

# **Steady State Analysis of Three-Phase Self-Excited Induction Generator**

*Thesis submitted in partial fulfillment of the requirements for the award of degree of*

**Master of Engineering  
in  
Power Systems & Electric Drives**



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## Certificate

I hereby certify that the work which is being presented in the thesis entitled, “**Steady State Analysis of Three Phase Self-Excited Induction Generator**”, in partial fulfillment of the requirements for the award of degree of Master of Engineering in *Power Systems & Electric Drives* submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Mr. Yogesh K. Chauhan.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.


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

  
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## **Abstract**

Use of an induction machine as a generator is becoming popular for the harnessing the renewable energy resources. Reactive power consumption and poor voltage regulation under varying load are the major drawbacks of the induction generator. The analysis of steady state performance is paramount as far as the running conditions of machine are concerned. To study the steady state aspects, we require methods by which the generator performance is predicted by using the induction motor data so that the effect of the basic parameters can be assessed. Having identified these it is essential to estimate correctly the magnetizing characteristics and related air-gap voltage under different flux conditions. Different methods are available to identify the steady state quiescent operating point under saturation for a given set of speed, load and excitation capacitor. These methods determine the saturated magnetizing reactance and per unit frequency. The operating air-gap flux can be then obtained by simulating zero rotor current conditions or a synchronous speed test. For its operation, the induction generator needs a reasonable amount of reactive power which must be fed externally to establish the magnetic field necessary to convert the mechanical power from its shaft into electrical energy.

The NR method, a conventional method used for several decades to analyze the steady state performance of SEIG but it has some limitations. The genetic algorithm which is based on natural selection process and survival of fittest theory has several advantages over conventional method.

The thesis work presents a steady state analysis of SEIG with a resistive and resistive–inductive load at various power factor using both NR and GA methods. Both simulated and experimental results are compared to examine the performance under various loading conditions. Both NR and GA simulated results are compared and performances with GA results are found to be slightly improving as compared to conventional NR method as far as the voltage regulation and loading is concern.

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## List of symbols

$\omega$	angular frequency
F	pu generated frequency
$I_L$	pu load current
$I_s$	pu stator current
$R_1$	pu stator resistance
$R_2$	rotor resistance
Rl	load resistance
$s$	slip factor
v	pu speed
Vl	pu load voltage
$V_s$	pu stator voltage
$V_g$	pu air gap voltage
$X_c$	pu shunt capacitance
$X_1$	pu stator reactance
$X_2$	pu rotor reactance
Xl	pu load reactance
$X_m$	pu magnetizing reactance
a	pu real term coefficient
b	pu imaginary term coefficient
j	pu imaginary operator

# Chapter 1

## Introduction

### 1.1 Historical background

Induction generators were used from the beginning of the 20<sup>th</sup> century until they were abandoned and almost disappeared in the 1960s. With the dramatic increase in petroleum prices in the 1970s, the induction generator returned to the scene. With such high-energy costs, rational use and conservation implemented by many process of heat recovery and other similar forms became important goals. By the end of the 1980s, wider distribution of population over the planet, as improved transportation and communication enabled people to move away from large urban concentration, and growing concerns with the environment led to demand by many isolated communities for their own power plants. In the 1990s, ideas such as distributed generation began to be discussed in the media and in research centers [1].

Traditionally, synchronous generators have been used for power generation but induction generators are increasingly being used these days because of their relative advantageous features over conventional synchronous generators. These features are brush less and rugged construction, low cost, maintenance and operational simplicity, self-protection against faults, good dynamic response, and capability to generate power at varying speed. For its simplicity, robustness, and small size per generated kW, the induction generator is favored for small hydro and wind power plants.

The need of external reactive power, to produce a rotating flux wave limits the application of an induction generator as a stand-alone generator. However, it is possible for an induction machine to operate as a self-excited induction generator (SEIG) if capacitors are connected to the stator terminals to supply sufficient reactive power.

## **1.2 Induction Generator**

The induction generator has the very same construction as induction motor with some possible improvements in efficiency. There is an important operating difference; the rotor speed is advanced with respect to stator magnetic field rotation. For prime mover speed above synchronous speed, the rotor is being driven at a speed more than synchronously rotating magnetic field. The rotor conductors are now being cut by the rotating flux in a direction opposite to that during motoring mode. This shows that rotor generated emf, rotor current and hence its stator components change their signs. As the speed during induction generator operation is not synchronous, it is also called an asynchronous generator.

## **1.3 Classification of Induction Generators**

The induction machine offers advantages for hydro and wind power plants because of its easy operation as either a motor or generator, it has different application in different areas, and depending upon them it has many classifications [1].

Induction generators can be classified on the basis of excitement process as

- Grid connected induction generator
- Self-excited induction generator

Further induction generators are classified on the basis of rotor construction as

- Wound rotor induction generator
- Squirrel cage induction generator

Depending upon the prime movers used and their locations, generating schemes can be broadly classified as under

- Constant speed constant frequency [CSCF]
- Variable speed constant frequency [VSCF]
- Variable speed variable frequency [VSVF]

### 1.3.1 Grid Connected Induction generator

The grid connected induction generator takes its reactive power for excitement process from the grid supply, so it is called grid connected induction generator. It is also called autonomous system. In this system generator is driven by a prime mover above its synchronous speed and hence the slip is negative in case of grid connected induction generator.

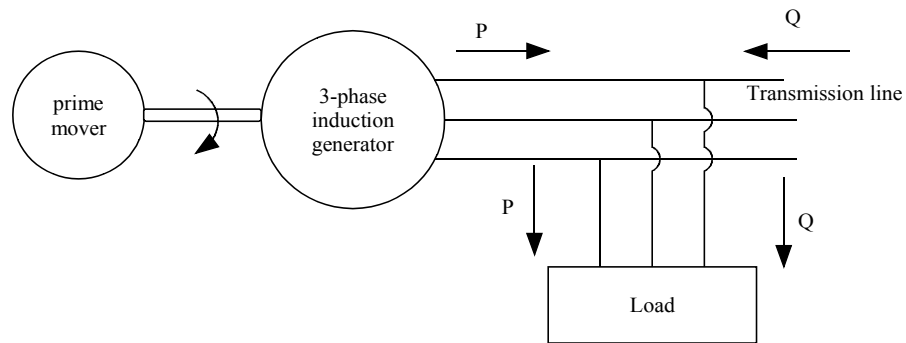


Figure 1.1: Grid connected induction generator

Figure 1.1 shows a grid connected induction generator. The power factor of the grid-connected induction generator is fixed by its slip and its equivalent circuit parameters and not affected by the load [2].

### 1.3.2 Self-excited Induction Generator

By self-excited induction generator (SEIG), we mean cage rotor induction machines with shunt capacitors connected at their terminals for self excitation.

The shunt capacitors may be constant or may be varied through power electronics (or step wise). SEIG may be built with single phase or three phase output and may supply AC loads or AC rectified autonomous loads [3].

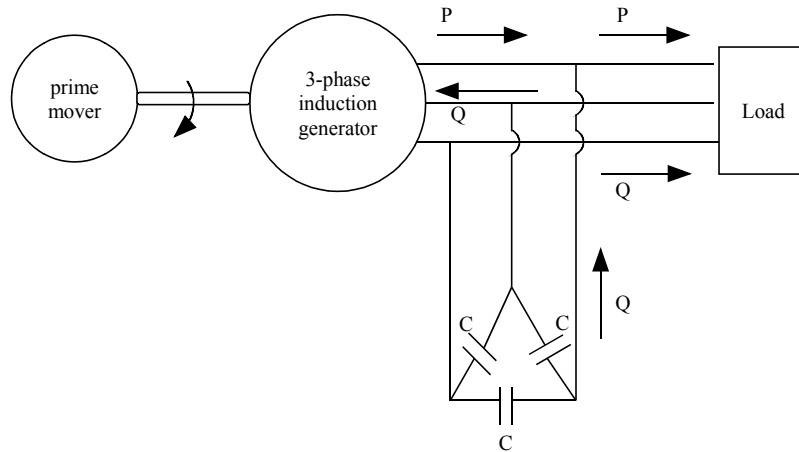


Figure 1.2: Self-excited induction generator

In figure 1.2 a capacitor bank is connected across the stator terminals of a 3-phase induction machine which supply the reactive power to the induction generator for self excitement process and as well as to the load.

### 1.3.3 Constant Speed Constant Frequency

In this scheme, the prime mover speed is held constant by continuously adjusting the blade pitch and/or generator characteristics. An induction generator can operate on an infinite bus bar at a slip of 1% to 5% above the synchronous speed. Induction generators are simpler than synchronous generators. They are easier to operate, control, and maintain, do not have any synchronization problems, and are economical [4].

### 1.3.4 Variable Speed Constant Frequency

The variable-speed operation of wind electric system yields higher output for both low and high wind speeds [4], [5]. This results in higher annual energy yields per rated installed capacity. Both horizontal and vertical axis wind turbines exhibit this gain under variable-speed operation. Popular schemes to obtain constant frequency output from variable speed are as

#### **1.3.4.1 AC–DC–AC Link**

With the advent of high-powered thyristors, the ac output of the three-phase alternator is rectified by using a bridge rectifier and then converted back to ac using line-commutated inverters. Since the frequency is automatically fixed by the power line, they are also known as synchronous inverters [4].

#### **1.3.4.2 Double Output Induction Generator (DOIG)**

The DOIG consists of a three-phase wound rotor induction machine that is mechanically coupled to either a wind or hydro turbine, whose stator terminals are connected to a constant voltage and constant frequency utility grid [6]. The variable frequency output is fed into the ac supply by an ac–dc–ac link converter consisting of either a full-wave diode bridge rectifier and thyristor inverter combination or current source inverter (CSI)-thyristor converter link. One of the outstanding advantages of DOIG in wind energy conversion systems is that it is the only scheme in which the generated power is more than the rating of the machine. However, due to operational disadvantages, the DOIG scheme could not be used extensively. The maintenance requirements are high, the power factor is low, and reliability is poor under dusty and abnormal conditions because of the sliding mechanical contacts in the rotor. This scheme is not suitable for isolated power generations because it needs grid supply to maintain excitation.

#### **1.3.5 Variable-Speed Variable Frequency**

With variable prime mover speed, the performance of synchronous generators can be affected. For variable speed corresponding to the changing derived speed, SEIG can be conveniently used for resistive heating loads, which are essentially frequency insensitive. This scheme is gaining importance for stand-alone wind power applications [7].

### **1.4 Merits and Demerits of Induction Generator**

Several types of generators can be coupled to the rotating power turbines; DC and AC types, parallel and compound DC generators, with permanent magnetic or electrical fields, synchronous or asynchronous, and, specially, induction generators. The right

choice of generator depends on a wide range of factors related to the primary source, the type of load, and the speed of the turbine, among others.

Induction generator having the following merits:

- Simple and robust construction
- Can run independently
- Inexpensive
- Minimal maintenance
- Inherent overload protection
- At high speed ~400 Hz, reduces size and weight of machine (roughly 0.33 m long , 0.5 m diameter) and filter components
- Stand-alone applications, no fixed frequency

Induction generator has the drawback that it requires significant reactive energy and it have poor power factor.

## **1.5 Application of Induction Generator**

Application of an induction generator can be classified as:

### **For the electrification of far flung areas**

(Extension of national grid is not economical)

- Remote family
- Village community
- Small agricultural applications
- Lighting and heating loads

### **For feeding critical locations**

- Library
- Computer centres
- Hospitals
- Telephone exchange
- Cinema Hall
- Auditorium
- Marketing complex

### **As a portable source of power supply**

- Decorative lighting
- Lightings for projects and constructional site

## **1.6 Literature Review**

### **1.6.1 Introduction**

Use of an induction machine as a generator is becoming popular for the renewable energy sources. Reactive power consumption and poor voltage regulation under varying frequency are the major drawbacks of the induction generators, but development of static power converters has facilitated the control of the output voltage of an induction generator [8]-[23]. This chapter presents an overview of 3-phase self-excited induction generator (SEIG).

### **1.6.2 Classification of Induction Generators**

Mainly IGs are two types wound rotor IGs and squirrel cage IGs further it can be classified as grid connected and self excited IGs. Depending upon their prime movers used and their locations these can be broadly classified as constant speed constant frequency (CSCF), variable speed constant frequency (VSCF) [19], [20] and variable speed variable frequency (VSVF) [9], [10].

