplement reactive power with increase in load current and hence provides a self regulating feature for SEIG.

The equivalent circuit of short shunt SEIG shown in Fig. 2.2 (a)

In this equivalent circuit

R_s, R_r = Per phase stator and rotor resistance
X_{Ls}, X_{Lr} = Per phase stator and rotor leakage reactance
X_m = magnetizing reactance
X_{ch} = Per phase capacitive reactance of shunt capacitor, C_{sh}
X_{ce} = Per phase capacitive reactance of series capacitor, C_{se}
R_L = Per phase load resistance
F, v = *p.u.* frequency and speed
I_s, I_r, I_L = per phase stator, rotor and load current
V_L, V_m, V_g= load, machine and air gap voltages.

The magnetization characteristic of the induction generator is the prime importance in analysis of SEIG for this purpose it is required to draw the characteristic of induction generator relating to the ratio of air gap voltage (V_g) to frequency $\frac{V_g}{F}$ with the magnetizing reactance (X_m). The saturation portion of this characteristic can be linearised and expressed mathematically in the form below.

$$\frac{V_g}{F} = K_1 - K_2 X_m \tag{2.10}$$

Where, K_1 and K_2 are constant, which depends upon the design and material of the machine for the purpose of obtaining the required operating point for the given values of X_{ch} and X_{ce}, the only unknown parameters for a given speed and load are X_m and F to evaluate, These parameters, the loop equation for the currents $\overline{I_s}$ can be written as

$$\overline{I_s Z_s} = 0 \tag{2.11}$$

Where

$$\overline{Z_s} = \overline{Z}_1 + \frac{\overline{Z_{ch}}.\overline{Z_L}}{\left(\overline{Z_{ch}} + \overline{Z_L}\right)} + \frac{\overline{Z_2}.\overline{Z_m}}{\overline{Z_2} + Z_m} \tag{2.12}$$

$$\overline{Z_1} = R_s + jX_s.F, \overline{Z_{ch}} = -\frac{jX_{ch}}{F}, \tag{2.13}$$

$$\overline{Z_L} = R_L - \frac{jX_{ce}}{F} \tag{2.14}$$

$$\overline{Z_2} = \frac{R_r - F}{F - v} + jFX_r \tag{2.15}$$

$$\overline{Z_m} = jFX_m \tag{2.16}$$

Since under steady state operation of SEIG, I_s cannot be zero

$$\overline{Z_s} = 0 \tag{2.17}$$

This equation after separation into real and imaginary parts, can be rearranged into the following non – linear equations, which are function of X_m and F, denoted by $f(X_m, F)$ and $g(X_m, F)$

$$f(X_m, F) = (C_1 X_m + C_2)F^4 + (C_3 X_m + C_4)F^3 + (C_5 X_m + C_6)F^2$$
$$+ (C_7 X_m + C_8)F + (C_9 X_m + C_{10}) = 0 \tag{2.18}$$

$$g(X_m, F) = (D^1 X_m + D_2)F^3 + (D_3 X_m + D_4)F^2$$
$$+ (D_5 + X_m + D_6)F + (D_7 X_m + D_8) = 0 \tag{2.19}$$

Where, C_1, C_2, ...C_{10} and D_1, D_2... D_8 are constant

These two equations can be solves by using any of the suitable numerical techniques to obtain the values of X_m and F. Newton Raphson method has been employed in this project work to solve these equations.

After obtaining X_m and F by choosing suitable initial values V_g can be computed from equation (2.10) then the following relationship can be used to compute the generator performance at a particular load and speed.

$$\overline{I_s} = \frac{\overline{V_g}}{\overline{Z_1} + \frac{\left[\overline{Z_L}.Z_{ch}\right]}{\left[Z_L + Z_{ch}\right]}} \tag{2.20}$$

$$\overline{I_r} = \frac{\overline{Vg}}{\frac{R_r F}{(F-V)}} + jFX_r \tag{2.21}$$

$$I_L = \frac{\overline{I_s . Z_{ch}}}{\left[\overline{Z_L} + \overline{Z_{ch}}\right]} \tag{2.22}$$

$$V_m = \overline{I_L}.\overline{Z_L} \tag{2.23}$$

$$\overline{V_L} = \overline{I_L}.\overline{R_L} \tag{2.24}$$

Input power, $P_{in} = -3I_2^2 \frac{R_r F}{(F-v)}$ (2.25)

Output power, P_{out} $3I_L^2 R_L$ (2.26)

2.4 RESULT AND DISCUSSION

A standard three phase induction generator 3.7 kW, 415V, 7.6A, 4–poles delta connected with the parameters detailed in Appendix I has been considered for the present study.

(A) SELECTION OF SHUNT CAPACITANCE

The variation of no load terminal voltage with the shunt capacitance C_{sh} is shown in Fig. 2.5(a). it has been seen that V increases with C_{sh}. Appropriate value of shunt capacitance can be chosen depending on the maximum permissible voltage across the generator terminals and the voltage requirements on the part loads. As a first approximation, value of C_{sh} corresponding to no load terminal voltage equal to rated value has been considered. It is observed that for the 3.7 kW, 415V delta connected SEIG, a shunt excitation capacitance of 17μF per phase is necessary to generate rated voltage (415V) at no–load.

(B) SELECTION OF SERIES CAPACITANCE

Fig. 2.5 (b) depicts the variation of full load voltage regulation with series capacitance obtained through both experimentation and computation, here the voltage regulation is defined as the percentage change in the load voltage as the generator delivers power from zero to rated value. Usually variation of terminal voltage with load is permitted with in a specified band. Taking the permissible voltage variation of ± 6%. The range of C_{se} for this band is shown in the Fig. 2.5 (b) Hence a range of C_{se} (30 – 70 μF) is available for this selection. It reveals that there is a distinct minimum value of voltage regulation, the corresponding value of C_{se} (27 μF) is the best value as far full load voltage regulation is concerned. Further, a close agreement between computed and experimented results can be voted.

(C) EFFECT OF C_{SE} ON V_M AND I_S

It is seen that once the mathematical equations are formulated, selection of proper values of capacitive elements of short shunt SEIG for minimum regulation becomes very simple based on the procedure already explained. Having identified this method for the selection of capacitors, it is important to see how best this selection is, as far as the other relevant performance indicies of the machine are concerned.

An important criterion is that the machine should deliver needed power at desired voltage levels without exceeding the permissible electrical and magnetic loading. The effect of C_{se} on load voltage (V_L) and machine terminal voltage (V_M) is shown in Fig. 2.5 (c) it is observed that there is a rise in the value of machine terminal voltage for lower values of C_{se}, where as, higher values of C_{se} results in poor regulation.

Fig. shows the variation of winding currents with output power. It is seen that for lower value of C_{se} the power capability of the SEIG reduces since at rated winding current it can deliver less than rated power, needing the machine to be derated. Where as in the case of higher C_{se} the power capability of the SEIG increases at the cost of high capacitance and poor regulation.

2.5 CONCLUSION

This chapter presents a simplified method to study the steady state performance of series compensated (short–shunt) 3d self excited induction generator selection criterion for shunt and series and series excitation capacitors have been described. It has been observed that a suitable combination of C_{sh} and C_{se} results in improved voltage regulation teature of SEIG

It has also been found that there is close agreement between simulated and measured results. Hence the validity of the developed model is confirmed. The steady state voltage of the bus is observed to the proportional to the shunt capacitor.