### **1.6.3 Self Excitation Process and Voltage Buildup in SEIG**

The process of voltage buildup in an induction generator is very much similar to that of a dc generator. There must be a suitable value of residual magnetism present in the rotor. In the absence of a proper value of residual magnetism, the voltage will not build up. So it is desirable to maintain a high level of residual magnetism, as it does ease the process of machine excitation [24] - [43]. T. Ahmed [24] present a paper for variable speed prime mover for minimum capacitance required for self excitation, he used a nodal admittance approach to find it. Li Wang [25] presents a simple and direct approach based on first-order Eigen value sensitivity method to determine both maximum and minimum values of capacitance required for an isolated self-excited induction generator (SEIG) under different loading conditions. G.K.Singh [33] presents a paper for 6-phase induction

generator using capacitive self excitation. Décio Bispo [36] takes the magnetic saturation effects and third harmonics which are generated due to this magnetic effect in analysis for self excitation process. An unbalanced excitation scheme is proposed by Bhattacharya [38] which improves balance overall and maximizes the allowable power output of a particular machine. The minimum terminal capacitor required for induction generator to build up is the main concern. Eltamaly [39] proposed technique, which uses nodal analysis instead of loop analysis to obtain just one formula for the minimum capacitance required for induction generator operation at different load and speed conditions. In this technique, the operating frequency can be obtained directly from equating the real part of admittance with zero where the real part does not function in  $X_c$ , then use the imaginary part to calculate the value of  $X_c$ .

#### **1.6.4 Steady State Analysis**

The analysis of steady state performance is important for ensuring good quality power and assessing the suitability of the configuration for a particular application. In an isolated power system, both the terminal voltage and frequency are unknown and have to be computed for a given speed, capacitance, and load impedance. A large number of articles have appeared on the steady state analysis of SEIG [8], [9], [11], [44] – [72].

L. Shridhar *et al.* [44] presents a paper for dynamic load as induction motor, they applied an algorithm, based upon per phase equivalent circuit of SEIG and find out the unknown values of magnetizing reactance and frequency, after solving two non linear equations. Bhim Singh *et al.* [45] have proposed a technique for SEIG steady state analysis using different mode of operation of a single phase SEIG. S.C. Kuo and L. Wang [46] analyzed the harmonics effect in SEIG feeding a rectifier load. A hybrid model based on abc and q-d induction machine models is employed to describe the dynamic equations of the studied system to improve simulation results.

S. S. Murthy *et al.* [47] have presents a Matlab based generalized algorithm to predict the dynamic and steady state performance of self-excited induction generators (SEIG) under any combination of speed, excitation capacitor and loading. Three different methods, operational equivalent circuit, Newton-Raphson and equivalent impedance method are used for analyzing under any given situation. Chan [49] has proposed two

solution technique for the steady state analysis of self-excited induction generator. He proposed an iterative technique by assuming some initial value for frequency and magnetizing reactance and then solving for a new value considering a small increment until the result converges.

Murthy *et al.* [59] presents the steady state analysis of a SEIG feeding three phase unbalance load. Symmetrical component theory was used to obtain relevant performance equations through sequence quantities. T. Chandra Sekhar *et al.* [70] uses the phasor notations for steady state analysis of SEIG as spiral vector theory.

Abdulrahman L. Alolah [71] has proposed an optimization based approach for steady state analysis of SEIG; the problem is formulated as a multidimensional optimization problem. A constrained optimizer is used to minimize a cost function of the total impedance or admittance of the circuit of the generator to obtain the frequency and other performance of the machine. Yaser N. Anagreh [72] has further posed an another optimization technique for steady state analysis; the method is based on the implementation of a constrained optimizer “finincon”, which is built in MATLAB, to minimize the total impedance equation of the generator and then determining the required unknown parameters. The main advantage of this technique, compared with other methods of analysis, is its simplicity since no lengthy algebraic derivations are required.

### **1.6.5 Transient Analysis**

The analysis during the transient condition helps in determining the insulation strength, suitability of winding, shaft strength, value of capacitor, and devising the protection strategy. The operation of a self-excited induction generator under unbalanced operating condition causes additional losses, excessive heating, large insulation and shaft vibrations. The various dynamic models have been proposed to study the dynamic and transient behavior of SEIG. Most of the transient studies of SEIG are related to voltage buildup due to self excitation [8], [10], [24], [25], [44]-[47], [51], [56], [59], [64]-[67], [73]-[79].

S. S. Murthy *et al.* [47] presents a Matlab based generalized algorithm to predict the dynamic performance of SEIG, they proposed an iterative technique to find out the dynamic performance. M.H. Salama [58] presents that a selection of capacitance and

loading can compensate for saturation effects on the self-excitation process. Sufficient remanence to initiate self-excitation is assumed and it is shown that there is critical minimum load impedance and a critical minimum value of terminal capacitance required to permit self-excitation. The critical value of capacitance for self-excitation is shown to be significantly affected by the rotor speed and the load power factor. A second mathematical model in the form of a lumped-parameter equivalent circuit is presented. Analysis shows that the value of capacitance used for self-excitation and the nature of the load significantly affect magnetizing reactance.

Mahmoud M. Neam *et al.* [73] presents the analysis, design and simulation of wind-powered SEIG. The three -phase SEIG is driven by a variable speed prime mover (VSPM) such as a wind turbine for the clean alternative renewable energy in rural areas. The VSPM is modeled by as a variable-speed separately-excited DC motor to simulate to the wind turbine. Also, the paper describes the dynamic performance of the VSPM and SEIG which includes prime mover torque, rotor speed, rotor frequency, and d-q axes dynamic stator voltages, As well as the electromagnetic torque and the magnetizing inductance of the SEIG. During voltage build up of the SEIG, the variation of the magnetizing inductance is considered. Bhim Singh *et al.* [74] presents a transient analysis of a SEIG with electronic load controller (ELC) used in stand-alone micro-hydro power generation employing uncontrolled turbines and supplying static and dynamic loads. Avinash Kishore *et al.* [75] proposed a generalized state-space dynamic modeling of a three phase SEIG has been developed using d-q variables in stationary reference frame for transient analysis. The proposed model for induction generator, load and excitation using state space approach can handle variable prime mover speed, and various transient conditions e.g. load perturbation, switching states etc. Also the effect of variation of excitation capacitance on system is analyzed.

Li Wang [76] has proposed an algorithm for dynamic performance of SEIG under unbalanced excitation capacitor. Mahto *et al.* [77] presents a transient behavior of a single phase self regulated SEIG using a 3-phase SEIG. D.Seyoum [78] presents the effect of magnetizing inductance on self-excitation. It also describes the loading analysis of an isolated induction generator, and how the operating frequency and generated voltage are affected by the change in operating slip value for regulated and unregulated

rotor speed. P. K. Shadhu Khan *et al.* [79] presents transient behavior of the integrated system of stand-alone SEIG and inductively loaded current controlled solid-state (ICSL) VAR compensator has been carried out when the system is subjected to different dynamic conditions. Analytical transient model for the system has been developed. Waveforms of the voltage build up due to self excitation of the generator at specific switching delay angle of the compensator, output terminal voltage, currents etc. due to perturbations in load and switching delay angle of the compensator and the overload condition of the generator have been analyzed to bring out the special features of the integrated system under transient condition.

### **1.6.6 Voltage and Frequency Control Strategy**

The induction generator having mainly two drawbacks one is need of reactive power support and second is poor voltage regulation [8]. The voltage regulation can be improved by using additional series capacitors in its short and long shunt configurations. Different controllers are used for improving the frequency and voltage regulation. A considerable amount of work has been directed towards the design and the analysis of voltage and frequency regulators [80]-[87].

Tarek Ahmed *et al.* [80] proposed an impedance approach for voltage and frequency regulation. a proportional–integral (PI) closed-loop feedback voltage regulation of the three-phase SEIG driven by the VSPM on the basis of the static var compensator (SVC) composed of the thyristor phase-controlled reactor in parallel with the thyristor switched capacitor and the fixed-excitation capacitor bank is designed and considered for the wind generation as a renewable power conditioner. The simulation analysis and experimental results obtained from the three-phase SEIG with SVC for its voltage regulation prove the practical effectiveness of the additional SVC with the PI-controller-based feedback loop in steady-state operation in terms of high performance with low cost. B.Venkatesa Perumal [81] has proposed that a dc link capacitor provided with the STATCOM, battery energy storage improves system stability and prevents power wastage.

H.C. Rai *et al.* [82] proposed a scheme which used passive element such as capacitors, saturable reactors, and constant voltage regulator for improvement of performance of SEIG. Bhim Singh *et al.* [83] have proposed a analysis of SEIG operating

with an Electronic Load Controller (ELC) for regulating its voltage and frequency under varying load condition. The ELC consists of a rectifier and a chopper circuit whose operation generates harmonics on AC side of the SEIG system. To achieve adequate performance characteristics of the SEIG with ELC information of harmonic contents and real power is necessary. In this a complete description of the AC current harmonics generated in the ELC operation and their effects on the performance of SEIG is presented in detail. Dheeraj Joshi *et al.* [84] applied genetic algorithm for constant voltage and constant frequency operation.

S. K. Jain *et al.* [85] proposed the use of damping resistors across series capacitors is proposed to damp out the starting transients and for the stable operation. The simulated annealing like approach is used to solve voltage regulation optimization problem. S. S. Murthy *et al.* [86] presents an analytical technique to predict the steady state performance of SEIG for autonomous power generation which employs both shunt and series capacitors for voltage regulation. The system is modeled using an equivalent circuit which interconnects the machine, capacitor and the load. G. V. Jayaramaiah [87] presents a DSP-based constant voltage controller for stand alone wind energy conversion system using an induction generator. The system uses a pulse-width modulated voltage source inverter (PWM-VSI) with a start-up battery. To overcome from voltage regulation problem, a DSP-based voltage controller is developed. It regulates the voltage when SEIG is subjected to a sudden application/removal of load.

Rohin M. Hilloowala [88] proposed a fuzzy logic based controller for the output control for PWM inverter system used for voltage regulation which is further used for voltage regulator for voltage and frequency compensation or constant voltage and frequency operation of self-excited induction generators

### **1.6.7 Parallel Operation of SEIG**

As there are constraints on SEIG ratings per unit for micro hydro or wind turbines, several such SEIGs may have to be operated in parallel. Several papers have been presented over parallel operation of SEIGs [89]-[92].

Chandan Chakraborty *et al.* [89] have proposed an iterative solution for the problems related to steady state performance of self-excited induction generators operating in

parallel. The analysis is based on voltage and current balance equations derived from an inverse model for steady state equivalent circuit of induction machines. The non-linearity in the magnetization characteristics has been taken into account by piecewise linearization. The proposed method is general and can be applied for analysis of any number of parallel connected machines. Further Li Wang *et al.* [90] proposed a novel approach based on eigenvalue and eigenvalue sensitivity analyses to predict both minimum and maximum values of capacitance required for self-excitation of parallel operated three-phase induction generators.

A.H. Al-Bahrani [91] describes two methods of analysis to control the common bus voltage of any number of parallel SEIGs, under steady state balanced conditions. The proposed methods are general and can be used for a single or a group of SEIGs employing similar or different machines with equal or unequal prime movers speeds. F. A. Farret [92] presents an innovative and automatic numerical solution for steady-state and transient analysis of any number of SEIGs operating in parallel, by classical state space modeling.

### **1.6.8 Practical Applications of SEIGs**

Recently, the induction generators have been widely employed to operate as wind-turbine generators and small hydroelectric generators of an isolated power system. Stand-alone generator systems are used in a wide variety of situations such as remote area power supplies, lighting, transportation, life support systems, communications etc [8]. Several papers have been presented over the application field of induction generators [93], [94].

Rajesh Chaturvedi *et al.* [93] present an experimental study undertaken to assess the suitability of conventional induction motors as wind driven capacitor self-excited induction generators for autonomous power generation. T.L. Maguire [94] describes the design and laboratory testing of a novel generation apparatus for supplying an isolated dc load from a self-excited induction generator. The squirrel-cage induction motor, which is used in the apparatus, is very well suited for use in isolated locations operable at variable speed.

## **1.7 Organization of Thesis**

**Chapter 1** This chapter entitled as “Introduction” include the historical background of the Induction Generator it also include the different types of classification of the Induction Generator and its applications. The literature survey of three decades is also included in this chapter.

**Chapter 2** This entitled as “Steady State Analysis of Simple SEIG” this chapter mainly includes the steady state analysis of the SEIG using NR method. The practical results are validated with simulated results.

**Chapter 3** This chapter entitled as “Theory of Genetic Algorithm” this includes the basic theory and operators of GA. This chapter also includes the advantages and applications of GA.

**Chapter 4** This chapter entitled as “Steady State Analysis of SEIG using GA” this includes the steady state analysis of the SEIG using GA method. The NR results are validated with simulated GA results.

**Chapter 5** This chapter entitled as “Conclusion and Future Scope” mainly includes the conclusion and future scope of this thesis work.