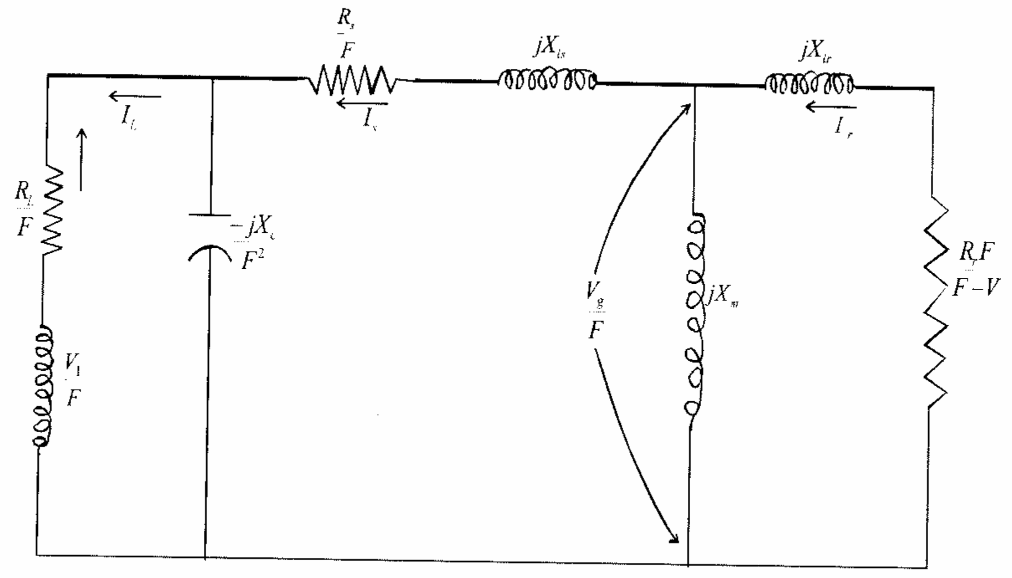


Fig. 2.1 (a) Equivalent Circuit of SEIG

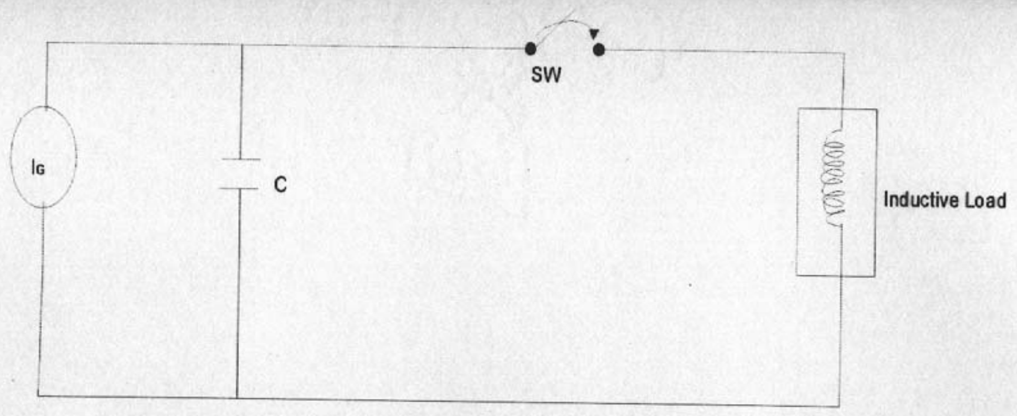


Fig. 2.1 (b) Single Line Diagram of SEIG Feeding Inductive Load

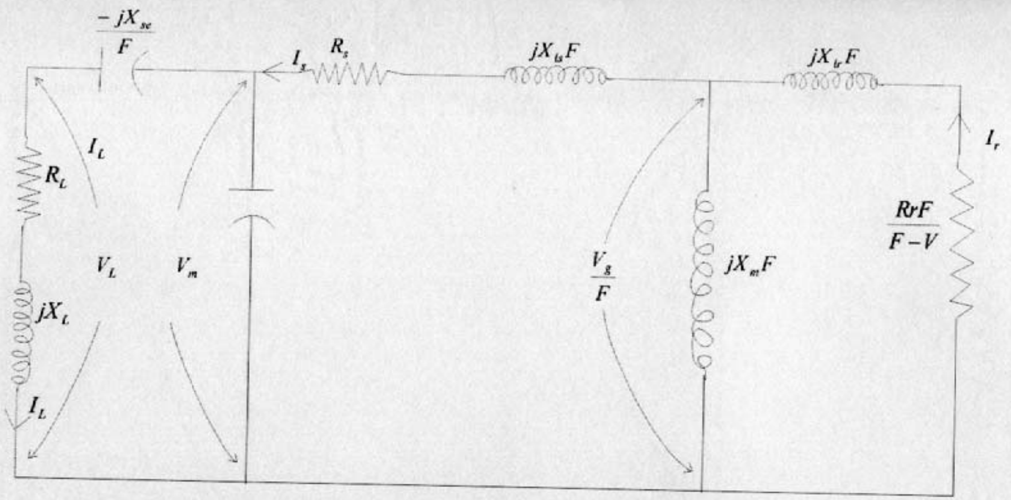


Fig. 2.2 (a) Equivalent Circuit of Short Shunt SEIG

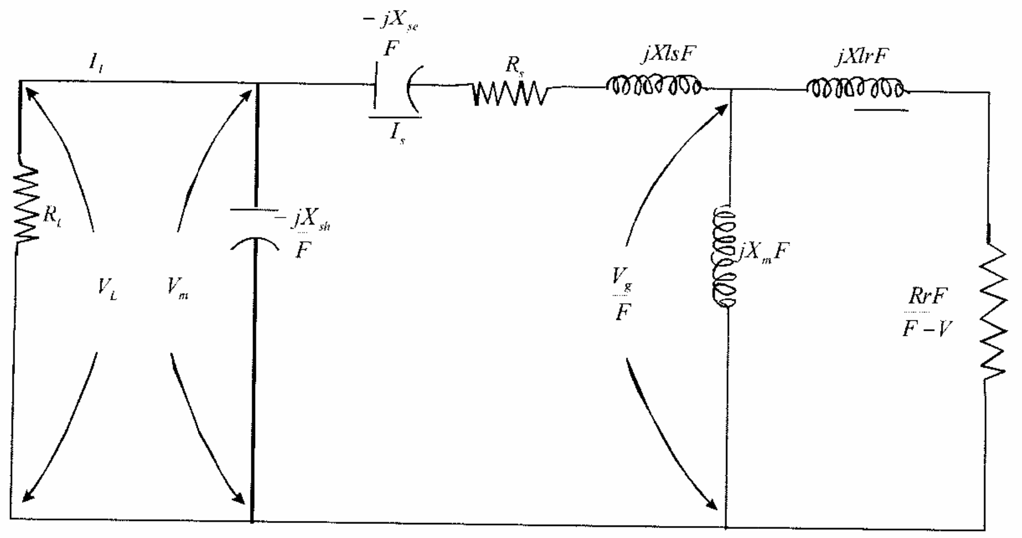


Fig. 2.2 (b) Equivalent Circuit of Long Shunt SEIG

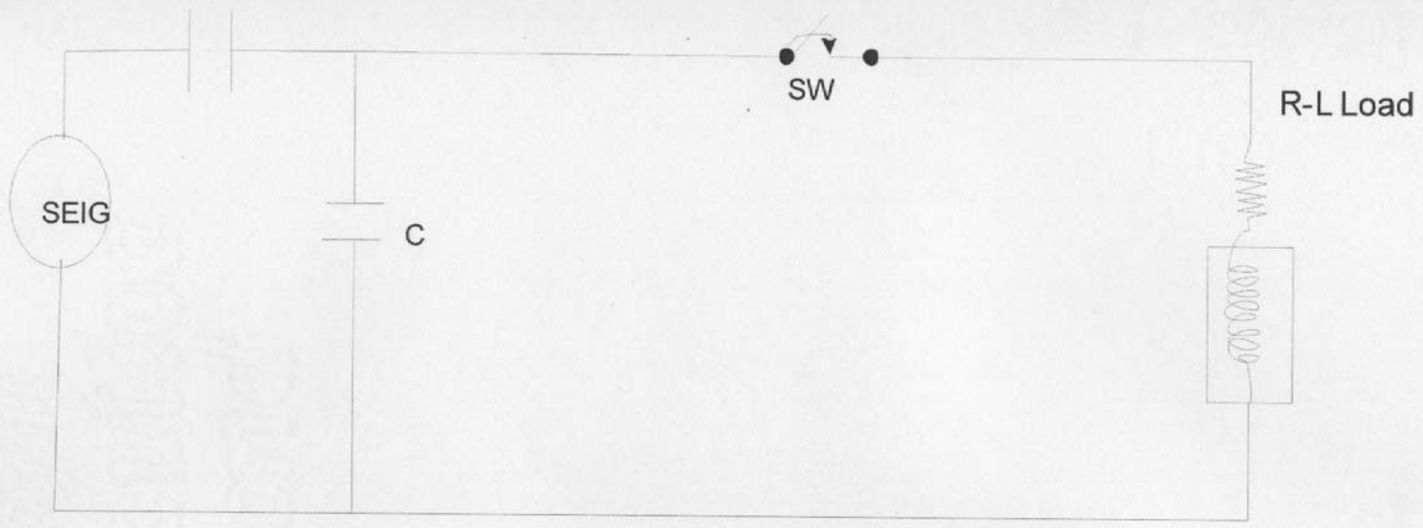


Fig. 2.2 (c) Single line Diagram of Long shunt SEIG Feeding R –L Load

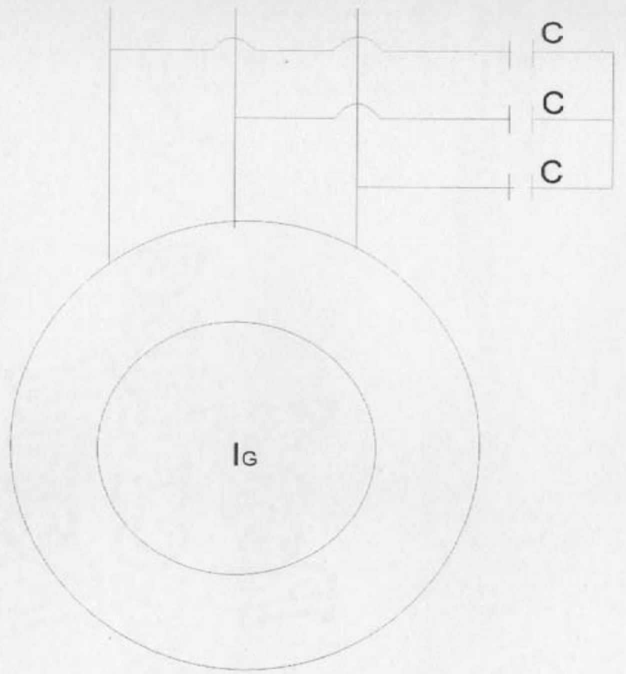


Fig. 2.3 (a) SEIG Excitation Capacitance Connection

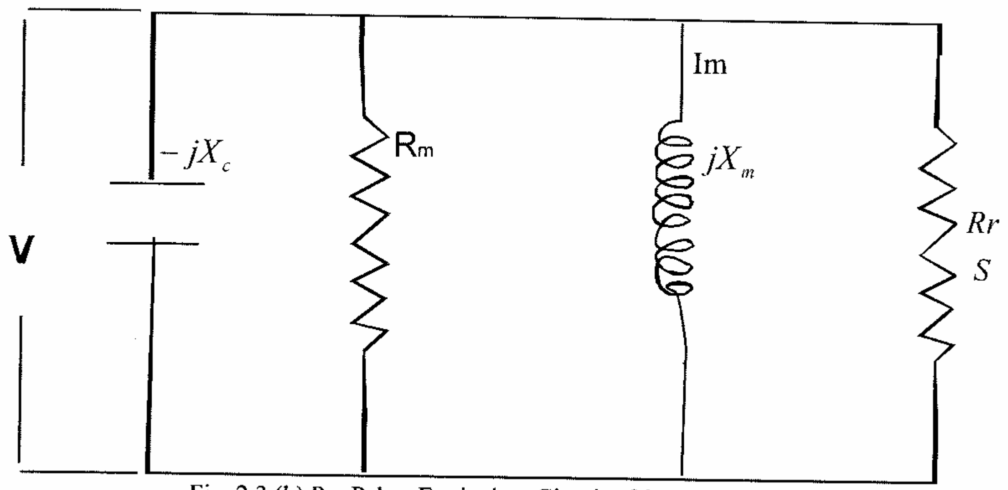


Fig. 2.3 (b) Per Pahse Equivalent Circuit of SEIG at No–Load

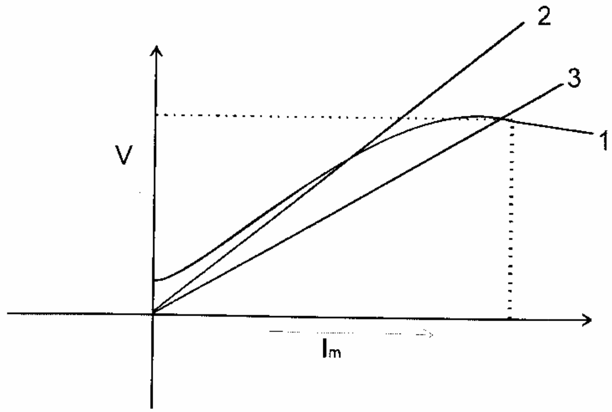


Fig. 2.4 (a) Saturation Curve of Induction Generator

Fig. 2.4 (b) Variation of Magnetizing Inductance Vs Voltage

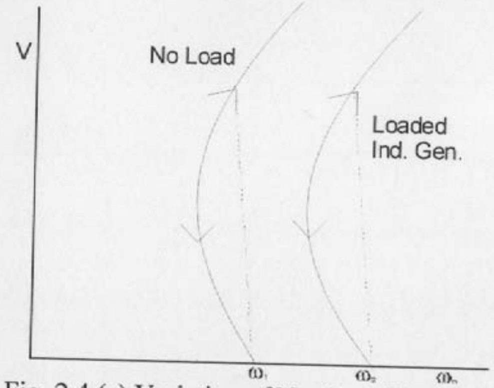


Fig. 2.4 (c) Variation of No–Load Vs Speed

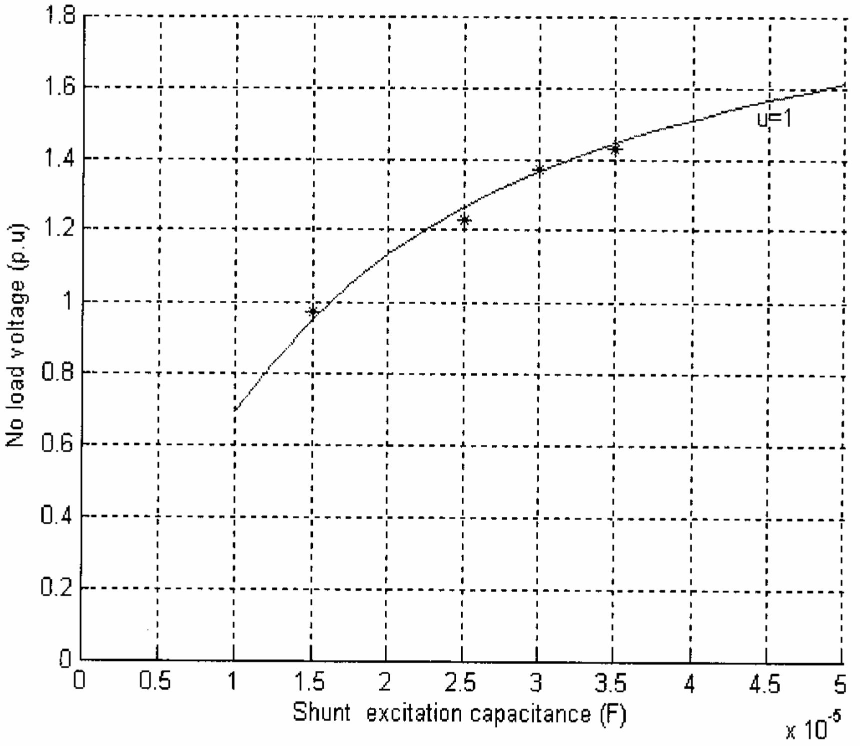


Fig. 2.5(a) No-load characteristics of the 3.7 kW SEIG

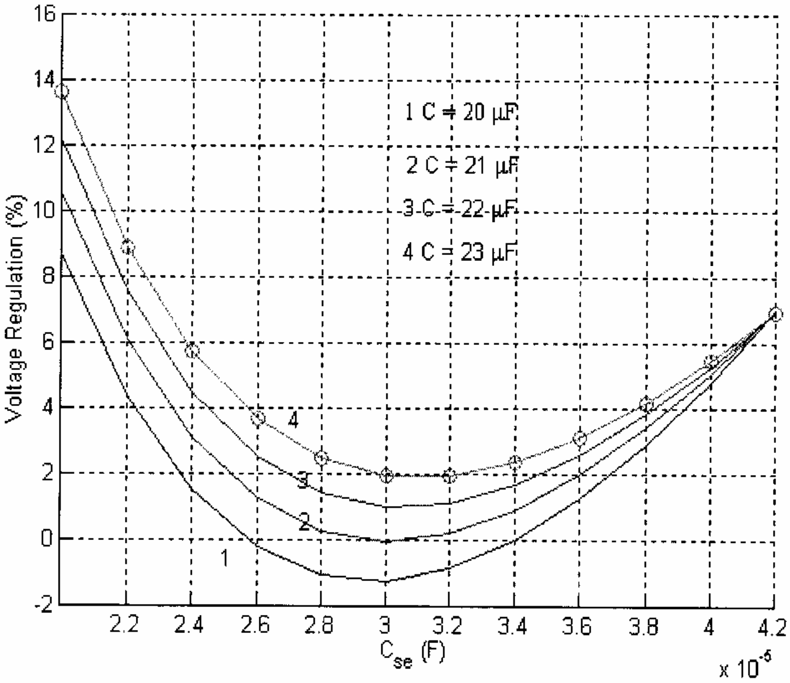


Fig. 2.5(b) Voltage regulation characteristic of short shunt SEIG (3.7 kW) with unity p.f. load