## **1.8 Aim of Thesis**

The aim of the thesis work is to simulate the results using NR and GA method for steady state performance of SEIG under various power factor loading conditions. The results to obtained are experimentally validated and to show the further voltage regulation characteristic of SEIG.

## **1.9 Conclusion**

The investigations carried since three decades indicate the technical and economic viability of using induction generator for electric power generation to harness the renewable energy sources, particularly in remote and far flung areas where extension of grid is not economically feasible. The technology of induction generator, once fully developed and realized to the stage of large practical applications, has many advantages to offer over conventional systems.

This chapter has presented a comprehensive literature review on important aspects of SEIG such as the process of self-excitation and voltage buildup, modeling, steady-state and transient analysis, reactive power/voltage control, parallel operation, and applications. It is expected that better methods of reactive power/voltage-control techniques will make the SEIG more suitable for isolated applications.

## **Chapter 2**

### **Steady State Analysis of SEIG**

#### **2.1 Introduction**

The analysis of steady state performance is paramount as far as the running conditions of machine are concerned. To study the steady state aspects, we require methods by which the generator performance is predicted by using the induction motor data so that the effect of the basic parameters can be assessed. Having identified these it is essential to estimate correctly the magnetizing characteristics and related air-gap voltage under different flux conditions. Different methods are available to identify the steady state quiescent operating point under saturation for a given set of speed, load and excitation capacitor. These methods determine the saturated magnetizing reactance and per unit frequency. The operating air-gap flux can be then obtained by simulating zero rotor current conditions or a synchronous speed test. For its operation, the induction generator needs a reasonable amount of reactive power which must be fed externally to establish the magnetic field necessary to convert the mechanical power from its shaft into electrical energy.

When capacitors are connected to induction machine terminal for reactive power requirement, the system is usually called a SEIG, first invented by Basset and Potter in 1935.

#### **2.2 Self Excitation Process in SEIGs**

The process of voltage buildup in induction generator is similar to that in dc shunt generator. When the rotor of induction machine is run at the required speed, residual magnetism present in the rotor iron generates a small terminal voltage 'oa' across stator terminals; figure 2.1. This voltage produces a capacitor current ob. This current ob creates a flux which aid the residual flux, thus producing more flux and therefore more generated voltage 'bc' across stator terminals. This voltage 'bc' sends a current 'od' in the capacitor bank which eventually generates voltage de. This cumulative of voltage buildup continue till the saturation curve of induction generator intersects the capacitor

load line at point f, thus giving a no load generated emf of 'gf' for magnetizing current  $I_{m1}$ . The slope of load line is given by  $\tan^{-1}\left(\frac{1}{\omega C}\right)$ .

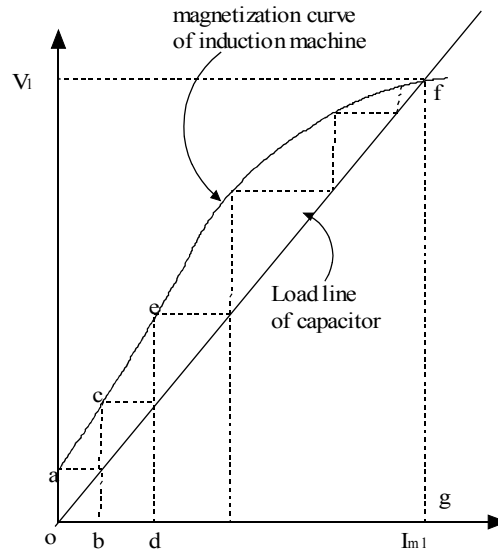


Figure 2.1: Self excitation process in SEIG with residual magnetism

If the residual flux is absent in the rotor iron, the induction generator will not build up. This problem can be overcome by running the machine as a poly phase induction motor for some time to create residual magnetism.

Note that the voltage build up depends upon the value of capacitor. Higher the value of capacitance, greater is the voltage build up, figure 2.2. In case capacitor load line does not intersect the magnetization curve of induction machine, there would be no voltage build up. In figure 2.2, voltage build up for capacitor  $C_4$  does not occur.

The voltage build up process in self excited induction generator is similar to DC generator. Build up process depends upon its residual voltage which is nearly 6 volt to 10 volt for a 220 volt machine; a battery of small value can be connected across the rotor terminal to generate the residual voltage or residual flux into rotor iron, once a machine run as a generator residual magnetism remains for a few days

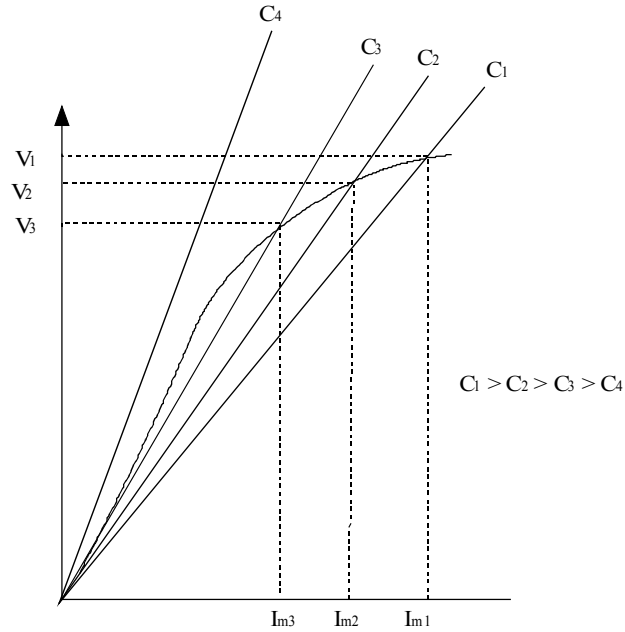


Figure 2.2: Effect of capacitances on voltage builds up process

## 2.3 Steady State Performance of Three-Phase SEIG

Steady state analysis of SEIG is of interest, both from the design and operational points of view. In isolated power system both terminal voltage and frequency are unknown and have to be computed for a given speed, capacitance and load impedance.

### 2.3.1 Mathematical Modeling of SEIG

An equivalent circuit of the induction machine, also known as the per-phase equivalent model is represented in figure 2.3, which will be used further for steady state analysis of SEIG. In this figure  $R_1$  and  $X_1$  the resistance and leakage reactance respectively of the stator,  $R_m$  and  $X_m$  are the loss resistance and the magnetizing reactance, and  $R_2$  and  $X_2$  the resistance and reactance of the rotor.  $I_1$  and  $I_r$  are the stator current and rotor current respectively.

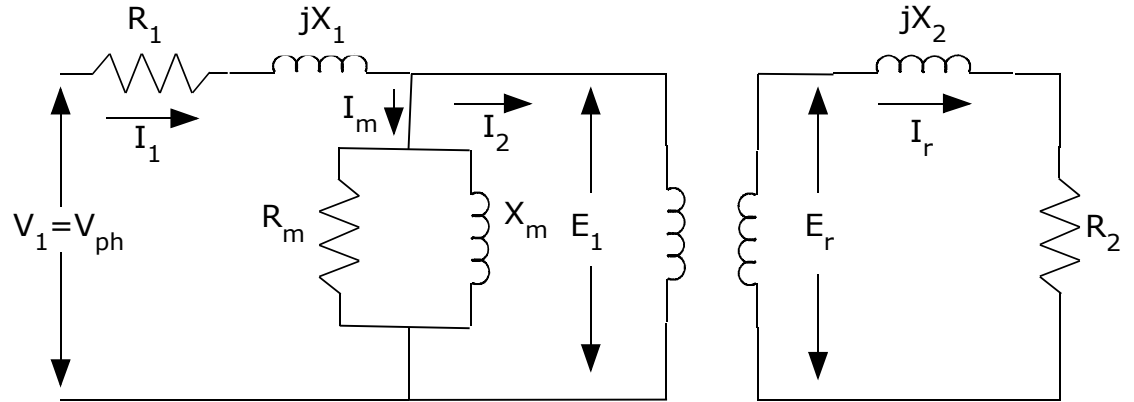


Figure 2.3: Equivalent model of induction machine

The equivalent circuit of the induction generator and of the transformer differ fundamentally in that in the induction generator, the rotor voltage is subject to a variable frequency making  $E_r$ ,  $R_2$  and  $X_r$  also variable. Here  $X_r = X_2$  (rotor side reactance).

$$E_r = sE_{r0} \quad (2.1)$$

where  $s$  is the slip factor

$$X_r = sX_{r0} \quad (2.2)$$

where  $X_{r0}$  is the blocked rotor reactance.

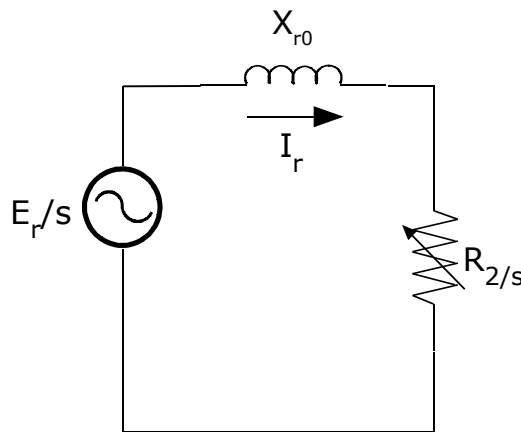


Figure 2.4: Rotor side equivalent model of induction machine

Figure 2.4 displays the equivalent circuit of the rotor impedance  $Z_{r0} = R_{r0} + jX_{r0}$  as a function of slip factor given by

$$I_r = \frac{E_r}{Z_2} = \frac{sE_{r0}}{R_2 + jsX_{20}} = \frac{E_{r0}}{\frac{R_2}{s} + jX_{20}} \quad \text{or}$$

$$Z_2 = \frac{E_{r0}}{I_r} = \frac{R_2}{s} + jX_{r0} \quad (2.3)$$

## 2.4 Problem Formulation

The voltage regulation optimization is carried out using the per phase steady state equivalent circuit of simple SEIG which are shown in figure 2.5.

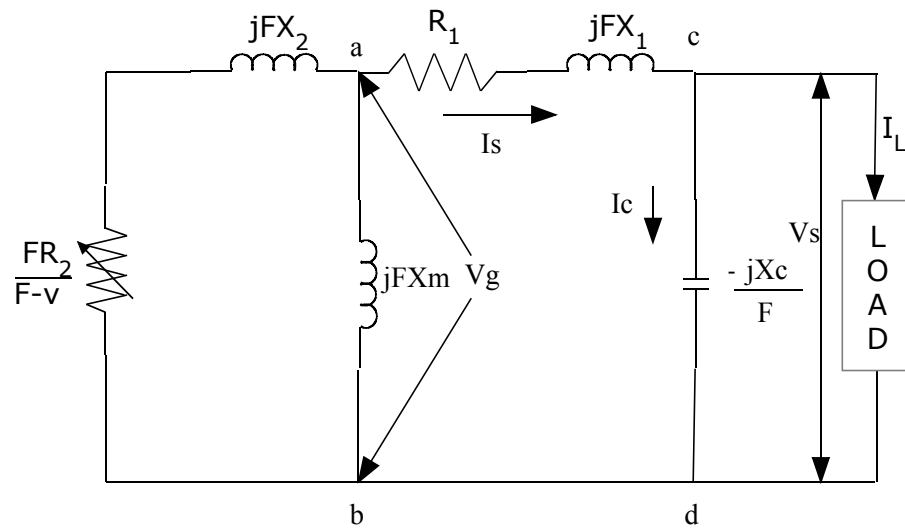


Figure 2.5: Equivalent model of SEIG for analysis

where

$R_1, R_2$  = per phase stator and rotor (referred to stator) resistance.

$X_1, X_2$  = per phase stator and rotor (referred to stator) leakage reactance.

$X_m$  = magnetizing reactance.

$X_c$  = per phase capacitive reactance of the terminal capacitor.

load = load resistance per phase.

$F, v$  = p.u. frequency and speed respectively.

Two non linear equations, which are real and imaginary parts of the impedance, are solved for two unknowns, generated frequency ( $F$ ) and magnetic reactance ( $X_m$ ) using Newton-Raphson method.

Various methods to calculate the steady state performance of SEIGs were proposed.

- Loop impedance method
- Nodal admittance method

Since under steady state condition for loop impedance method

Impedance  $Z_T=0$

$$Z_T = Z_{ab} + Z_{ac} + Z_{cd} \quad (2.4)$$

where

$$Z_{ab} = \left( \frac{FR^2}{F-v} + jFX^2 \right) \parallel jFXm$$

$$Z_{ac} = Rl + jFX1$$

$$Z_{cd} = Rl \parallel \left( \frac{-jXc}{F} \right)$$

After solving this we separate real and imaginary parts for resistive and resistive-inductive load, which can be written in form as for resistive load

$$f(Xm, F) = (A_1Xm + A_2)F^2 + \dots + (A_5Xm + A_6) + A_7 = 0 \quad (2.5)$$

$$g(Xm, F) = (B_1Xm + B_2)F^3 + \dots + (B_7Xm + B_8) + B_9 = 0 \quad (2.6)$$

where the constants  $A_1-A_7$  and  $B_1-B_9$  are functions of machine parameters which are given in appendix A. Same equations can be formed for resistive-inductive load.