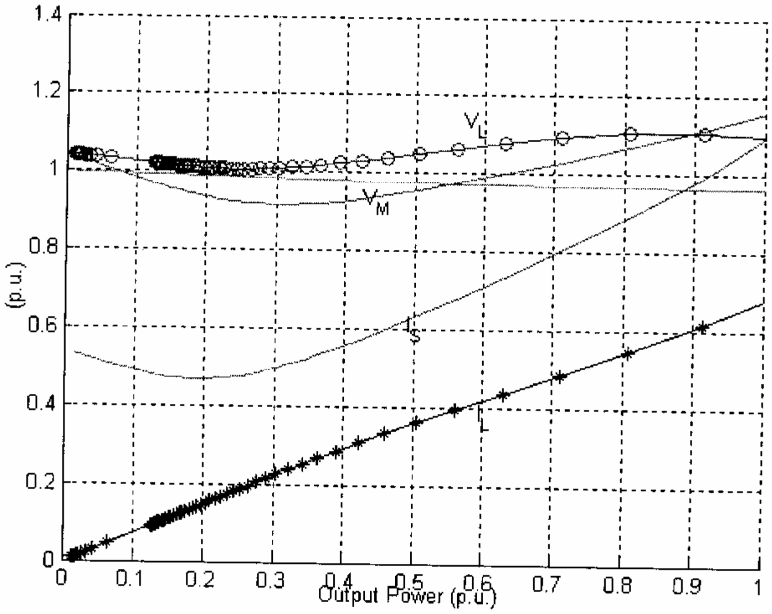


Fig. 2.5 (c) Performance characteristic of short shunt SEIG (3.7 kW) with unity p.f. load C = 16 μF, C_{se} = 30 μF

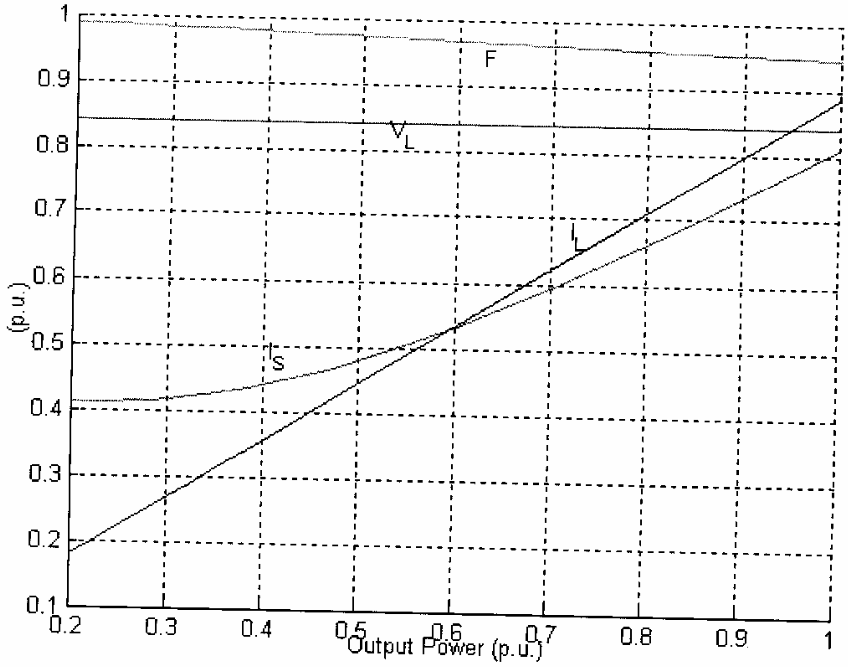


Fig. 2.5(d) Performance characteristic of long shunt SEIG with C = 20 μF and C_{se} = 60 μF while feeding unity p.f. load

Chapter – III

TRANSIENT ANALYSIS OF THREE PHASE SERIES COMPENSATED SEIG

3.1 INTRODUCTION

Self excited induction generators have obtained increased attention in recent years. This could be due to the suitability of these generators for various application, such as wind and small hydroelectric (micro – hydro) energy conversion. The generated energies of such generators are generally employed for lighting or cooking to reduce the firewood or fuels in the villages, where high power quality is not required. The self excited induction generator has distinct advantages for such systems. In remote locations harnessing of electrical energy from such local resources can be cheaper and easier compared to gird connection, which involves long transmission lines and associated losses. A micro hydro system using natural hydro potential require minimal civil works. It is a strong alternative in this race. However the system must be economical, rugged and user friendly since local communities are often not technically experts. Uncontrolled low head turbines are prescribed for such applications which maintain almost constant input power due to fixed head and discharge.

The self excited induction generator has its inherent advantages such as brushless construction (with squirrel –cage rotor), reduced size, absence of DC power supply for excitation, reduced maintenance cost, and better transient performances. Constancy of power requires a system to maintain generated output power constant at varying consumer loads. The behavior of a self excited induction generator with its stator winding and external connected capacitors mutually excited have been studies for over sixty years, since 1935.

When SEIG is employed is isolated power source, the terminal voltage and frequency are severely influenced by the rotor speed, excitation capacitor, and connected loads, hence SEIG is not suitable for supplying dynamic loads which are insensitive to the variations of voltage and frequency. This project concentrates on the dynamic performance of an SEIG feeding R load with and without series capacitance.

The technique of dynamic eigen value analysis is used to examine the small sign and stability of the studied system. Under various operating conditions such as buildup voltage, supply an IM load/R – l load, and increasing the loading of IM/R - L.

3.2 CIRCUIT CONFIGURATION

The necessary circuit configuration and equivalent circuit diagrams have shown in Fig. 3.2 (a) and 3.2 (b) respectively.

3.2.1 TRANSIENT MODEL

For transient model the single line diagram for an isolated self excited induction generator feeding on R – L load is shown in Fig. 3.2 (a). The excitation capacitor C is used to self excite the machine's for voltage buildup.

Fig 3.2 (b) shows the d – q axis equivalent circuit model of three phase symmetrical, induction machine connected with excitation capacitance under arbitrary reference frame.

The stator q – d axis flux linkages λ_{qs} and λ_{ds} and the rotor flux linkages λ_{qr} and λ_{dr} are given by

$$\lambda_{qs} = -L_{ls}.\lambda_{qs} + M(i_{qr} - i_{qs}) \tag{3.1}$$

$$\lambda_{ds} = -L_{ls}.\lambda_{ds} + M(i_{dr} - i_{ds}) \tag{3.2}$$

$$\lambda_{qr} = L_{lr}.i_{qr} + M(i_{qr} - i_{qs}) \tag{3.3}$$

$$\lambda_{dr} = L_{lr}.i_{dr} + M(i_{dr} - i_{ds}) \tag{3.4}$$

Where R_s and R_r are stator and rotor resistance respectively.
L_{ls} and L_{lr} are stator and rotor leakage inductances respectively.
M is Mutual inductance between stator and rotor windings.

The saturation effect has also been considered in this case. The non – linear characteristic relating Xm various Im of the SEIG is determined by experimental tests as show in Fig 3.3 (c)

Where, magnetizing current I_m is defined as:

$$I_m = \sqrt{(i_{qr} - i_{qs})^2 + (i_{dr} - i_{ds})^2} \qquad (3.5)$$

For a SEIG the coefficients are identified as the flowing values $\alpha = 69.386$, $\beta = 1.797$, $\gamma = 0.96$ and $\delta = \tan^{-1}(\gamma)$. The coefficient α makes the estimated X_m equal to the measured reactance corresponding to the measured maximum value I_m. The coefficient β and γ both influence the values of maximum reactance and initial reactance. The coefficient δ makes the flux linkages to zero when I_m is zero. The value of initial reactance can be obtain from equation (3.5) using 'L' Hopital's rule.

Taking the cross saturation effect into account, inductance coefficients become time varying and the rates of charge of stator and rotor flux components are given as under

$$p.\lambda_{qs} = -L_s.pi_{qs} + Mp.i_{qr} + i_{qm}p.M \qquad (3.6)$$

$$p.\lambda_{ds} = -L_s.pi_{ds} + Mp.i_{dr} + i_{dm}p.M \qquad (3.7)$$

$$p.\lambda_{qr} = -M.pi_{qs} + L_r.p.i_{qr} + i_{qm}pM \qquad (3.8)$$

$$p.\lambda_{dr} = -M.pi_{ds} + L_r.p.i_{dr} + i_{dm}p.M \qquad (3.9)$$

Where, $i_{qm} = i_{qr} - i_{qs}$
$i_{dm} = i_{dr} - i_{ds}$
$L_s = L_{ls} + M$
$L_r = L_{lr} + M$

The rate of charge of mutual inductance M can be written as

$$pM = \frac{dm}{di_m}.\frac{di_m}{di_{qs}}.p.i_{qs} + \frac{dm}{di_m}.\frac{di_m}{di_{ds}}.p.i_{ds} + \frac{dm}{di_m}.\frac{di_m}{di_{qr}}.p.i_{qr} + \frac{dm}{di_m}.\frac{di_m}{di_{dr}}.p.i_{dr} \qquad (3.10)$$

Where

$$\frac{di_m}{di_{qs}} = \frac{-i_{qm}}{i_m},\ \frac{di_m}{di_{ds}} = \frac{i_{dm}}{i_m},\ \frac{di_m}{di_{qr}} = \frac{i_{qm}}{i_m},\ \frac{di_m}{di_{dr}} = \frac{i_{dm}}{i_m} \qquad (3.11)$$

The derivative of M with respect to i_m can be obtained without difficulty. Substituting the time derivatives of the stator and rotor flux linkage into (3.1) to (3.4)

The voltage equations can be written in matrix form as

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -R_s & -\omega L_s & 0 & \omega M \\ \omega Ls & -R_s & -\omega .M & 0 \\ 0 & (\omega_r - \omega)M & R_r & L_r(\omega - \omega_r) \\ (\omega - \omega_r)M & 0 & (\omega_r - \omega)L_r & R_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

$$+ \begin{bmatrix} L_{qs} & M_{12} & M_{13} & M_{14} \\ M_{21} & L_{ds} & M_{23} & M_{24} \\ M_{31} & M_{32} & L_{qr} & M_{34} \\ M_{41} & M_{42} & M_{43} & L_{dr} \end{bmatrix} \mathrm{p} \begin{bmatrix} \mathrm{i}_{\mathrm{qs}} \\ \mathrm{i}_{\mathrm{ds}} \\ \mathrm{i}_{\mathrm{qr}} \\ \mathrm{i}_{\mathrm{dr}} \end{bmatrix} \tag{3.12}$$

Where,

$$L_{qs} = -\left(Ls + \frac{L_{qm}^2}{i_m} \cdot \frac{dM}{di_m} \right), \mathrm{L}_{\mathrm{ds}} = -\left(Ls + \frac{L_{dm}^2}{i_m} \cdot \frac{dM}{di_m} \right)$$

$$L_{qr} = -\left(Lr + \frac{L_{qm}^2}{i_m} \cdot \frac{dM}{di_m} \right), \mathrm{L}_{\mathrm{dr}} = -\left(Lr + \frac{L_{dm}^2}{i_m} \cdot \frac{dM}{di_m} \right)$$

$$M_{12} = M_{21} = M_{32} = M_{41} = \frac{i_{qm} \times i_{dm}}{i_m} \cdot \frac{dM}{di_m}$$

$$M_{13} = -M_{31} = M + \frac{i_{qm}^2}{i_m} \cdot \frac{dM}{di_m}$$

$$M_{14} = M_{23} = M_{34} = M_{43} = \frac{i_{qm} \cdot i_{dm}}{i_m} \cdot \frac{dM}{di_m}$$

$$M_{24} = -M_{42} = M + \frac{i_{dm}^2}{i_m} \cdot \frac{d_m}{di_m}$$

If the derivative of M with respect to i_m is set to zero, i.e. $\frac{dM}{di_m} = 0$ then the cross saturation effect is ignored and the inductance coefficient are kept constant. It is noted that the voltage equation in (3.12) can be regarded as a generalized model of

IM. The induction machine is also employed as a dynamic load for IG, Therefore the subscript g and subscript m are respectively added to the equations. On connecting the IM to the common bus, the voltage – current equations of the capacitor bank shown in Fig. 3.2 (b) can be expressed in d – q axis equivalent circuit model as below.

$$i_{qc} = \omega \cdot C \cdot V_{ds} + C_p V_{qs} \tag{3.13}$$

$$i_{dc} = \omega \cdot C \cdot V_{qs} + C_p V_{ds} \tag{3.14}$$

The torque and rotor speed of the IG with subscript g are related by

$$2H_g p\omega_g = T_{mg} + M_g\left(i_{dsg} \cdot i_{qrg} - i_{qsg} \cdot i_{drg}\right) - D_g \omega_{rg} \tag{3.15}$$

Where T_{mg} is input mechanical torque. H_g is the inertia constant, and D_g is the friction coefficient. The prime mover of the IG is similated by separately – excited dc motor, which has the speed – torque characteristic similar to a hydro – turbine at a constant water load. The torque equation of X_m load with subscript M is given below

$$2H_m p\omega_{rm} = M_m\left(i_{dsm} \cdot i_{qrm} - i_{qsm} \cdot i_{drm} - T_L - D_m \cdot \omega_{rm}\right) \tag{3.16}$$

It is clear that two d –q axis models based on stationary reference frame and synchronously rotating reference frame were respectively employed to study to IG feeding a dynamic IM load. Combining equation (3.12) and (3.16) and setting $\omega = 0$, The machine model is based on stationary reference frame. On the other hand, if the q axis is aligned with the stator terminal voltage phasor by setting $V_{ds} = 0$ and its deviation $p.V_{ds}=0$ in equation (3.12) to (3.14), then the system model is based on synchronously rotating frame. The system synchronous frequency is expressed as

$$\omega_e = \frac{i_{dc}}{C \cdot V_{qs}} \tag{3.17}$$

Combining equations (3.12) and (3.13) and (3.15) & (3.16) and replacing arbitrary angular speed ω with synchronous angular speed ω_e, the complete system model based on synchronously rotating reference frame consists of 22 nonlinear equations. The major advantage of this frame is that all variable is zero under a steady state condition.

3.3.1 TRANSIENT MODEL OF SHORT – SHUNT SEIG

Mathematical Model

The damping resistors across series capacitor and resistive load are considered for the generalized formulation to study their effects on the performance of this configuration. The necessary calculation for the required parameters obtained through the following steps.

(i) Evaluate the impedance offered by the induction motor. The procedure to evaluate the slip of an induction motor delivering a given output P_{out}^{m} for the specified terminal voltage is briefly reviewed in Appendix A. After finding the slip and magnetizing reactance X_m^M [8], the impedance offered by induction motor is computed as

$$Z_{LM} = R_{LM} + jX_{LM} \cdot F$$
$$R_s^m + jX_s^m \cdot F + \left[jX_m^M F \middle\| \left(\frac{R_r^m}{s} + jX_{lr}^m F \right) \right] \tag{3.18}$$

(ii) Transform the impedance offered by the resistive and motor load into an equivalent series R-L load

$$Z_L = (R_L + jX_L) = \frac{R_L^{st} Z_{LM}}{R_L^{st} + Z_{LM}} \tag{3.19}$$

(iii)Compute damping resistance and transform the parallel combination of damping resistance and series capacitance into an equivalent series R – C.

The R of n appropriate value, which is capable of eliminating the unstable behavior without cutting off the compensation resulted by series capacitors, may be needed for stable operation. It can be evaluated by the empirical relation [9] as

$$R_d = \frac{Xv \cdot s \sqrt{1 - \dfrac{X_m^{m^2}}{X_s^m \cdot X_v^m}}}{\left(1 - \dfrac{X_m^{m^2}}{X_s^m \cdot X_v^m}\right) \sqrt{\dfrac{X_{vs}}{R_s^m}} - \left(\dfrac{R_s^m}{X_s^m}\right)} \tag{3.20}$$

Where $X_s^m = X_{ls}^m + X_m^m$ and $X_r^m = X_{lr}^m + X_m^m$

The equivalent series $R-C\left(R_{ES}-j\frac{X_{ES}}{F}\right)\cdot F$ is obtained as

$$R_{ES}=real\left(3R_d||-j\frac{X_{es}}{F}\right)$$

$$X_{ES}=-i_{mag}\left(3R_d||-j\frac{X_{es}}{F}\right)\cdot F \tag{3.21}$$

(iv)Obtain the reduced equivalent of short – shunt SEIG-IM as shown in Fig. 2(b) by modifying the load resistance as

$$R_L=R_L+R_{ES} \tag{3.22}$$

3.3.2 TRANSIENT MODEL OF LONG SHUNT SEIG

In long shunt connection, the stator terminals of the Self Excited Induction Generator is connected to the parallel connection of capacitor C and load via long shunt capacitance C_{long} as shown in Fig 3.3 (d)

In Fig. 3.3 (e) and 3.3 (f) has shown the arbitrary reference frame d –q axis equivalent circuit for a three phase, symmetrical SEIG are shown, whose voltage equations can be written as:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix}=\begin{bmatrix} R_s+pL_s & \omega L_s & pM & \omega\cdot M \\ -\omega L_s & R_s+pL_s & -\omega M & pM \\ pM & (\omega\cdot\omega_r)M & (R_r+pL_r) & (\omega-\omega r)L_r \\ -(\omega_r-\omega)M & pM & (\omega_r-\omega)L_r & R_r+pL_r \end{bmatrix}\begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{rq} \\ i_{dr} \end{bmatrix} \tag{3.23}$$

Where the subscripts s and r denote stator and rotor quantities, respectively it is clear that the current flow from the SEIG to load. This equation can employed to represent the dynamic model of the IM except that the current must be reversed. The *v*–i equations of the excitation capacitor bank in Figs. 3.3 (e) and (f) can be written as:

$$\begin{bmatrix} i_{cq} \\ i_{cd} \end{bmatrix}\begin{bmatrix} pC & \omega C \\ -\omega C & pC \end{bmatrix}\cdot\begin{bmatrix} v_{cq} \\ v_{cd} \end{bmatrix} \tag{3.24}$$

The above equation can be modified to represent the v – i equation of long shunt configuration. It is convenient to relate the generator equations (3.18) and capacitor v–i equations (3.19) to the stationary reference frame ($\omega = 0$)

3.4 RESULTS AND DISCUSSIONS

In this section, transient responses are obtained experimental, under balanced excitation capacitors. Each experimental result shown is obtained from laboratory oscilloscope whose scales on X – axis and Y – axis are respectively 0.2s/div and 50V/div.

Three capacitors are selected to be $C_1 = C_2 = C_3 = 17\mu F$. The transient responses of the studied SEIG under (a) voltage buildup process, (b) sudden disconnection of balanced resistive load without series capacitors. (c) sudden connection of balanced resistive load with series excitation capacitance will be respectively shown in the following subsections.

(a) Voltage Buildup Process Under. No–load Condition.

Since the employed excitation capacitors are the same, the entire system is now under three – phase balanced condition. Fig. 3.4 respectively show the experimental responses of the generated line voltage (in V) for the studied SEIG under no – load condition. The transient responses of the other line voltages have also the same characteristics. It is observed from Fig. that both magnitude and frequency of line voltage are nearly the same. Figure also shows the transient response of the line current. It is observed that, when SEIG is driven at rated speed 1500 rpm and a delta connected capacitor bank with 17 μF per phase capacitance is switching areas SEIG terminals the no –load voltage build up till saturation is reached in the machine.

(b) Sudden Connection of Resistive Load Without Series Capacitor

When SEIG is able to generate rated voltage (415V) at no – load, at rated speed, a resistive load of 1 kW capacity in switched across its terminals. It is observed from Fig. 3.5 that due to sudden application of load, the SEIG voltage falls and settle to a lower new value (380V). It shows the poor voltage regulation of SEIG.

(c) Sudden Connection of Resistive Load with Series Capacitor

Fig 3.6 (a) shows the experimental results of SEIG terminal voltage, current and load current, when a resistive load of 1 kW but with a series capacitance of 20μF per phase in short shunt configuration is switched areas SEIG terminals. It is observed that due to series compensator (short–shunt) the falls in terminal voltage with load is almost insignificant, resulting in constant load voltage profile.

Fig. 3.6 (b) shows the behavior of SEIG while operating in long–shunt connection while operating in long–shunt connection and feeding resistive load. It is observed that now a shunt excitation of 22μF and series capacitance of 60μF is needed to generated 415V at no–load. Also, the SEIG line currents increased due to higher capacitance requirement. Thus, the long shunt has lower power generating capacity than short shunt configuration for the same rating machine.

3.5 CONCLUSIONS

This chapter has presented a dynamic model of three–phase induction machine operating as dynamic equations of an isolated self–excited induction generator (SEIG). The experimental results of the studied SEIG under voltage build process, suddenly switching off resistive load, and suddenly switching off load with series compensation have been presented and analyzed.

It is conclude that a series compensated SEIG requires higher values of shunt and series excitation capacitance in long shunt connection in comparison to short shunt configuration.

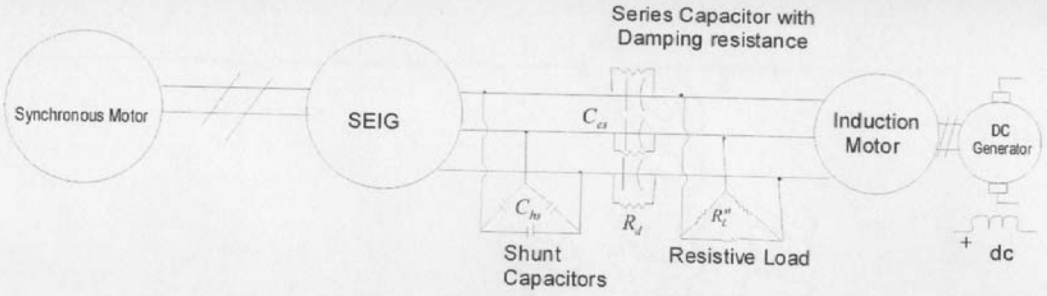


Fig. 3.2 (a) Schematic Diagram of Short Shunt SEIG

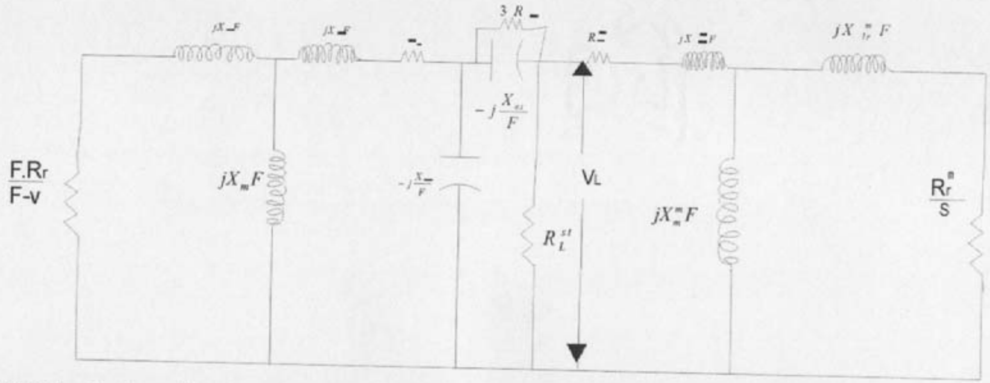


Fig. 3.2 (b) Equivalent Circuit for Transient Model of SEIG ΞIG for Transient Model