These equations are solved using the Newton-Raphson method after forming the jacobian matrix and using initial values for  $Xm$  and  $F$  as  $Xm$  unsaturated and  $v$  respectively.

After getting the values of  $Xm$  and  $F$ , solve for the performance parameters such as  $I_s$ ,  $I_l$ , output power, and  $V_s$ .

$$I_s = (Vg * F) / (Z_{ac} + Z_{cd}) \quad (2.7)$$

$$V_s = (Vg * F) - (I_s * Z_{ac}) \quad (2.8)$$

$$I_c = V_s / ((-j * X_c) / F) \quad (2.9)$$

$$I_l = I_s - I_c \quad (2.10)$$

$$power = V_s * I_l \quad (2.11)$$

## 2.5 Algorithm and Flow Chart of Newton Raphson method

The computational procedure of Newton Raphson method for solution of  $X_m$ ,  $F$ , and performance parameters of SEIG is as follows:

- Read machine data such as  $R_1$ ,  $X_1$ ,  $R_2$ ,  $X_2$ ,  $X_c$ ,  $R_l$ ,  $X_l$  etc.
- Assume initial values of  $X_m$  and  $F$ .
- Calculate  $\Delta fn1 = -fn1$  and  $\Delta fn2 = -fn2$  and  $\begin{bmatrix} \Delta fn1 \\ \Delta fn2 \end{bmatrix} = \begin{pmatrix} H & N \\ M & L \end{pmatrix} \begin{bmatrix} \Delta X_m \\ \Delta F \end{bmatrix}$  where  
 $fn1 = a1 * f^3 + a2 * f^2 + a3 * f + a4$  and  $fn2 = b1 * f^3 + b2 * f^2 + b3 * f + b4$ ,  
 $a1, a2, \dots$  are constants.
- Compute the elements for jacobian matrix.
- Compute the results as  $\begin{bmatrix} \Delta fn1 \\ \Delta fn2 \end{bmatrix} = \begin{pmatrix} H & N \\ M & L \end{pmatrix} \begin{bmatrix} \Delta X_m \\ \Delta F \end{bmatrix}$  where  $H$ ,  $M$ ,  $N$ , and  $L$  are the jacobian elements.
- Calculate  $\Delta X_m$  and  $\Delta F$ .
- $X_m = X_{m0} + \Delta X_m$  and  $F = F_0 + \Delta F$ . start the next iteration cycle with these modified results
- Continue until scheduled error is within a specified tolerance limit.
- Calculate the performance parameters of machine using equations (2.7) – (2.11).

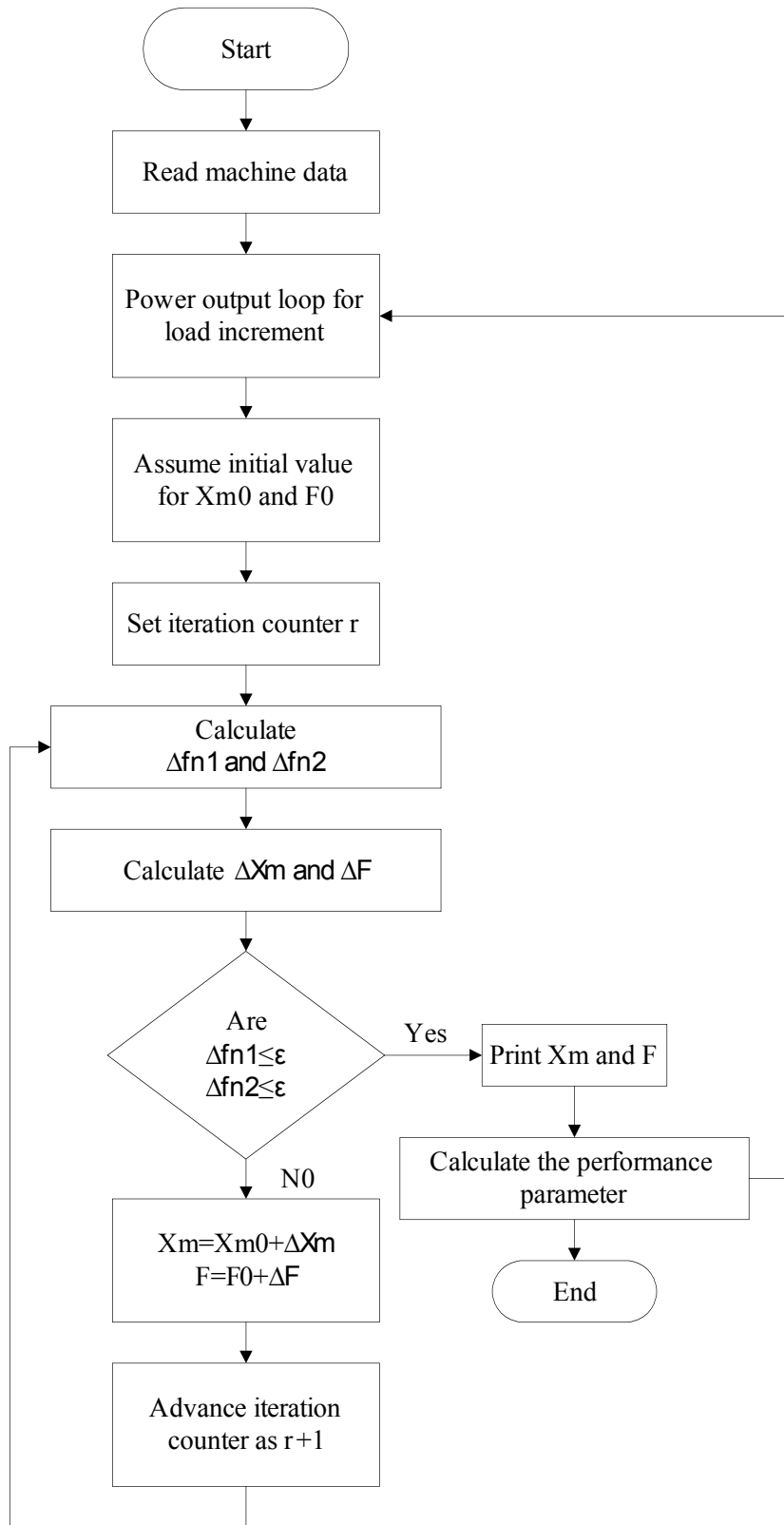


Figure 2.6: Flow chart of Newton Raphson method

## 2.6 Results and Discussion

Simulation and experimental results are compared in this section for resistive and resistive-inductive load at various power factors (lagging). Following studies have been performed.

- Variation of magnetizing reactance ( $X_m$ ) for different power factor load v/s output power.
- Variation of stator voltage ( $V_s$ ) for different power factor load at  $22\mu\text{F}$  and  $26\mu\text{F}$  capacitor.
- Variation of stator current ( $I_s$ ) for different power factor load at  $22\mu\text{F}$  and  $26\mu\text{F}$  capacitor.
- Variation of stator voltage ( $V_s$ ) and stator current ( $I_s$ ) for different speeds 1 pu and 0.9 pu

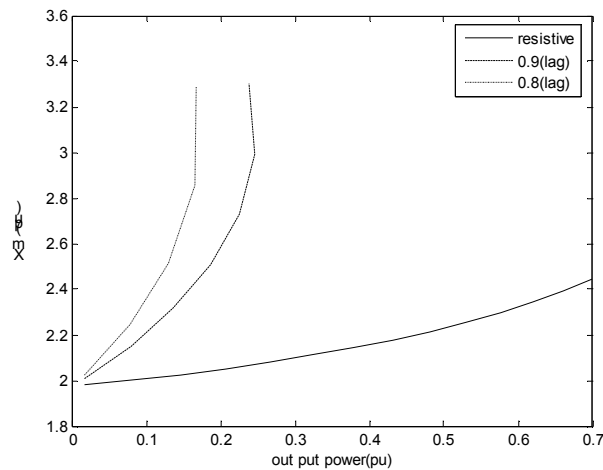


Figure 2.7: magnetizing reactance ( $X_m$ ) v/s power output at  $22\mu\text{F}$

Figure 2.7 shows the magnetizing reactance ( $X_m$ ) is plotted with respect to output power for various resistive and resistive-inductive loads. For resistive load the loading is more than resistive-inductive load and magnetizing reactance is nearly constant for resistive type load. Power output in resistive-inductive type load depends upon power factor and for 0.9 (lagging) power factor output loading is more as compared to 0.8 (lagging) power factor, variation in  $X_m$  for 0.9 (lagging) and 0.8 (lagging) is almost

same. These characteristics are calculated at  $22\mu\text{F}$  value of per phase capacitance of capacitor bank connected in shunt for excitation purpose.

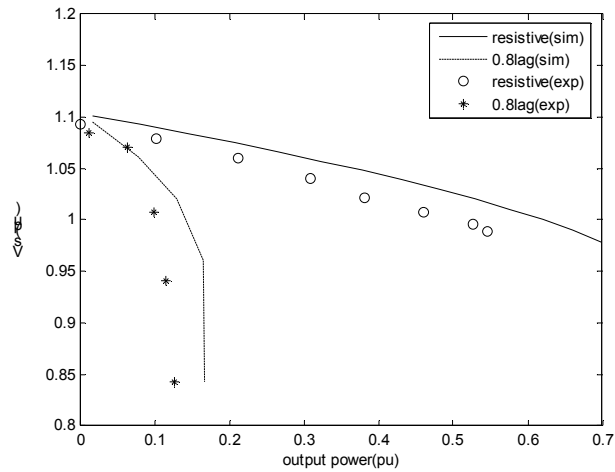


Figure 2.8: Stator voltage ( $V_s$ ) v/s power output at  $22\mu\text{F}$

Voltage drops is minimum and output loading is more in resistive type load as compared to resistive inductive load. Voltage regulation is 12.51% at resistive load. Both simulated and experimental results are validated on resistive and resistive-inductive loading, which is shown in figure 2.8.

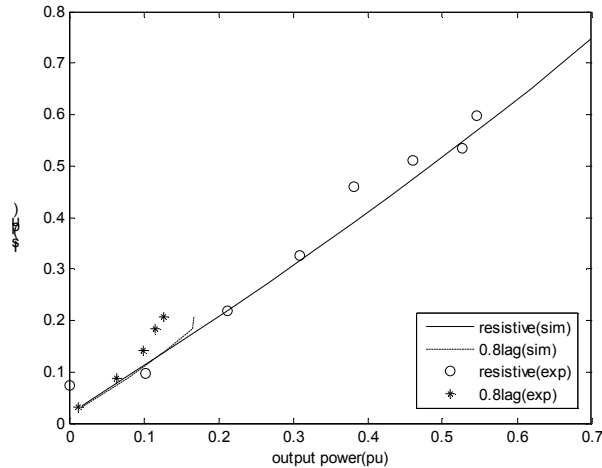


Figure 2.9: Stator current ( $I_s$ ) v/s power output at  $22\mu\text{F}$

Figure 2.9 shows the simulated and experimental results for stator current v/s output power. In the resistive loading SEIG draw the more current and the output loading is also

more as compare to resistive inductive loading. These characteristics show that for resistive load SEIG is suitable but for inductive type loading it is not suitable.

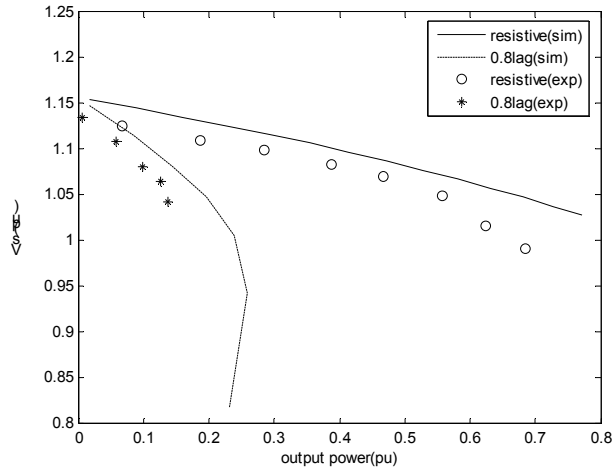


Figure 2.10: Stator voltage (Vs) v/s power output at 26 $\mu$ F

Figure 2.10 shows the stator voltage and output power characteristic at the shunt capacitance value of 26 $\mu$ F for various loading condition. Output loading increased in this case. Stator voltage is also more as compare to 22 $\mu$ F case. The output power increased from 0.7 pu to 0.8 pu, initial stator voltage increases from 1.1 pu to 1.15 pu for resistive load. Voltage regulation also improves from 12.51% to 12.31%. These characteristics show that more the value of shunt capacitance the output loading is more and stator voltage is also increase.