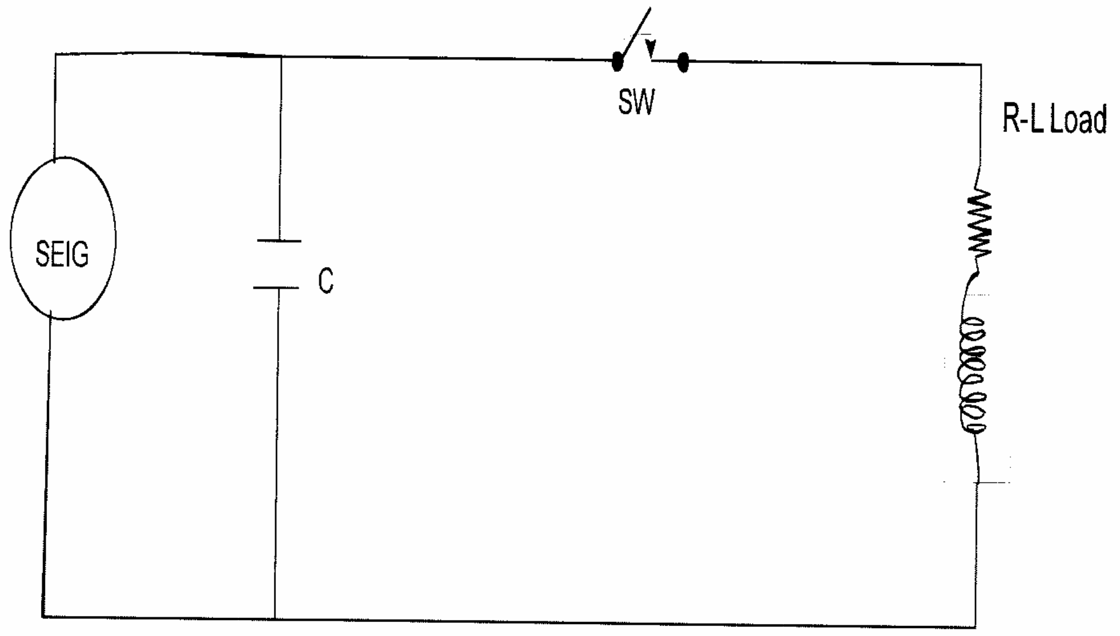


Fig. 3.3 (a) Single Line Diagram of SEIG Feeding R–L Load

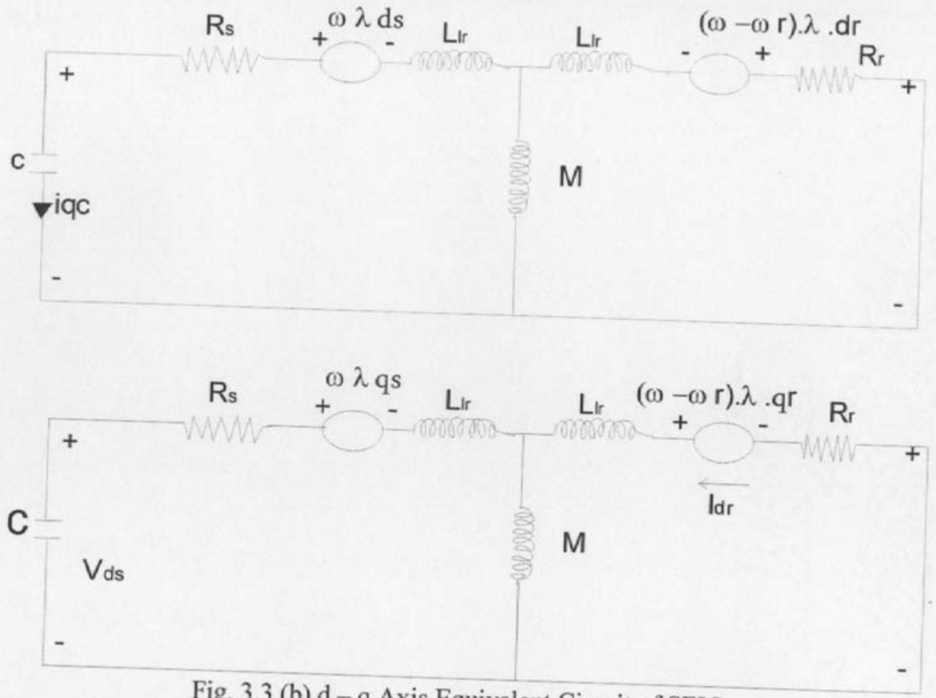


Fig. 3.3 (b) d – q Axis Equivalent Circuit of SEIG

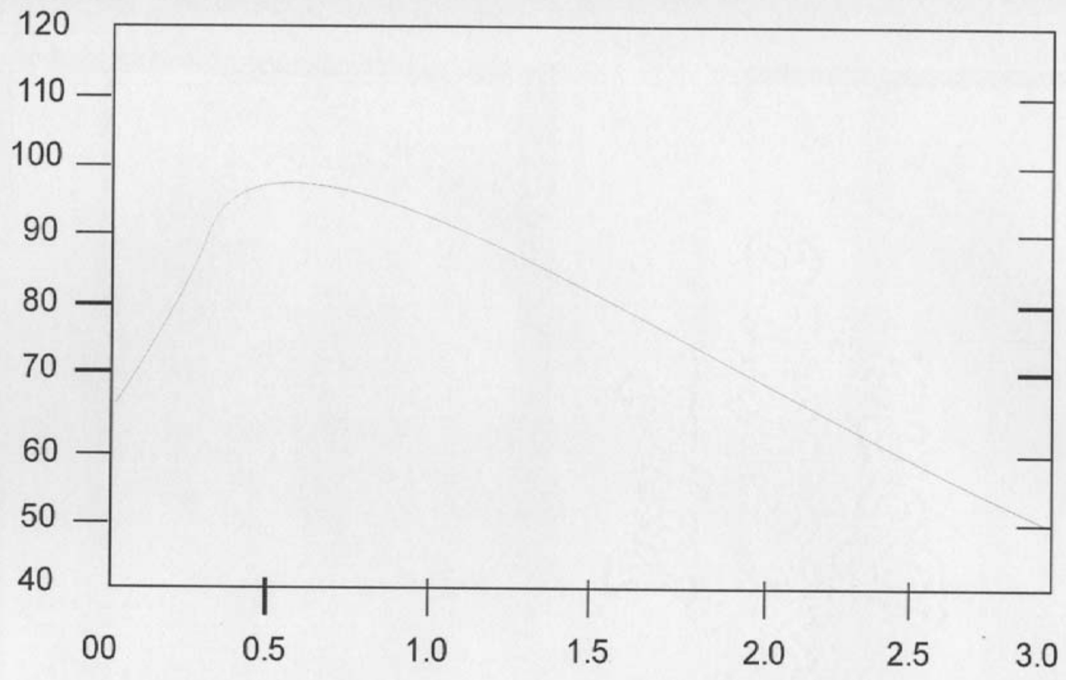


Fig. 3.3 (c) Magnetization Curve between X_m and I_m

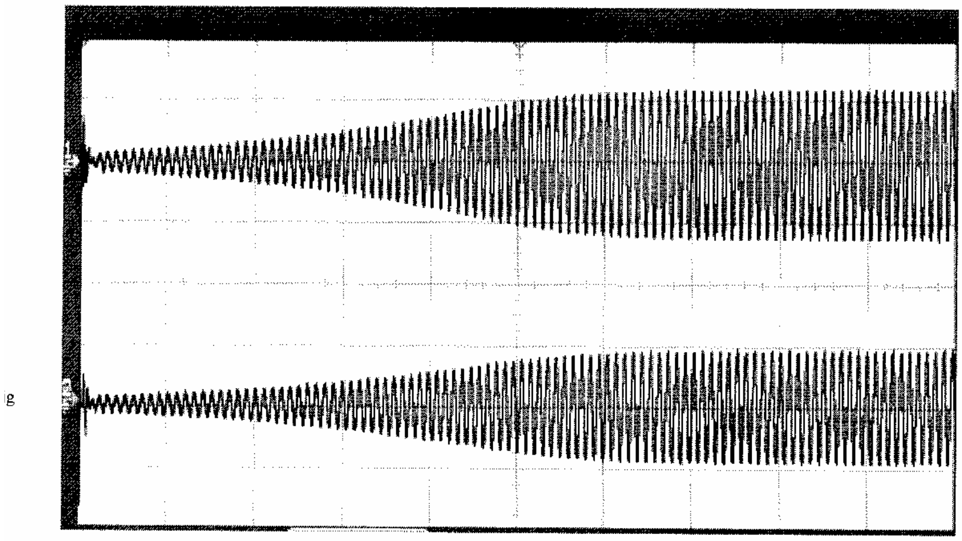


Fig. 3.4 Transient waveforms of SEIG (3.7 kW) voltage and current at no- load

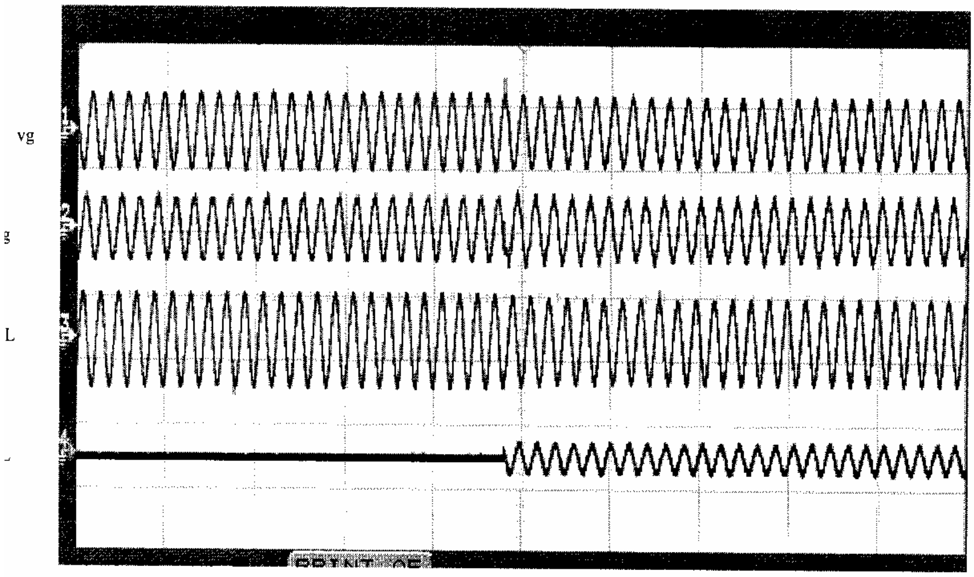


Fig. 3.5 Transient waveforms of short shunt SEIG (3.7 kW) voltage,current, load voltage and load current during variation of resistive load

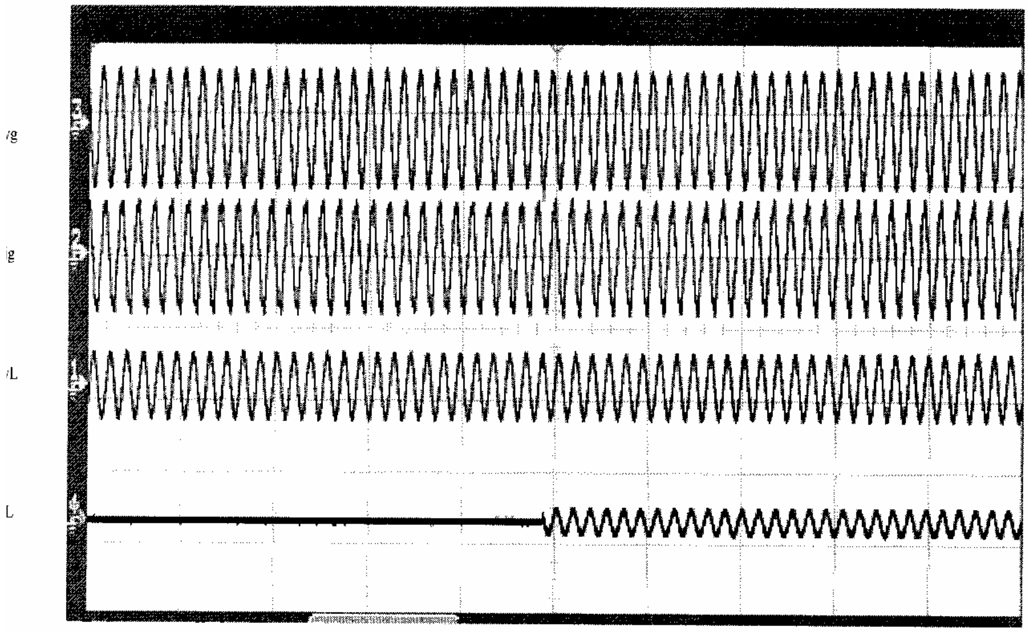


Fig. 3.6(a) Transient waveforms of short shunt SEIG (3.7 kW) voltage,current, load voltage and load current during variation of resistive load

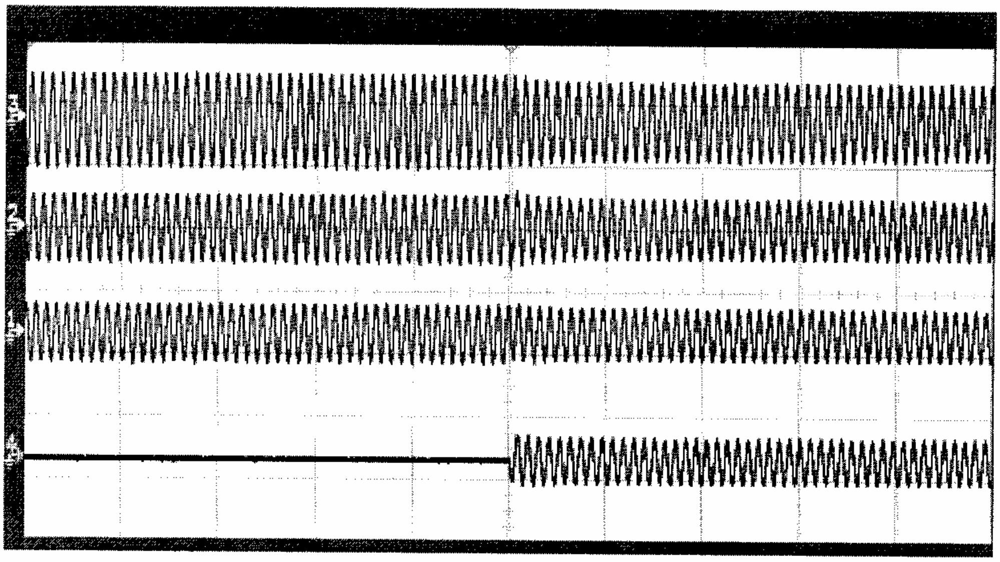


Fig. 3.6(b) Transient waveforms of long shunt SEIG (3.7 kW) voltage,current, load voltage and load current during variation of resistive load 1.5 kW

Chapter – IV

TRANSIENT PERFORMANCE OF THREE PHASE SELF EXCITED INDUCTION GENERATOR WITH LOAD CONTROLLER SUPPLYING

4.1 INTRODUCTION

The main advantages of a self excited induction generator are robustness, low cost, better transient performance, higher reliability, no need of DC power supply for field excitation, brushless construction (with squirrel cage rotor) negligible distribution losses, etc. In rural and remote locations SEIG is most popular source of electrical energy nowadays. Need for standby power is also increasing rapidly due to unreliable utility supplies. Heavy distribution losses and investment in transmission lines compel one to seek autonomous power generation, depletion of fossil fuels has turned our attention towards renewable energy sources. For power generation wind, small hydro and biomass are attractive options. Since, they are exceptionally to be located in isolated regions, the technology must be simple, energy conversion system has be developed for such applications. A micro – hydro system using natural hydro potential with minimal civil works is a best way to generate the electrical energy by such applications.