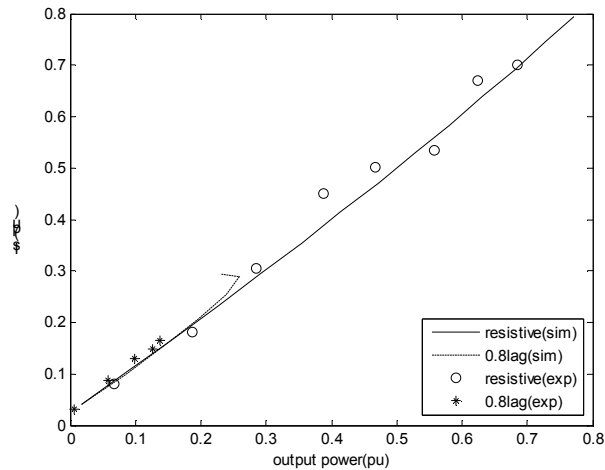


Figure 2.11: Stator current (Is) v/s power output at 26 $\mu$ F

Figure 2.11 shows that stator current increase at  $26\mu\text{F}$  that make the machine suitable for more loading, it increase from 7.5 pu to 8 pu for resistive load, both simulation and experimental results validate which show that output loading and stator current increases if the value of shunt capacitance increases.

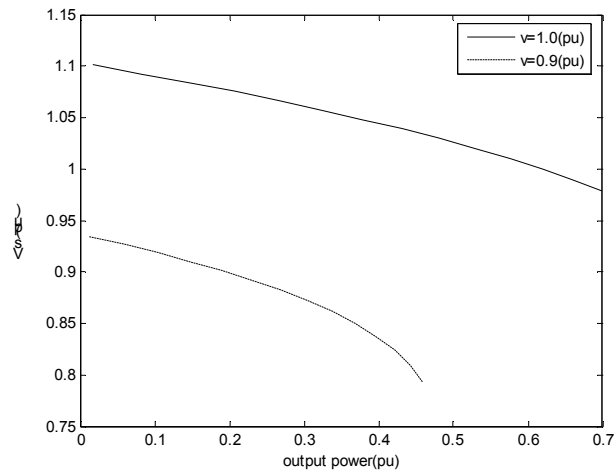


Figure 2.12: Stator voltage (Vs) v/s power output at  $22\mu\text{F}$  when speed change

Speed of prime mover play a vital role in performance of induction generator, if the speed of prime mover changes it affects the slip of induction generator which further affects the stator terminal voltage. Vs decrease if speed decrease, it changes from 1.10 pu to 0.93 pu when speed changes from 1.0 pu to 0.9 pu. It shows that if the speed of prime mover decrease it decrease the stator terminal voltage also. Figure 2.12 shows that output loading also affected due to changes in speed, output power decreases from 0.69 pu to 0.46 pu when speed changes from 1.0 pu to 0.9 pu.

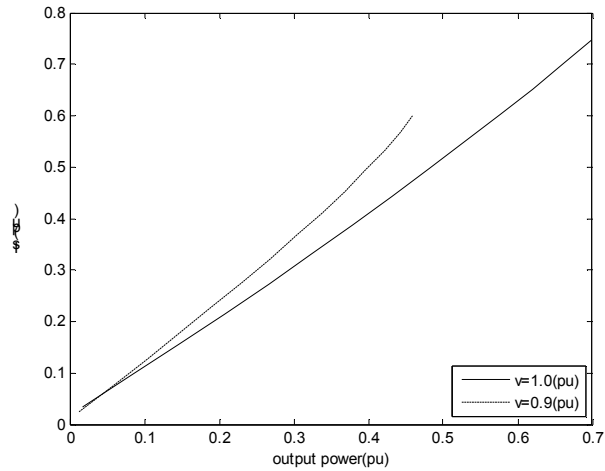


Figure 2.13: Stator current ( $I_s$ ) v/s power output at  $22\mu\text{F}$  when speed change

Speed changes affects the stator current as shown in figure 2.13, it start increasing when the speed decrease.  $I_s$  increase from 0.45 pu to 0.6 pu when speed changes from 1.0 pu to 0.9 pu at output loading 0.45 pu.

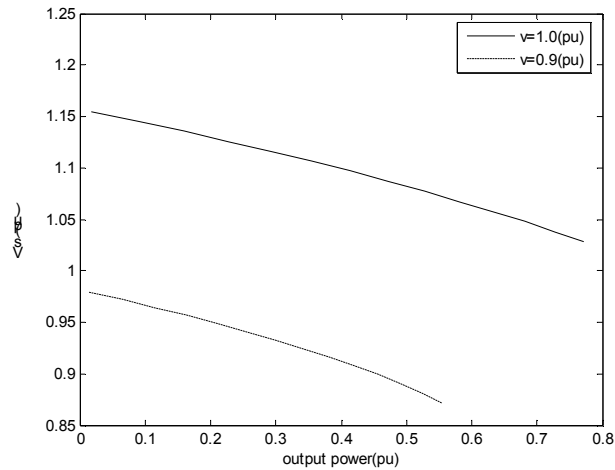


Figure 2.14: Stator voltage ( $V_s$ ) v/s power output at  $26\mu\text{F}$  when speed change

Effect of shunt capacitance shown in figure 2.14 when the capacitance value changes from  $22\mu\text{F}$  to  $26\mu\text{F}$   $V_s$  increases from 1.10 pu to 1.15 pu at 1.0 pu speed. When the speed decrease the more value of shunt capacitor improve the stator terminal voltage. Voltage regulations improve from 12.51% to 12.31% at speed 1.0 pu and 17.84% to

12.40% at speed 0.9 pu at a common loading for both type of load. Loading capability of SEIG increases from 0.69 to 0.77 pu at speed 1.0 pu and 0.46 to 0.55 pu at speed 0.9 pu.

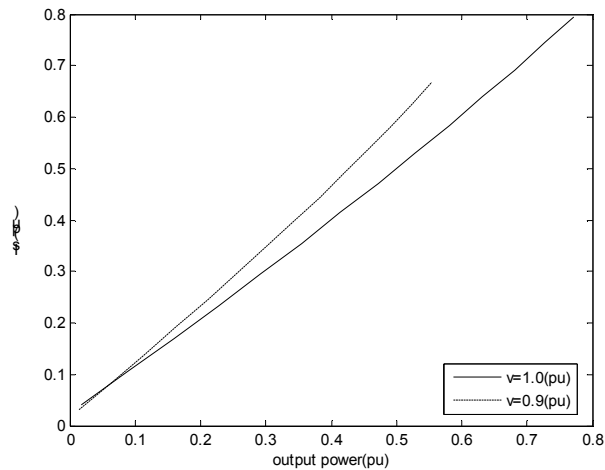


Figure 2.15: Stator current ( $I_s$ ) v/s power output at  $26\mu\text{F}$  at different speeds

Stator current performance improve when the capacitance value increase. When capacitance is of  $22\mu\text{F}$  the stator current was 0.45 pu if the capacitance value increase to  $26\mu\text{F}$   $I_s$  decrease to 0.4 pu at 0.9 pu speed as shown in figure 2.15.

## 2.6 Conclusion

Simulation and experimental results validated for resistive and resistive-inductive loading at various power factor. Shunt capacitance, which is used for excitation purpose have special role in performance of SEIGs, it affects its loading capability and as well as its voltage regulation. Stator terminal voltage depends upon shunt capacitance value, if the value of shunt capacitance increases the value of stator terminal voltage increase. Speed variation also affects the voltage regulation of SEIG, it change its stator terminal voltage as well as its output power. Shunt capacitance further improve the performance of SEIG if the speed of prime mover change

## **Chapter 3**

### **Theory of Genetic Algorithm**

#### **3.1 Introduction**

The goals of creating artificial intelligence and artificial life stem from the very beginnings of the computer age. The earliest computer scientists Alan Turing, John Von Neumann, Norbert Weiner, and others were motivated in large part by visions of imbuing computer programs with intelligence, with the life-like ability to self-replicate, and with the adaptive capability to learn and to control their environments. These early pioneers of computer science were as much interested in biology and psychology as in electronics, and looked to natural systems as guiding metaphors for how to achieve their visions. It should be no surprise, then, that from the earliest days, computers were applied not only to calculating missile trajectories and deciphering military codes, but also to modeling the brain, mimicking human learning, and simulating biological evolution. These biologically motivated computing activities have waxed and waned over the last forty years, but in the last ten years they have all undergone resurgence in the computation research community. The first has grown into the field of neural networks, the second into machine learning, and the third into what is now called evolutionary computation," of which genetic algorithms (GAs) are the most prominent example [95].

GAs were first described by John Holland in the 1960s and further developed by Holland and his students and colleagues at the University of Michigan in the 1960s and 1970s. Holland's goal was to understand the phenomenon of adaptation" as it occurs in nature and to develop ways in which the mechanisms of natural adaptation might be imported into computer systems [96].

Genetic Algorithms are a family of computational models inspired by evolution. These algorithms encode a potential solution to a specific problem on a simple chromosome like data structure and apply recombination operators to these structures so as to preserve critical information. Genetic algorithms are often viewed as function

optimizers, although the range of problems to which genetic algorithms have been applied is quite broad.

### 3.2 Components of Genetic Algorithm

The GA begins, like any other optimization algorithm, by defining the optimization variables, the fitness function, and the fitness. It ends like other optimization algorithms too, by testing for convergence. In between, however, this algorithm is quite different. A path through the components of the GA is shown as a flowchart in figure 3.1; the main operators of GA are selection, crossover and mutation.

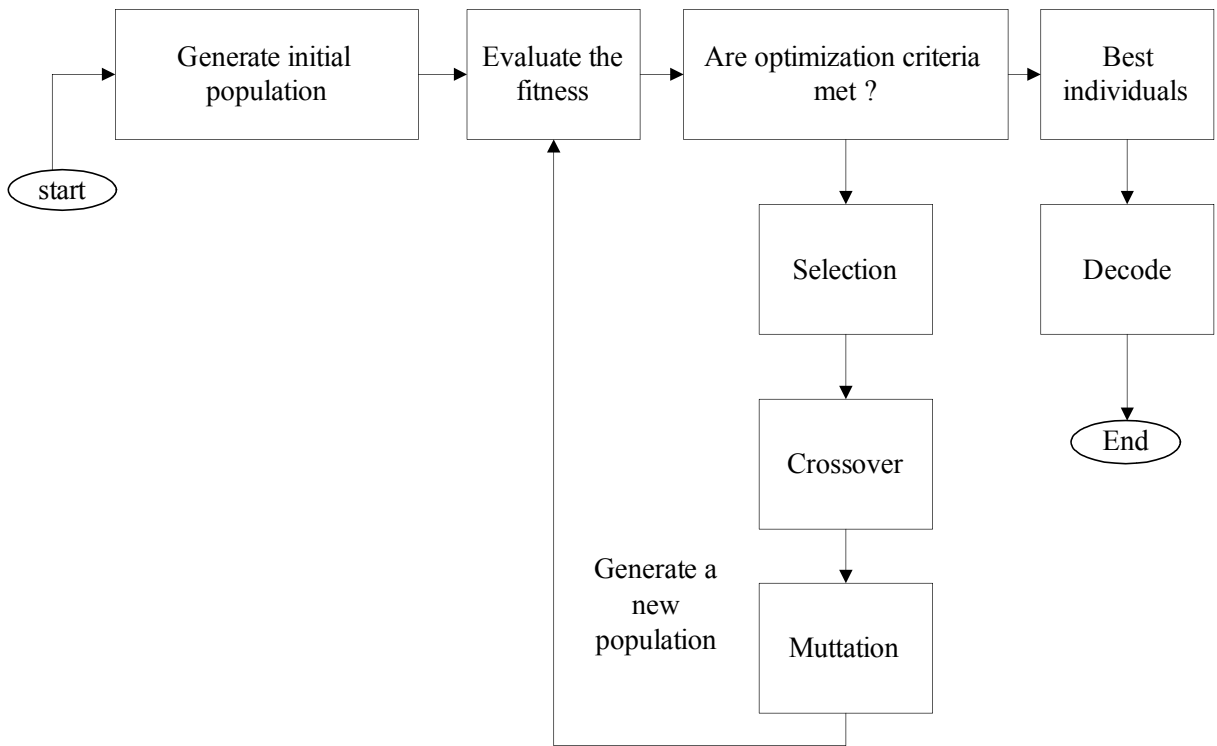


Figure 3.1: Flow chart of Genetic Algorithm

#### 3.2.1 Selecting the Variables and the Fitness Function

A fitness function generates an output from a set of input variables (a chromosome). The fitness function may be a mathematical function, an experiment, or a game. The object is to modify the output in some desirable fashion by finding the appropriate values

for the input variables. GAs is usually suitable for solving maximization problems. Minimization problems are usually transformed into maximization problems by some suitable transformation. In general, fitness function  $F(X)$  is first derived from the objective function and used in successive genetic operations.

Certain genetic operators require that fitness function be non-negative, although certain operators do not have this requirement. Consider the following transformations

$$F(X) = f(X) \text{ for maximizing problem}$$

$$F(X) = 1/f(X) \text{ for minimization problem, if } f(X) \neq 0$$

$$F(X) = 1/ (1+f(X)), \text{ if } f(X) = 0$$

A number of such transformations are possible.

### 3.2.2 Selection or Reproduction

The reproduction operator is a probabilistic selection in which strings are selected so as to produce offspring based on their fitness value. Reproduction is usually the first operator applied on population. Chromosomes are selected from the initial population to be parent to cross over and produce offspring. According to Darwin's evolution theory of survival of the fittest, the best ones should survive and create new offspring. The various methods of selecting chromosomes for parents to cross over are;

- Roulette-wheel selection
- Boltzmann selection
- Tournament selection
- Rank selection
- Steady state selection

The commonly used reproduction operator is the roulette-wheel selection method where a string is selected from the mating pool with a probability proportional to the fitness.

The  $i^{\text{th}}$  string in the population is selected with a probability proportional  $F_i$  where  $F_i$  is the fitness value for that string. The probability of the  $i^{\text{th}}$  string is

$$p_i = \frac{F_i}{\sum_{j=1}^n F_j} \quad (3.1)$$

where 'n' is the population size.

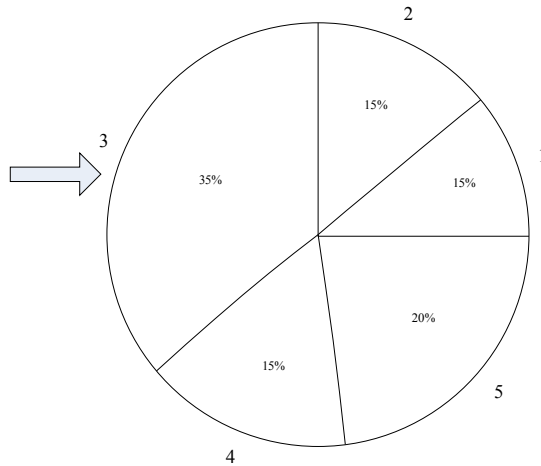


Figure 3.2: A roulette-wheel is marked for five individuals according to their fitness values.

The roulette-wheel mechanism is expected to make  $F_i / \bar{F}$  copies of  $i^{\text{th}}$  string of the mating pool. The average fitness

$$\bar{F} = \sum_{j=1}^n F_j / n \quad (3.2)$$

In the figure 3.2 a roulette wheel selection terminology has been given. Since the third individual has a higher fitness value than any other, it is expected that the roulette wheel selection will choose the third individuals more than any other individuals.

This selection method is less noisy and is known as stochastic remainder selection [97].

The tournament selection strategy provides selective fitness by holding a tournament competition among individuals. The best individual from the tournament is the one with the highest fitness which is the winner of individuals. Tournament competitor and the winner are then inserted into the mating pool. The tournament competition is repeated until the mating pool for generating new offspring is filled.

In rank selection method, first it ranks the population and taken every chromosome, receive fitness from the ranking. The worst will have fitness 1, and the best will have fitness  $N$  ( $N$  is the number of chromosome in the population).

Steady state selection is not a particular method of selecting the parents. The main idea of the selection is that bigger part of chromosome should survive to next generation. In every generation are selected, a few chromosome having high fitness, for creating new off springs. Then, some chromosomes with bad fitness are removed and new off spring is placed in that place. The rest of population survives a new generation.

### **3.2.3 Crossover Operation**

After the reproduction phase is over, the population is enriched with better individuals. Crossover operator is applied to the mating pool with a hope that it would create a better string. The aim of the crossover operator is to search the parameter space. Crossover is a recombination operator, which proceeds in three steps. First, the reproduction operator selects at random a pair of two individual string for mating, then a crossover site is selected at random along the string length and the position values are swapped between two string following the cross site.

There exist many types of crossover operations in genetic algorithm such as

- Single site cross over
- Two point cross over
- Multi point cross over
- Uniform cross over
- Matrix cross over

The one-point crossover is shown in figure 3.3. By this method, for a chromosome of a length ' $L$ ', a random number ' $r$ ' between 1 and  $L$  is first generated. The first child chromosome is formed by appending the last  $L-r$  elements of the first parent chromosome to the first ' $r$ ' elements of the second parent chromosome. The second child chromosome is formed by appending the last  $L-r$  elements of the second parent

chromosome to the first 'r' elements of the first parent chromosome. Typically, the probability for crossover ranges from 0.6 to 0.95.

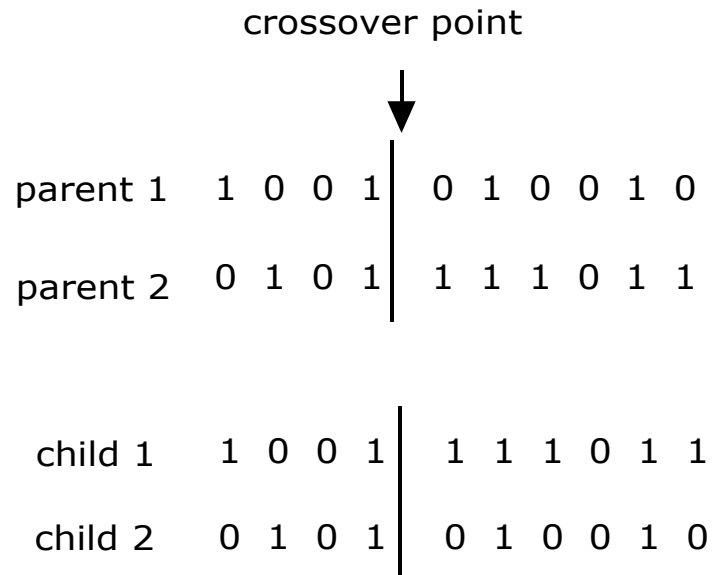


Figure 3.3: Single site crossover operation

In a two point cross over operator, two random sites are chosen and the contents bracketed by these sites are exchanged between two mated parents. If the cross site 1 is three and cross site 2 is six, the strings between three and six are exchanged as shown in figure 3.4.

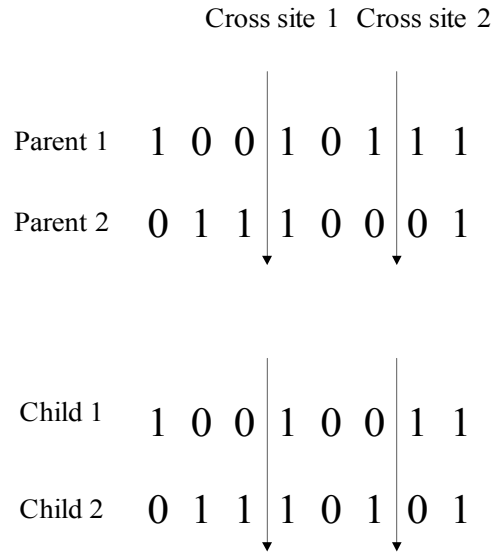


Figure 3.4: Two point crossover operation

In a multi point crossover again there are two cases. One is even number of cross sites and the second one is the odd number of cross sites. In case of even numbered cross sites the string is treated as a ring with no beginning or end. The cross sites are selected around the circle uniformly at random if the number of cross sites is odd, then a different cross point is always assumed at the string beginning

### 3.2.4 Mutation

The final genetic operator in the algorithm is mutation. The mutation operator is used to inject new genetic materials into the population as shown in figure 3.5.

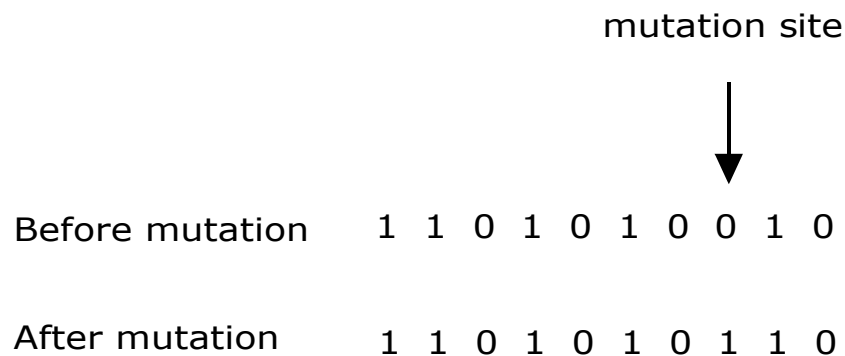


Figure 3.5: Mutation operations

Mutation prevents the premature stopping of the algorithm in a local solution. The mutation operator is defined by a random bit value change in a chosen string with a low probability of such change. The mutation adds a random search character to the genetic algorithm, and it is necessary to avoid that, after some generations, all possible solutions were very similar ones. Bit wise mutation is performed here, which switches a few randomly chosen bits from 1 to 0 (or) 0 to 1 with a small probability ( $P_m$ ). After mutation, the new generation is complete and the procedure begins again with the fitness evaluation of the population

All strings and bits have the same probability of mutation. For example, in the string 1101010010, if the mutation affects to time bit number eight, the string obtained is 1101010110.

### 3.3 Other GAs Operators

Besides the three main operators named as selection, cross over, and mutation some other operators are can also be used in genetic algorithm. These operators are

- Elitism
- Inversion
- Deletion and duplication
- Deletion and regeneration
- Segregation

In the elitism first the best chromosome or few best chromosome are copied to new population. The rest is done in classical way. Elitism can vary rapidly increase the performance of GA because it prevents losing the best-found solutions.

In the inversion a string from the population is selected and the bits between two random sites are inverted.

In duplication any two bits at random in order are selected and the previous bits are duplicated with them.

In regeneration genes between two cross sites are deleted and regenerated randomly.

Segregation is just like single site cross over; the bits of the parents are segregated and then crossed over to produce offspring.

### 3.4 Application and Advantages of GA

GA can be applied in lot of areas in human life. GA is rich in application across a large number of disciplines. Table 3.1 gives the fields where GA is successfully applied [98].

GA is very advantageous since it is easy to understand, good for noisy environment, and support multi objective optimization.

Some of the advantages of a GA include that it

- Optimizes with continuous or discrete variables,
- Doesn't require derivative information,
- Simultaneously searches from a wide sampling of the fitness surface,
- Deals with a large number of variables,
- Is well suited for parallel computers,
- Optimizes variables with extremely complex cost surfaces (they can jump out of a local minimum),
- Provides a list of optimum variables, not just a single solution,
- May encode the variables so that the optimization is done with the encoded variables, and
- Works with numerically generated data, experimental data, or analytical functions.

Domain	Application types
Control	Gas pipe line, pole balancing, missile evasion, pursuit
Design	Semiconductor layout, aircraft design, communication network
Scheduling	Manufacturing, facility scheduling, resource allocation
Robotics	Trajectory planning
Machine learning	Designing neural networks, classification algorithm
Signal processing	Filter design
Combinational optimization	Set covering, travelling salesman, routing

Table 3.1: GA application

### **3.5 Conclusion**

The genetic algorithm performed best (compared to exact solution methods) on the problems with multi-modal activities. The extra combinations introduced by the multiple execution modes did not hurt the genetic algorithm performance. In fact, in some cases it made the problem easier for the genetic algorithm. This suggests that the genetic algorithm is well-suited to more-complicated problems with a mix of continuous and discrete components.

# Chapter 4

## Steady State Analysis of SEIG Using GA

### 4.1 Introduction

The performance characteristics of a self-excited induction generator can be obtained after the determination of two unknown parameters, such as the magnetizing reactance and frequency. Usually, Newton–Raphson method and Nodal-Admittance method are used to determine the generator’s unknown parameters which are the conventional methods used since three decades. If either of these two methods is used, lengthy mathematical derivations should be carried out to formulate the required equations in a suitable simplified form. The real and imaginary term separations are carried out by hand, and therefore considerable amounts of time and effort are needed. Moreover, having mistakes in the final form equations is possible. However, mistakes can be avoided if the mathematical derivations are carefully carried out. The Newton–Raphson method may lead to inaccurate results if initial estimates of magnetizing reactance and frequency are not very carefully selected. The other limitation of these methods is the difficulty in using them for the analysis of self-excited induction generator feeding a dynamic load. For this type of analysis, more than two unknowns have to be determined, and these parameters cannot be directly determined using either of these methods [99].