Constancy of generated requires a system to maintain generator output power constant at varying consumer loads. Normally, a device names as load controller (LC) is used for this purpose.

A load controller consists of an uncontrolled rectifier–chopper system feeding a dump resistive load, with the power in the dump load controlled through variable duty cycle of the chopper to keep the sum of consumer load and LC dump power constant.

The types of load experienced of such stand – alone micro – hydro generating system would be fans, compressors, mixers, flower mills etc. and static loads mainly for lighting and heating purposes, sudden switching in of such loads (especially dynamic loads) causes transients in the system, which are of critical interest.

This project deals with the unexplored are relevant topic of transient behavior of an uncontrolled micro – hydro turbine driven self excited induction generator with electronic load controller system soding both dynamic and static loads. Subsystems comprising the prime mover, ELC system in the laboratory feeding both dynamic and static loads and compared with simulated results.

4.2 CIRCUIT CONFIGURATION AND EQUIVALENT CIRCUIT

The Circuit Configuration is shown in Fig. 4.2 (a)

4.3 MODELING OF SELF EXCITED INDUCTION GENERATOR FOR TRANSIENT ANALYSIS

The proposed self excited induction generator with load controller system consists of an induction generator, capacitor bank, consumer load and load controller. A dynamic model of the SEIG – LC system with load consists of modeling of the above subsystems as explained below.

4.3.1 MODELING OF SELF EXCITED INDUCTION GENERATOR

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -R_s & -\omega L_s & 0 & \omega M \\ \omega Ls & -R_s & -\omega.M & 0 \\ 0 & (\omega_r-\omega)M & R_r & L_r(\omega-\omega_r) \\ (\omega-\omega_r)M & 0 & (\omega_r-\omega)L_r & R_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix}$$

$$+\begin{bmatrix} L_{qs} & M_{12} & M_{13} & M_{14} \\ M_{21} & L_{ds} & M_{23} & M_{24} \\ M_{31} & M_{32} & L_{qr} & M_{34} \\ M_{41} & M_{42} & M_{43} & L_{dr} \end{bmatrix} \mathrm{p} \begin{bmatrix} \mathrm{i}_{\mathrm{qs}} \\ \mathrm{i}_{\mathrm{ds}} \\ \mathrm{i}_{\mathrm{qr}} \\ \mathrm{i}_{\mathrm{dr}} \end{bmatrix} \qquad (4.1)$$

Where

$$L_{qs} = -\left(Ls + \frac{L_{qm}^2}{i_m} \cdot \frac{dM}{di_m} \right), \mathrm{L}_{\mathrm{ds}} = -\left(Ls + \frac{L_{dm}^2}{i_m} \cdot \frac{dM}{di_m} \right)$$

$$L_{qr} = -\left(Lr + \frac{L_{qm}^2}{i_m} \cdot \frac{dM}{di_m} \right), \mathrm{L}_{\mathrm{dr}} = -\left(Lr + \frac{L_{dm}^2}{i_m} \cdot \frac{dM}{di_m} \right)$$

$$M_{12} = M_{21} = M_{32} = M_{41} = \frac{i_{qm} \times i_{dm}}{i_m} \cdot \frac{dM}{di_m}$$

$$M_{13} = -M_{31} = M + \frac{i_{qm}^2}{i_m} \cdot \frac{dM}{di_m}$$

$$M_{14} = M_{23} = M_{34} = M_{43} = \frac{i_{qm} \cdot i_{dm}}{i_m} \cdot \frac{dM}{di_m}$$

$$M_{24} = -M_{42} = M + \frac{i_{dm}^2}{i_m} \cdot \frac{d_m}{di_m}$$

$$I_m = \frac{\left[\left[i_{ds} + i_{dr} \right]^2 + \left[i_{qs} + i_{qr} \right]^2 \right]^{\frac{1}{2}}}{\sqrt{2}} \tag{4.2}$$

The magnetizing inductance (L_m) is calculated from the magnetizing characteristic which is obtained by synchronous speed test for the machine under test (5HP) operating as SEIG and it is defined as:

$$L_m = a + bI_m + c \cdot I_m^2 + d \cdot I_m^3 \tag{4.3}$$

Where a, b, c and d are coefficients analyzed in Appendix II

Three – phase generator currents are obtained from d –q axes components using the relation

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \tag{4.4}$$

For the delta connection of the SEIG shown in Fig. 4.2 (a) the line currents of SEIG (i_{ga}, i_{gb} and i_{gc}) can be expressed in term of phase currents as

$$\left.\begin{aligned} i_{ga} &= i_c - i_a \\ i_{gb} &= i_a - i_b \\ i_{gc} &= i_b - i_c \end{aligned}\right] \tag{4.5}$$

Further $V_a + V_b + V_c = 0$ (4.6)

4.3.2 MODELING OF CONSUMER LOADS

A consumer loads consisting of delta connected and resistive load (static load) which are shown in Fig. 4.2 (c) are modeled as follows

$$i_{aL} = i_{pa} - i_{pc} = \left(\frac{V_a}{R_{La}}\right) - \left(\frac{V_c}{R_{Lc}}\right) \tag{4.7}$$

$$i_{bL} = i_{pb} - i_{pa} = \left(\frac{V_b}{R_{Lb}}\right) - \left(\frac{V_a}{R_{La}}\right) \tag{4.8}$$

$$i_{cL} = i_{pc} - i_{pb} = \left(\frac{V_c}{R_{Lc}}\right) - \left(\frac{V_b}{R_{Lb}}\right) \tag{4.9}$$

4.3.3 MODELING OF LOAD CONTROLLER

The developed load controller is shown in Fig. 4.2 (a), consists of uncontrolled diode rectifier bridge, control circuit, and a solid state switch (IGBT) operating as chopper, as shown in Fig. 4.2 (a). The stator voltage is fed to the LC circuit consisting of diode rectifier through a small value of source inductance (L_f) and resistance (R_f). A filtering capacitor (C) is connected across the rectifier output to filter out the ripples of the DC voltage. The volt current relation defining the complete load controller system is:

$$v_{\max} = R_f i_d + L_f p i_d + v_d \tag{4.10}$$

From which the derivative of LC current (i_d) is defined as

$$pi_d = \frac{(v_{\max} - v_d - R_f i_d)}{L_f} \tag{4.11}$$

Here $v_{\max}$ is the maximum value of AC line voltage depending on which diode pair is conducting and v_d is the DC link voltage. The AC dump load currents in the three phase (i_{Da}, i_{Db} and i_{Dc}) are obtained by using the magnitude of i_d and direction (sign) corresponding to the conducting pairs of diodes.

Charging and discharging of the filtering capacitor of the LC (C) is expressed as:

$$p \cdot v_d = \frac{i_d - i_L}{C} \tag{4.11}$$

Where $i_L = \left\{ \left(\frac{v_d}{R_{dL1}} \right) + S_w \left(\frac{v_d}{R_{dL2}} \right) \right\}$; here S_w is the switching function indicating the switching status of the IGBT switch. When the switch is closed then $S_w = 1$ and when the switch is opened then $S_w = 0$. The switching states of the IGBT chopper $S_w = 1$ or o, depend on the output of the PI voltage controller, which is compared with the saw – tooth carrier wave resulting in PWM output of the varying duty cycle.

4.4 RESULTS AND DISCUSSION

Experiments are carried out on the developed prototype of the SEIG – LC system to verify the effectiveness of LC in regulating the voltage and frequency of SEIG with variation in main load. The induction generator is coupled to a closed loop speed – controlled converter fed DC drive, testing consists of three phase 3.7 kW, 415 V, 7.6, 4 pole Δ connected squirrel–cage induction machine which is operated as a generator and a load consists of a load controller and resistive load (main).

The different wave forms of SEIG voltage, SEIG line current and load currents are shown in Fig. 4.3. To obtain the rated voltage at rated speed (1500 rpm) a capacitor bank of 22μF/phase is connected across the SEIG terminals. It can be observed from these results that under the steady state voltage of SEIG is feeding resistive load of 3 kW at rated voltage. Now, if the main resistive load of SEIG is varied in steps, it is observed that SEIG terminal voltage remain constant, but due to decrease of load current the load controller current increases. This ensures constant output power from SEIG irrespective of variation in main consumer load, have maintaining the voltage as well as frequency of SEIG constant. However, due to rectifier circuit the load controller draws non linear current and hence SEIG terminal voltage is little distorted.

4.5 CONCLUSION

The developed load controller for the SEIG with has been found suitable in improving the voltage regulation of SEIG. Based on this study, the developed SEIG – LC system can be installed in the field. It has been observed that the LC is capable of handling the transients caused by load switching. The SEIG voltage is found within acceptable limits with full variation of consumer loads.