This chapter deals with the implementation of a new approach, based on genetic algorithm, for the performance analysis of self-excited induction generator. Unlike conventional methods of analysis, lengthy algebraic derivations or accurate initial estimates are not required. In addition, the same objective function is to be minimized irrespective of the unknown parameters. The other important feature of the present approach is the possibility of determining more than two unknown parameters simultaneously. Therefore, it can be used to obtain the performance characteristics of three-phase self-excited induction generator.

## 4.2 Problem Formulation

The voltage regulation optimization of simple SEIG is carried out in the previous chapter by Newton Raphson method. In this chapter we perform the same work but using the Genetic Algorithm.

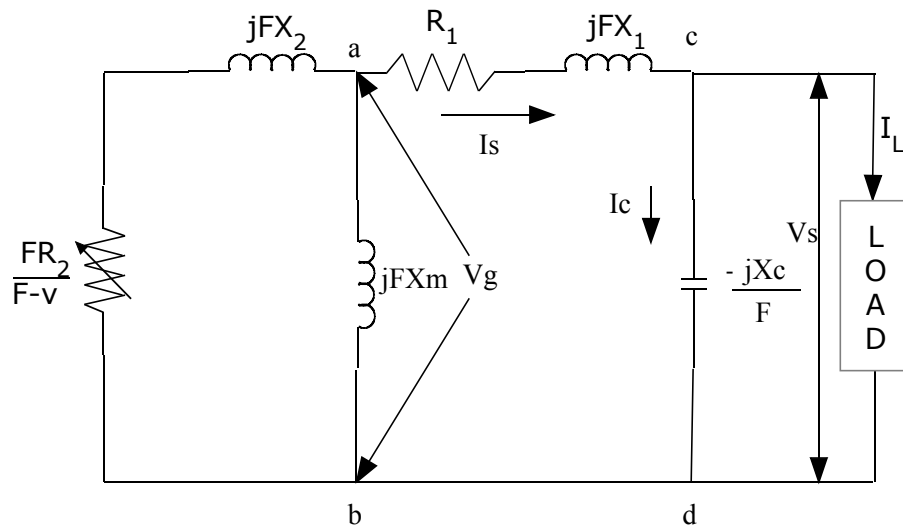


Figure: 4.1 Equivalent model of SEIG for analysis using GA

where

$R_1, R_2$  = per phase stator and rotor (referred to stator) resistance.

$X_1, X_2$  = per phase stator and rotor (referred to stator) leakage reactance.

$X_m$  = magnetizing reactance.

$X_c$  = per phase capacitive reactance of the terminal capacitor.

Load = load resistance per phase.

$F, v$  = p.u. generated frequency and speed respectively.

$V_g$  = air gap voltage

The objective function of the circuit shown in figure 2.5 is calculated as

$$Z_T = 0$$

where

$$Z_T = Z_{ab} + Z_{ac} + Z_{cd} \quad (4.1)$$

$$Z_{ab} = \left( \frac{FR_2}{F - v} + jFX_2 \right) \parallel jFXm \quad (4.2)$$

$$Z_{ac} = R_1 + jFX_1 \quad (4.3)$$

$$Z_{cd} = Rl \parallel \left( \frac{-jXc}{F} \right) \quad (4.4)$$

This is the objective function for resistive load, for a resistive-inductive load now  $Rl$  is  $Rl + jFXl$ .

Equation 4.1 is a nonlinear equation with four variables as  $Xm$ ,  $Xc$ ,  $v$ , and  $F$ . if two of these is known than other two can be calculated using conventional method such as NR method, but it is a very lengthy method due to real and imaginary term calculation and derivative term. The chances of mistakes will always remain due to its complexity.

Genetic algorithm provides a simple solution technique for the solution of variables named as  $Xm$  and  $F$ . GA optimization is started with a population of  $N$  randomly generated individuals representing a set of solutions to the problem. Each individual is composed of the problem's variables, which can be encoded into binary strings called chromosomes. GA works on these chromosomes instead of the variables themselves. The variables can also be represented using real-valued (decimal) encoding. For this type of encoding, GA operates directly on the variables of the optimization problem. In the present work, a simple binary genetic algorithm is applied, the population size  $N$  is chosen to be 160. The roulette wheel selection is applied followed by uniform cross over with probability of 0.8 and it is further followed by mutation with probability of 0.05.

### **4.3 Algorithm and Flowchart of GA for Steady State Analysis of SEIG**

The computational procedure of GA for solution of  $X_m$ ,  $F$ , and performance parameters of SEIG is as follows:

Step 1: initialize all parameters and read machine parameter and magnetizing curve.

Step 2: set step out power output counter for performance calculation.

Step 3: generate  $X_m$  and  $F$  randomly.

Step 4: evaluate fitness of impedance function.

Step 5: check whether the fitness is more than the define value of error constant, if yes go to step number 12 otherwise go to step number 6.

Step 6: reproduction will perform using roulette wheel selection.

Step 7: convert  $X_m$  and  $F$  into binary string.

Step 8: perform uniform crossover with crossover probability 0.8 on binary string of  $X_m$  and  $F$ .

Step 9: perform mutation operation with probability of 0.05.

Step 10: decode  $X_m$  and  $F$  into real integer form.

Step 11: check fitness again on new population, if fitness is more than error constant than go to step number otherwise go to step number 6.

Step 12: perform performance analysis using equation numbers 2.7 to 2.11.

Step 13: check if output power is greater than rated output power than stop, other wise go to step number 2.

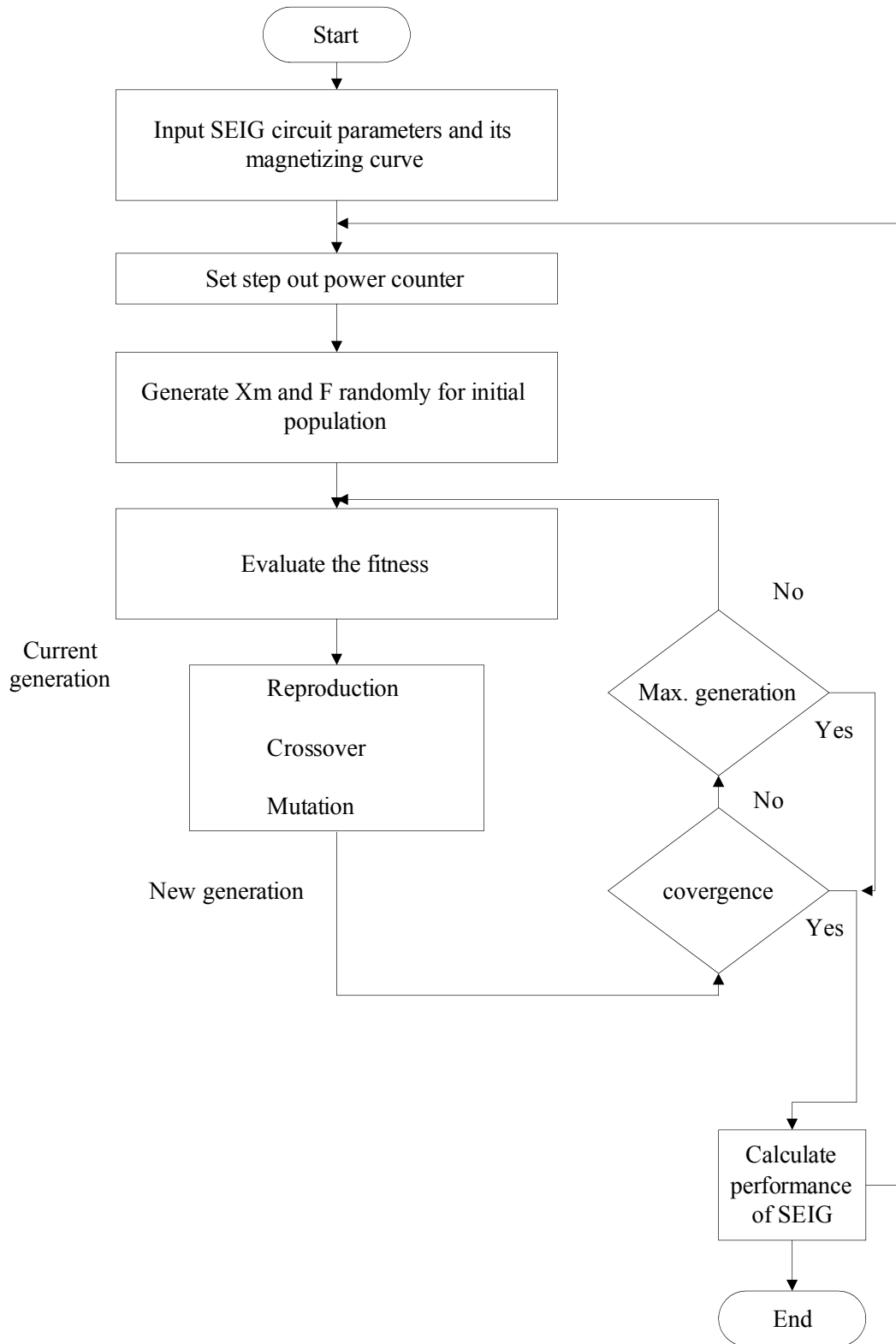


Figure 4.2: Flowchart of GA for steady state analysis of SEIG

## 4.4 Results and Discussion

The steady state performance of SEIG has been evaluated with GA. The important characteristics have been shown with respect to output power.

The simulation results are compared with NR solutions in this section for resistive and resistive-inductive load at various power factors (lagging). The following studies have been performed.

- Variation of stator voltage ( $V_s$ ) for different power factor load at  $22\mu\text{F}$  and  $26\mu\text{F}$  capacitor.
- Variation of stator current ( $I_s$ ) for different power factor load at  $22\mu\text{F}$  and  $26\mu\text{F}$  capacitor.
- Variation of stator voltage ( $V_s$ ) and stator current ( $I_s$ ) for different speeds 1 pu and 0.9 pu

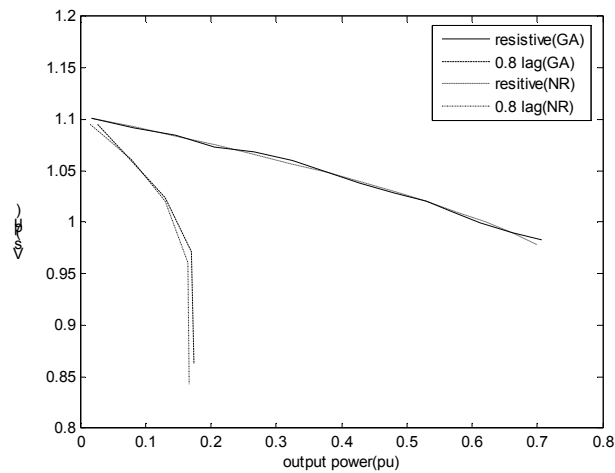


Figure 4.3: Stator voltage ( $V_s$ ) v/s power output at  $22\mu\text{F}$

Figure 4.3 shows the characteristics of stator terminal voltage with output power loading at  $22\mu\text{F}$ , the result comprise between two methods NR and GA, both results are validated here. The stator terminal voltage is 1.01pu and the voltage regulation is 11.97% in case of resistive loading where it was 12.51% when it is calculated using NR method. The voltage profile for resistive-inductive load also improves which is shown in figure 4.3.

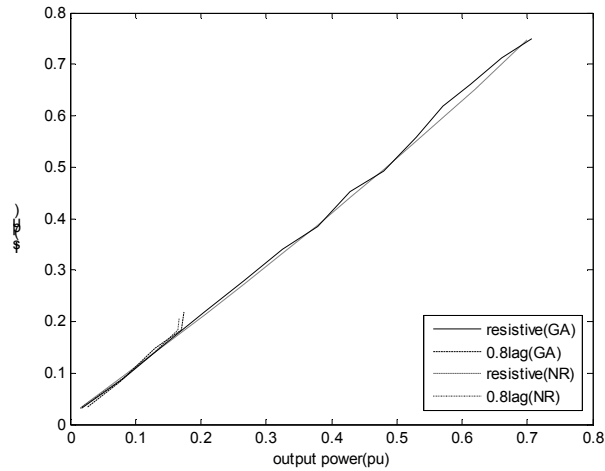


Figure 4.4: Stator current ( $I_s$ ) v/s power output at  $22\mu\text{F}$

The results show in figure 4.4 that the GA gives the better performance in case of stator current also. Stator current improves with the comparison of NR method. The output loading also improves to marginally with the help of GA analysis.