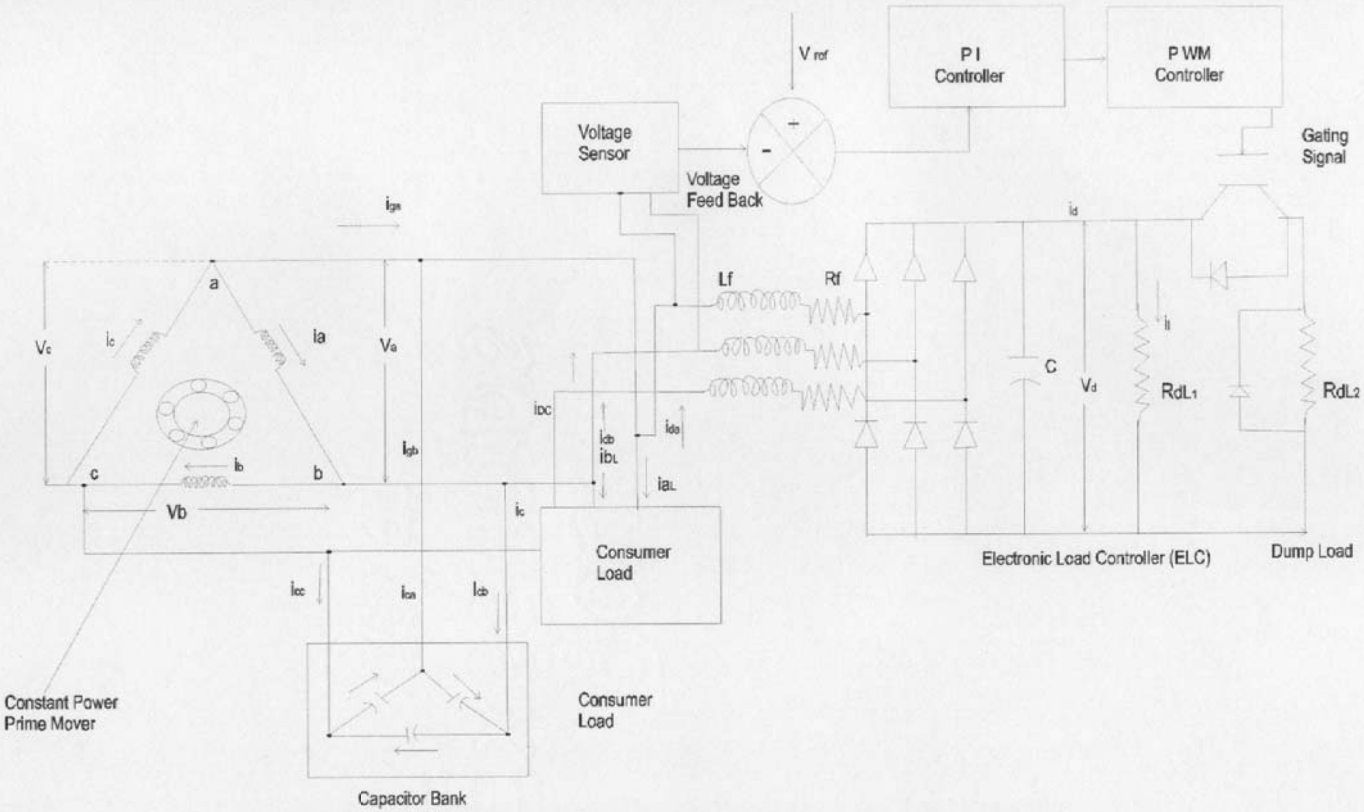


Fig. 4.2 (a) Schematic Diagram of Three Phase SEIG with Load Controller

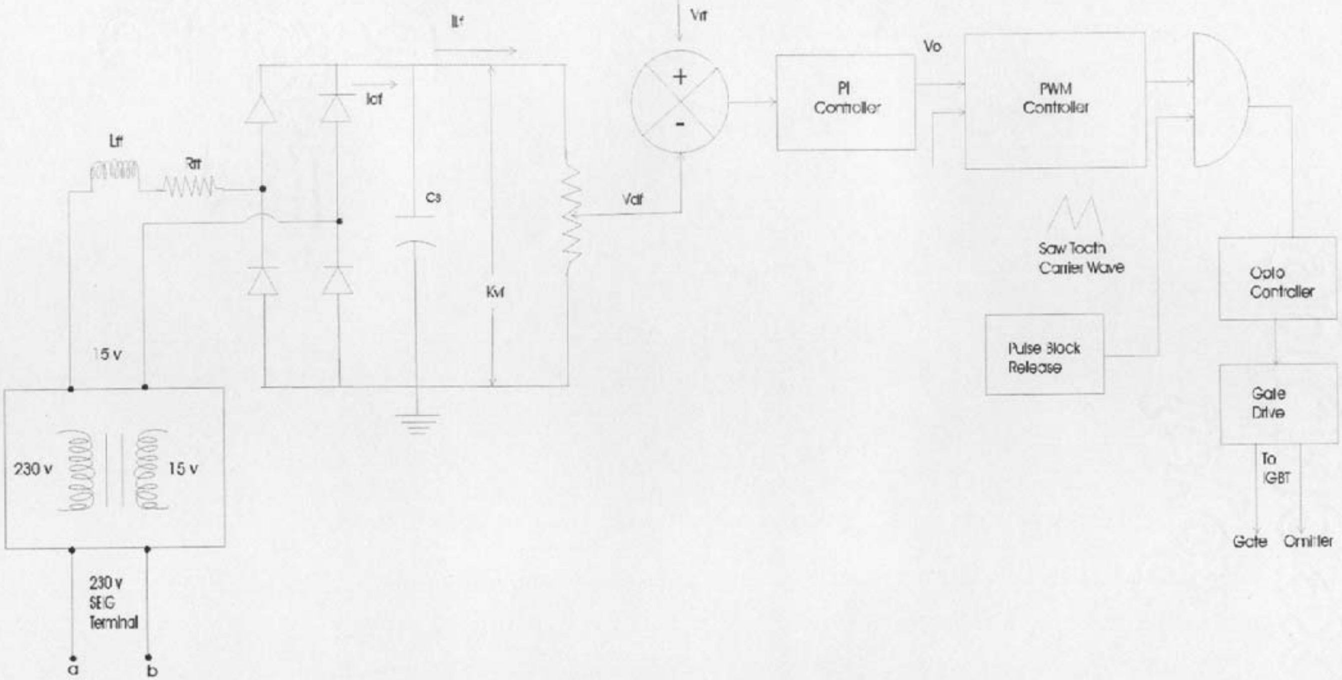


Fig. 4.3 (a) Control Circuit of Chopper Based Electronic Load Controller

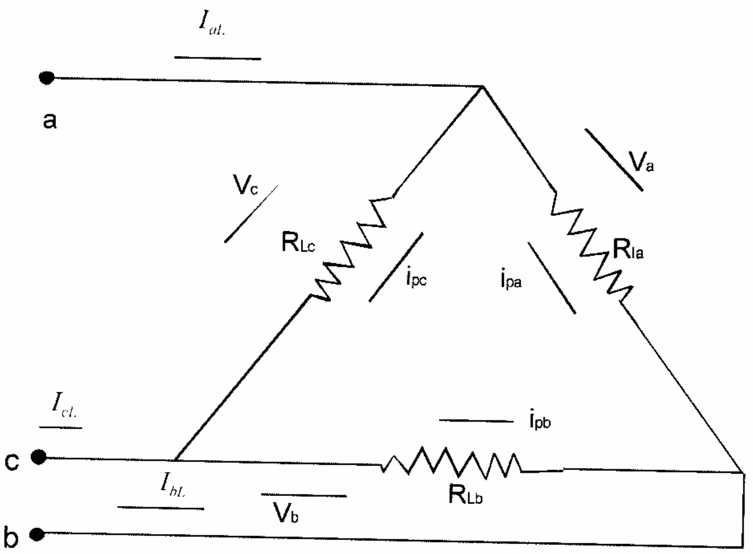


Fig. 4.3 (b) Circuit Diagram of Three Phase Resistive Load

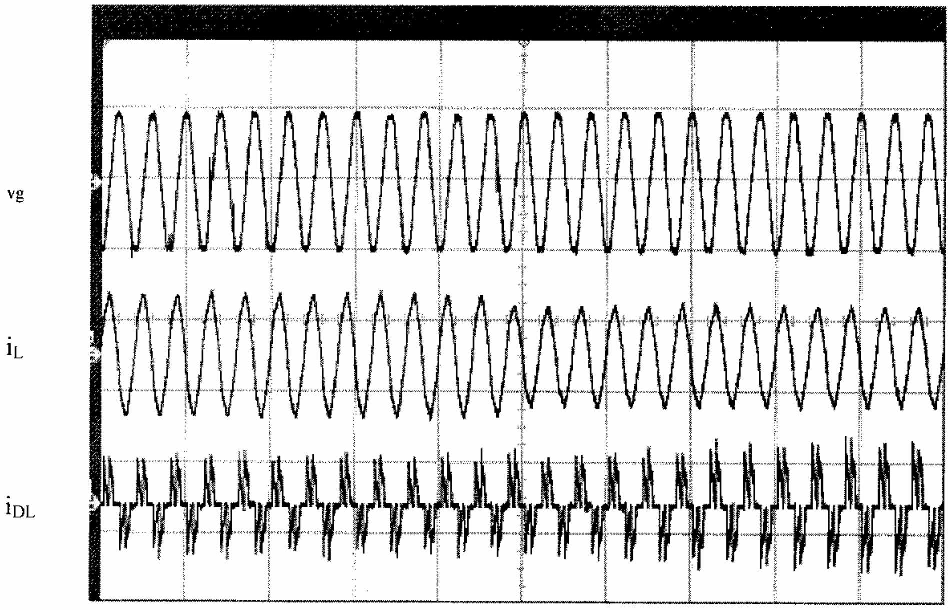


Fig. 4.3 Transient waveforms of SEIG (3.7 kW) voltage, main load current and dump load current during variation of main load

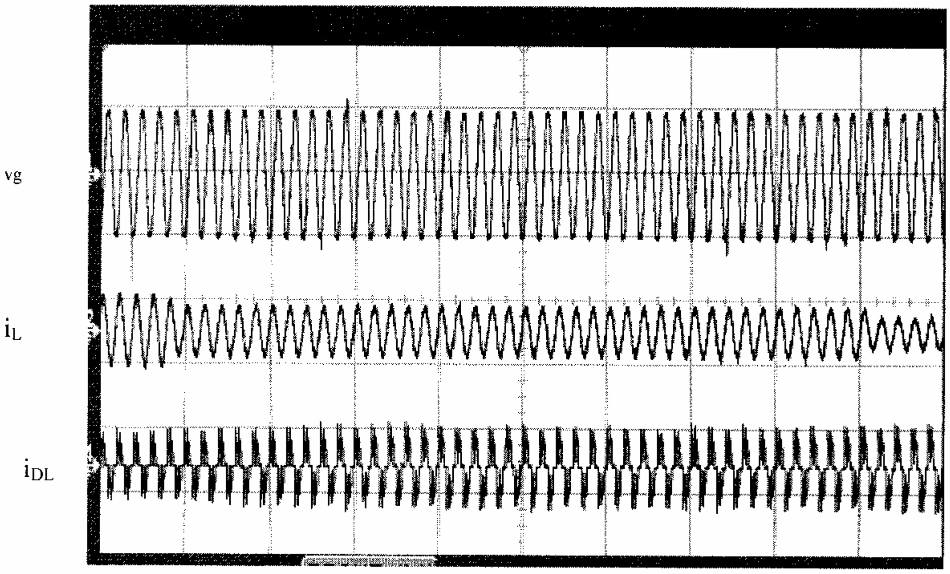


Fig. 4.4 Transient waveforms of SEIG (3.7 kW) voltage, main load current and dump load current during variation of main load

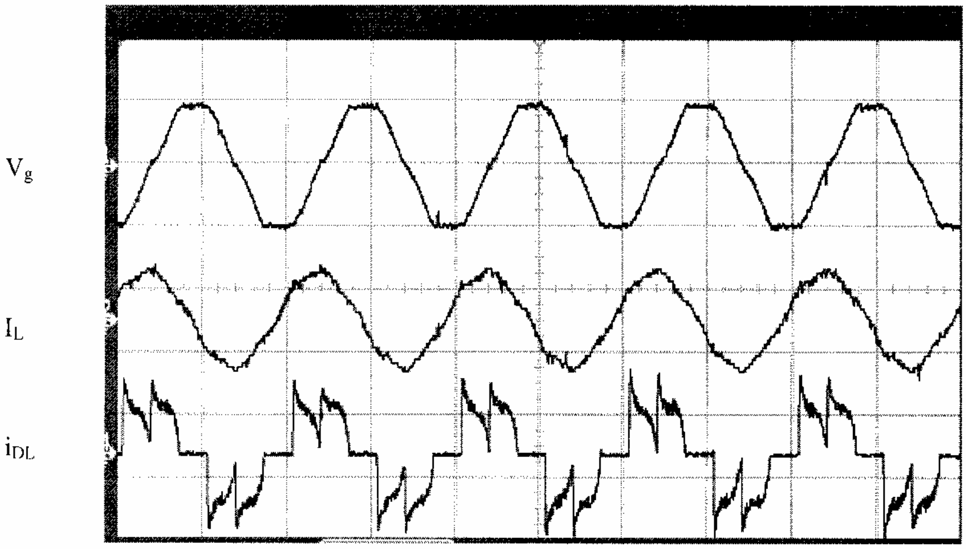


Fig. 4.5 Steady state SEIG (3.7 kW) voltage, main load current and dump load current

CHAPTER – V

Conclusion and Scope of Further Work

5.1 GENERAL

Present investigation is mainly aimed at analyzing the steady state and transient behavior of three phase self excited induction generator. The steady state performance of the system with and without series compensation have been analysed.

5.2 MAIN CONCLUSIONS

Steady state and transient analysis of balanced three phase SEIG with load have been presented. The steady state model is based on the nodal admittance method. The method is quite flexible and simplified and can be adopted for different schemes by assigning the suitable values to the circuit element of the scheme under study. Typical steady state characteristic under short shunt and long shunt configuration have been identified. Effect of shunt and series capacitance values on steady state performance have been studied thoroughly. A methodology have been developed to select optimum value of excitation and series capacitors for satisfactory operation of the system.

Addition of series capacitor provide self regulatory feature to the self excited induction generator and results almost flat load characteristic through out its operating range. Various results have been taken by performing experiments to find optimum values of series capacitor.

It has been found that by performing investigations on addition of series capacitor results more appropriate from operational point of view suitable experimentation have been performed to assess transient behavior of the system. The process of voltage build–up, load perturbation with and without series capacitors in SEIG system.

A study on the voltage control of SEIG using load controller is also presented. A prototype model of load controller was developed and tested for satisfactory operation of the system.

5.3 FUTURE SCOPE OF WORK

Although the main objective of the project was to study the steady – state and transient performance of series compensated SEIG, however the following points could be investigated in future.

(a) Design modification of induction machine for improved performance of SEIG in terms of better voltage regulation.

(b) Development of controllers to regulate the voltage and frequency irrespective of the nature of the load.

(c) Steady state and transient analysis of the self excited induction generator with new type of voltage regulators.

APPENDIX I

Matrices of (1) are defined as

$$(v) = \begin{pmatrix} v_{ds} & v_{qs} & v_{dr} & v_{qr} \end{pmatrix}^T \qquad (i) = \begin{pmatrix} i_{ds} & i_{qs} & i_{dr} & i_{qr} \end{pmatrix}^T$$

[R], [L] and [G] in (1) represent 4 × 4 matrices of resistance, transformer inductance, and speed inductance, respectively, and are defined as

$$[R] = diag[R_s \quad R_s \quad R_r \quad R_r]$$

$$[L] = \begin{bmatrix} L_{ss} & 0 & L_m & 0 \\ 0 & L_{ss} & 0 & L_m \\ L_m & 0 & L_{rr} & 0 \\ 0 & L_m & 0 & L_{rr} \end{bmatrix}$$

$$[G] = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_m & 0 & L_{rr} \\ L_m & 0 & L_{rr} & 0 \end{bmatrix}$$

Where $L_{ss} = L_s + L_m$ and $L_{rr} = L_r + L_m$. here, subscripts *d*, *q* refer to *d* and *q* axes (in the stationary reference frame), and *r* refer to stator and rotor, and *m* refers to the magnetizing component.

APPENDIX II

Parameters of SEIG (3.7 kW) – A 415V, 7.3 – A, 50 Hz four pole three – phase squirrel –cage induction machine is used as the SEIG. The parameters of the SEIG are as follows:

$$R_s = 1\Omega$$
$$R_r = 0.77\Omega$$
$$X_{ls} = \omega L_s = 1\Omega$$
$$X_{lr} = \omega L_r = 1\Omega$$
$$J = 0.1384 \frac{kg}{m^2}$$

The coefficients of the magnetizing curve in the equation $\left(Lm = a + b\,Im + cI_m^2 + dI_m^3\right)$ for a 3.7 kW SEIG are as follows:

a = 0.1407   b = 0.0014   c = - 0.0012   d = 0.00005

APPENDIX A

SLIP FOR SPECIFIED VOLTAGE AND INPUT POWER

The per – phase steady – state equivalent circuit of induction machine fed from infinite bus and the operating slip s for the specified output P_{out}^{m} can be obtained by its Thevein equivalent.

Output power and rotor current are expressed as

$$P_{out}^{m} = I_r^{m2} R_r^{m} \frac{(1-s)}{s} \tag{A.1}$$

$$I_r^{m} = \frac{V_{th}}{\left(R_{th} + \frac{R_r^{m}}{s}\right) + jX_{th}} \tag{A.2}$$

Where

$$Z_{th} = \left(jX_m^{m} F\right) \parallel \left(R_s^{m} + jX_{ls}^{m}\right) + jX_{lr}^{m}$$

$$V_{th} = \frac{\left(jX_m^{mF}\right) V^{\inf}}{\left(R_s^{m} + j\left(X_{ls}^{m} + X_m^{m}\right)\right)} \tag{A.3}$$

Substituting I_r^{m} from (A.2) to (A.1) results in

$$P_{out}^{m} = \frac{V_{th}^2 R_r^{m}}{\left(Rth + \frac{R_r^{m}}{s}\right)^2 + X_{th}^2} \frac{(1-s)}{s} \tag{A.4}$$

Equation (A.4) can be expressed into a second – order polynomial as (A.5). The solution of (A.5) gives the slip s

$$As^2 + B_s + C = 0 \tag{A.5}$$

Where

$$A = R_{th}^2 + X_{th}^2 - \frac{V_{th}^2 R_r^{m}}{P_{out}^{in}}$$

$$B = 2R_{th} R_r^{m} + \frac{V_{th}^2 R_r^{m}}{P_{out}^{in}}$$

$$C =_r^{m,2}$$

APPENDIX B

LOOP – IMPEDANCE CONSTRAINTS

Under steady–state condition while maintaining self–excitation (stator current is not zero), the loop impedance Z_{loop} must be zero at each load point

$$Z_{loop} = Z_s + Z_{mr} + Z_{Lc} = 0$$

Where

$$Z_s = R_s + jX_{ls}F$$

$$Z_{mr} = \frac{Z_m Z_r}{(Z_m + Z_r)}$$

$$ZLc = \frac{(Z_L + Z_{ES})Z_{hs}}{(Z_L + Z_{ES} + Z_{hs})}$$

$$Z_r = \frac{R_r F}{(F - v)} + jX_{lr}F$$

$$Z_m = jX_m F$$

$$Z_L = R_L + jX_L F$$

$$X_{es} = \frac{3}{(\omega C_{es})}$$

$$X_{hs} = \frac{1}{(\omega C_{hs})}$$

$$Z_{ES} = -\frac{jX_{ES}}{F}$$

$$Z_{hs} = -\frac{jX_{hs}}{F}$$

Resolving Z_{loop} in real and imaginary parts results into fourth – and fifth – order polynomials T_1 and T_2 of unknown variables X_m and F, which are written

$$T_1(X_m, F) = \sum_{j=0}^{4}\left(C^{2j+1}X_m + C^{2j+2}\right)F^{4-j} = 0$$

$$T_2(X_m, F) = \sum_{j=0}^{5}\left(D^{2j+1}X_m + D^{2j+2}\right)F^{5-j} = 0$$

Constants for polynomial T_1

$$C^1 = -(R_L(X_{ls} + X_{lr}) + X_L(R_s + R_r))$$

$$C^2 = -(X_L(R_r X_{ls} + R_s X_{lr}) + X_{ls}X_{lr}R_L)$$

$$C^3 = v(R_s X_L + R_L(X_{ls} + X_{lr}))$$

$$C^4 = vX_{lr}(R_L X_{ls} + R_s X_L)$$

$$C^5 = R_L X_{hs} + (X_{ES} + X_{hs})(R_s + R_r)$$

$$C^{6} = \left(X_{ES} + X_{hs}\right)\left(R_s X_{lr} + R_r X_{ls}\right)$$
$$= R_r\left(R_L R_s + X_L X_{hs}\right) + R_L X_{hs} X_{lr}$$
$$C^{7} = -v\left(R_s\left(X_{ES} + X_{hs}\right) + R_L X_{hs}\right)$$
$$C^{8} = -vX_{lr}\left(R_L X_{hs} + R_s\left(X_{ES} + X_{hs}\right)\right)$$
$$C^{9} = 0.0$$
$$C^{10} = -R_r X_{ES} X_{hs}$$

Constants for polynomials T_2

$$D^{1} = -X_L\left(X_{lr} + X_{ls}\right)$$
$$D^{2} = -X_{lr} X_{ls} X_L$$
$$D^{3} = vX_L\left(X_{lr} + X_{ls}\right)$$
$$D^{4} = vX_{ls} X_{lr} X_L$$
$$D^{5} = R_L\left(R_s + R_r\right) + X_L X_{hs} + \left(X_{lr} + X_{ls}\right)\left(X_{ES} + X_{hs}\right)$$
$$D^{6} = X_{lr}\left(R_s R_L + X_L X_{hs} + X_{ls}\left(X_{ES} + X_{hs}\right)\right)$$
$$+ R_r\left(R_s X_L + R_L X_{ls}\right)$$
$$D^{7} = -v\left(X_L X_{hs} + R_s R_L + \left(X_{ES} + X_{hs}\right)\left(X_{ls} + X_{lr}\right)\right)$$
$$D^{8} = -vX_{lr}\left(X_L X_{hs} + X_{ls}\left(X_{ES} + X_{hs}\right) + R_s R_L\right)$$
$$D^{9} = -X_{ES} X_{hs}$$
$$D^{10} = -\left(X_{hs}\left(R_r R_l + X_{ES} X_{lr}\right) + R_r R_s\left(X_{ES} + X_{hs}\right)\right)$$
$$D^{11} = vX_{ES} X_{hs}$$
$$D^{12} = vX_{ES} X_{hs} X_{lr}$$

REFERENCES

[1] E. D. Bassett and F. M. Potter, "Capacitive Excitation for induction generator", *AIEE Trans.*, vol. 54, pp. 540 -545, May 1935.

[2] S.S. Murthy, O. P. Malik, and A. K. Tondon, "Analysis of self – excited induction generator," *Proc. Inst. Elect. Eng.*, pt. C., vol. 129, no. 6, pp 260-265, Nov 1982.

[3] J. M. Elder, J. T. Boys and J. L. Boys and J. L. Woodward, "The process of self excitation in induction generators", *IEE Proc.*, Pt. B, vol. 130, pp.103 -107, March 1983.

[4] A. K. Tandon, S. S. Murthy and G. J. Berg, "Steady state analysis of capacitor excited induction generators", *IEEE Trans. On Power App. And Sys.*, Vol. PAS – 103, pp. 612 618, March 1984.

[5] D. Sutanto, B. Mismail, H. R. Outhred, C. Grantham, P. Bryce and K. C. Daly, "Transient simulation of capacitively self – excited induction generators", Electric Energy Conference, Adelaide, 6 – 9 Oct. 1987.

[6] C. Grantham, D. Sutanto, and B. Mismail, " Steady – state and transient analysis of self – excited induction generators," *Proc. Inst. Eect. Eng.*, Pt. B, vol. 136, no. 2, pp. 61 – 68, Mar.1989.

[7] R. Bonert and G. Hoops, "Stand – alone induction generator with terminal impedance controller and no turbine controls," *IEEE Trans. Energy Convers.*, vol.5, no. 2, pp. 28 – 3, Mar. 1990.

[8] K. E. Hallenius, P. Vas, and J. E. Brown, "The analysis of a saturated self – excited asynchronous generator," *IEEE Trans. Energy Convers.*, vol. 6 no. 2, pp. 336 – 345, Jun. 1991

[9] L. Shridhar, Bhim Singh and C. S. Jha, "A step towards improvement in the characteristics of the self excited induction generator", *IEEE Trans. On Energy Conversion,* Vol. 8, no. 1, pp. 40 -46, March 1993

[10] L. Shridhar, and C. S. Jha, and B. P. Singh, "Analysis of self –excited induction generator feeding induction motor," *IEEE Trans. Energy Convers.*, vol. 9, no. 2, pp. 390 – 396. Jun. 1994

[11] N.P.A. Smith " Induction generators for stand – alone micro – hydro systems, " in *Proc. IEEE Int. conf. Power Electronics Drives and Energy System*, New Delhi, India. Jan 1996, pp. 669-673

[12] R. Bonert and S. Rajakaruna, "Self – excited induction generator with excellent voltage and frequency control.' Proc. IEEE – Generation, Transmission, Distrib., vol. 145, no. 1. pp. 33 -39, Jan. 1998.

[13] S. S. Murthy, R. Jose, and B. Singh, "Experience in the development of microhydel grid independent power generation scheme using induction generators for Indian condition," in *Proc. IEEE Int. Conf. Global Connectivity in Energy, Computer, Communication and Control*, vol.2, 1998, pp.461 – 465.

[14] Mustafa A. Al –Saffar, Eui – Cheol Nho, Thomas A. Lipo, "Controlled shunt capacitor self excited Induction Generator" *IEEE Trans. On energy Cons.*, pp. 1486 – 1490, 1998.

[15] B. Singh, L. Shridhar, and C. S. Jha, "Transient analysis of self – excited induction generator supplying dynamic Load," *Elect. Mach. Power Syst.*, vol. 27, pp. 941 – 954, 1999.

[16] L. Wang and C. H. Lee, "Dynamic analysis of parallel operated self –excited induction generators feeding an induction motor load," *IEEE Trans. Energy Convers.* vol. 14, no.3, pp. 749 – 485, Sep. 1999.

[17] Li Wang, Ruey Yong Deng, "Transient performance of an isolated induction generator under unbalanced excitation capacitors", *IEEE Trans. On Energy Conservation*, vol. 14, no. 4, pp. 887 – 893 Dec. 1999.

[18] Li Wang and Ching – Huei Lee, "Long – shunt and short – shunt connections on dynamic performance of a SEIG Leeding an Induction Motor Load," *IEEE Trans. Energy Convers.*, vol.15, no. 1, pp. 1- 7, Mar. 2000.

[19] Sung – Chun Kuo and Li Wang, "Dynamic eigen value analysis of a self – excited Induction Generator feeding an Induction Motor." *IEEE 2001* pp. 1393 -1397.

[20] Tarek Ahmed, Eiji Hiraki and Mutsuo Nakaoka and Naro, "Three – Phase self excited Induction Generator driven by variable – speed prime mover for clean renewable energy utilizations and its terminal voltage regulation characteristics by Static VAR Compensator", *IEEE 2003*, pp. 693 – 700.

[21] Tarek Ahmed, Osamu Noru, Kazuya Matsuo, Yuji Shindo and Musuo Nakaoka,"Minimum excitation capacitance requirements for wind turbine coupled stand alone self – excited induction generator with voltage regulation based on SVC,"IEICE/*IEEE*, INTELEC03, pp. 396 – 403 Oct. 2003.

[22] Bhim Singh, S.S. Murthy and sushma Gupta, "Modelling and Analysis of STATCOM based voltage regulator for self – excited induction generator with unbalanced loads," *IEEE*/2003, pp. TENCON 2003/1110 – 2003/1114

[23] Tarek Ahmed, Student Member IEEE, Osamu Noro, Eiji Hiraki, and Mutsuo Nakaoka, "Terminal voltage regulation characteristics by Static Var Compensator for a three – phase self excited induction generator," *IEEE Trans. on industary applications* Vol. 40, no. 4, pp. 978 – 988, July/Aug. 2004

[24] S. P. Singh, Sanjay K. Jain, and J. Sharma, "Voltage regulation optimization of compensated self – excited induction generator with dynamic load," *IEEE Trans. On Energy Conservation*, Vol. 19, no. 4, pp. 724 – 732, Dec 2004.

[25] G. V. Jayaramaiah, B. G. Fernandes "Analysis of voltage regulator for a 3–D self excited Induction Generator, using current controlled voltage source inverter." Pp 1404 -1408.

[26] Bhim Singh, S. S. Murthy and Susma Gupta, "Transient analysis of Self – Excited Induction Generator with Electronic Load Controller (ELC) Supplying Static & Dynamic Loads, pp. 771 -776

[27] Bhim Singh, S. S. Murthy and Sushma Gupta, "Transient analysis of self – excited induction generator with electronic load controller (ELC) supplying static and dynamic Loads," *IEEE Trans. on Industry Applications*, vol. no. 5, pp. 1194 - 1204, Sept/Oct. 2005