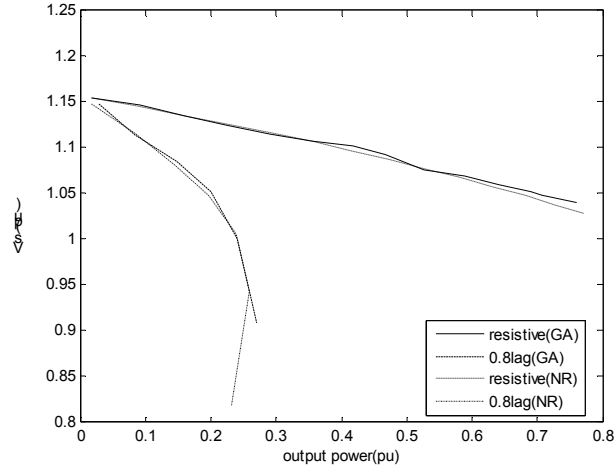


Figure 4.5: Stator voltage ( $V_s$ ) v/s power output at  $26\mu\text{F}$

When the value of shunt capacitance is increased to  $26\mu\text{F}$  the no load stator terminal voltage increased from 1.1 pu to 1.15 pu as shown in figure 4.5. The voltage regulation now becomes 11.01% using GA analysis where it was 12.31% in case of NR solution at

common loading (0.7 pu). The voltage regulation as well as output loading improves slightly when terminal capacitance increases from 22 $\mu$ F to 26 $\mu$ F.

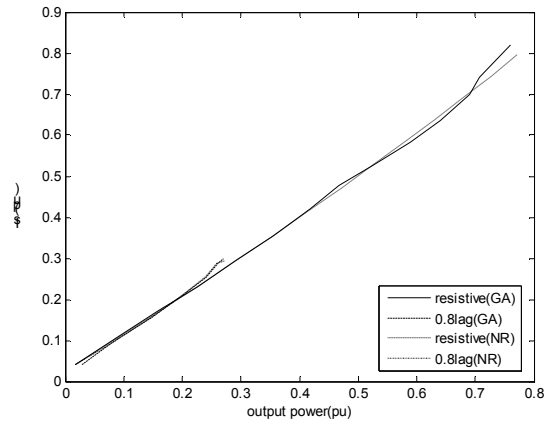


Figure 4.6: Stator current ( $I_s$ ) v/s power output at 26 $\mu$ F

Figure 4.6 shows the variation of stator current with output power when the value of shunt capacitance increased from 22 $\mu$ F to 26 $\mu$ F. The results with GA as well as NR result shown in figure 4.6. It shows that the current loading for resistive load is more than the current loading in case of resistive inductive loading as load requires additional reactive power, which is supplied by shunt capacitor bank.

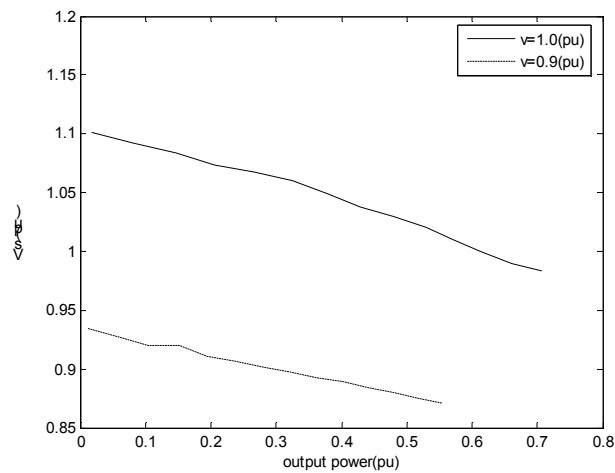


Figure 4.7: Stator voltage ( $V_s$ ) v/s power output at 22 $\mu$ F with speed changes

As per the discussion of pervious chapter the speed of prime mover play a vital role in performance of induction generator, if the speed of prime mover changes it affects the slip of induction generator which further affects the stator terminal voltage. Figure 4.7 shows  $V_s$  decrease if speed decrease, it changes from 1.10 pu to 0.93 pu when speed changes from 1.0 pu to 0.9 pu. At  $22\mu\text{F}$  it shows that if the speed of prime mover decrease it decrease the stator terminal voltage also. Output loading also affected due to changes in speed, output power decreases from 0.71 pu to 0.56 pu when speed changes from 1.0 pu to 0.9 pu. GA improves it results also in case of output loading at 0.9 pu speed.

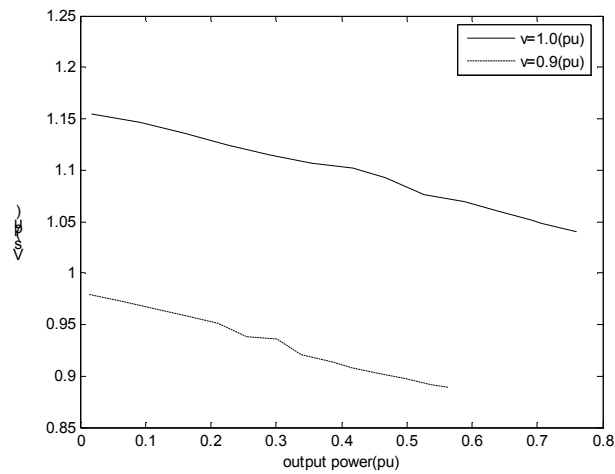


Figure 4.8: Stator voltage ( $V_s$ ) v/s power output at  $26\mu\text{F}$  with speed changes

Shunt capacitance also affects the performance, as shown in figure 4.8. When the speed changes from 1.0 pu to 0.9 pu. When the shunt capacitance value increased to  $26\mu\text{F}$  it increased the input stator terminal voltage from 1.1 pu to 1.15 pu and for 0.9 pu of speed it increased from 0.93 pu to 0.98 pu. Output loading also increased to 0.78 pu where it was 0.71 pu in case of  $22\mu\text{F}$  case.

## **4.5 Conclusion**

Simulation results of both NR and GA have been shown for resistive and resistive-inductive loading at various power factors. GA analysis improves slightly the performance of SEIG, it affects its loading capability and as well as its voltage regulation. The fineness of results can be further improved by either improving termination criteria or incorporating the additional feature of GA. Shunt capacitance value also affects its performance in such a manner that stator terminal voltage depends upon shunt capacitance value, if the value of shunt capacitance increases the value of stator terminal voltage increase, but it affect the insulation requirement. Speed variation also affects the voltage regulation of SEIG, it change its stator terminal voltage as well as its output power. Therefore optimum value of terminal capacitance, speed required to be selected for optimum performance of SEIG.

# Chapter 5

## Conclusion and Future Scope

### 5.1 Conclusion

Use of an induction machine as a generator is becoming popular for the renewable energy sources. SEIG has its advantage that there is no need of reactive power from transmission line as it draws reactive power from capacitor bank connected in shunt. Steady state analysis of SEIG carried out for evaluating running performance. Using the steady state analysis means voltage regulation, frequency regulation, and steady state temperature rise due to running of the machine continuously.

Two method of steady state analysis of SEIG presented in the thesis work, one is conventional method which is being used since last many years known as Newton Raphson method and the second one is based upon artificial intelligence and natural selection process known as Genetic Algorithm which mimics the survival of fittest theory.

The simulation results from both the techniques validated in this thesis with the experimental and results. Although there is slight deviation in both results, which shows various type of errors involved during experimentation. The thesis works mainly deals voltage regulation problem, which is the main concern of SEIG because SEIG has inherent poor voltage regulation. The voltage regulation problem can be improved by suitable selection of parameters like speed, terminal capacitance, and type of load of induction machine. Although it has been shown that the voltage regulation improves for different cases while solving with GA as compared to NR method. The GA results show the better performance of SEIG than NR method. The output loading of SEIG also increases using GA analysis and suitable selection of shunt capacitance value. The prime mover speed also affects the performance of SEIG as it change its frequency and we can say its slip factor which further changes its stator terminal voltage.

## 5.2 Future Scope

In the thesis work, the steady state performance has been carried out with conventional NR method and natural selection based GA method.

The results with GA are still mismatching (approximately 2%) with the result obtained with NR method. The improvement has to be investigated through various other form of GA operator such as multi point crossover and by changing different rate of operators.

The performance of SEIG mainly depends on voltage regulation, can be improved by compensated SEIG. The long shunt and short shunt compensation techniques used the series capacitance as well as shunt capacitance for fulfillment of its reactive power requirement. The analysis of compensated SEIG will give the better performance such as voltage regulation and output loading than simple SEIG. The compensated analysis will be further improved by using different genetic algorithm operator which makes the analysis easier and accurate.

The transient state analysis which is very important as far as design aspects of various parameter of SEIG are concerned, can be analyzed and performed.

The performance of SEIG can also be improved by better controlling the reactive power supplied/absorbed to the generator and load. The STATCOM assisted SEIG may be the solution but the cost of the system will be increased. Such system with power electronic converter can be explored for optimum performance.

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## Appendix – A

### Polynomial Coefficients for Simple SEIG with RL load

Coefficients of real term

$$a_1 = 0$$

$$a_2 = X_m (-X_2 R_1 - R_2 X_1 - X_1 R_1 - X_1 R_1) - X_1 X_2 R_1 - X_1 X_2 R_1 - X_1 X_1 R_2$$

$$a_3 = X_m (v X_2 R_1 + v X_1 R_1 + v X_1 R_1) + v X_2 X_1 R_1 + v X_1 X_2 R_1$$

$$a_4 = X_m (R_2 X_c + R_1 X_c + R_1 X_c) + R_2 X_c X_1 + R_1 X_2 X_c + R_1 R_2 R_1 + R_1 X_2 X_c + X_1 X_c R_2$$

$$a_5 = (-v R_1 X_c - v R_1 X_c) (X_2 + X_m)$$

Coefficients of imaginary term

$$b_1 = X_m (-X_2 X_1 - X_1 X_1) - X_1 X_2 X_1$$

$$b_2 = X_m (v X_2 X_1 + v X_1 X_1) + X_1 X_2 X_1 v$$

$$b_3 = X_m (R_2 R_1 + X_c X_1 + R_1 R_1 + X_c X_1) + X_c X_1 X_2 + R_1 R_1 X_2 + R_1 R_2 X_1 + X_1 R_1 R_2 + X_c X_1 X_2$$

$$b_4 = X_m (-v X_c X_1 - v R_1 R_1 - v X_1 X_c) - v X_2 X_c X_1 - v X_2 R_1 R_1 - v X_1 X_2 X_c$$

$$b_5 = -R_1 X_c R_2 - R_1 R_2 X_c$$

## Appendix – B

### Induction Machine Experimental Data:

Relevant experiments are carried out on a three-phase,  $415 \pm 10\%$  V, 10.1 A, 5.5 kW, 4-pole, delta connected, squirrel cage induction motor.

By the open circuit, short circuit, and synchronous speed test we find out the machine parameters as:

$$R_1 = 0.0633 \text{ p.u.}$$

$$R_2 = 0.0247 \text{ p.u.}$$

$$X_1 = X_2 = 0.0633 \text{ p.u.}$$

$$X_m = 1.9588 \text{ p.u.}$$

$$V_{\text{base}} = 415 \text{ V}$$

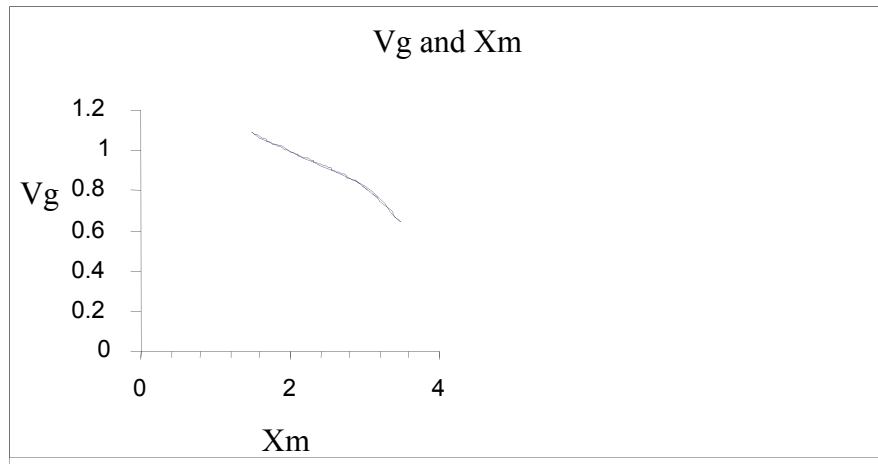
$$I_{\text{base}} = 5.83 \text{ A}$$

$$Z_{\text{base}} = 71.168 \text{ ohm.}$$

## Appendix – C

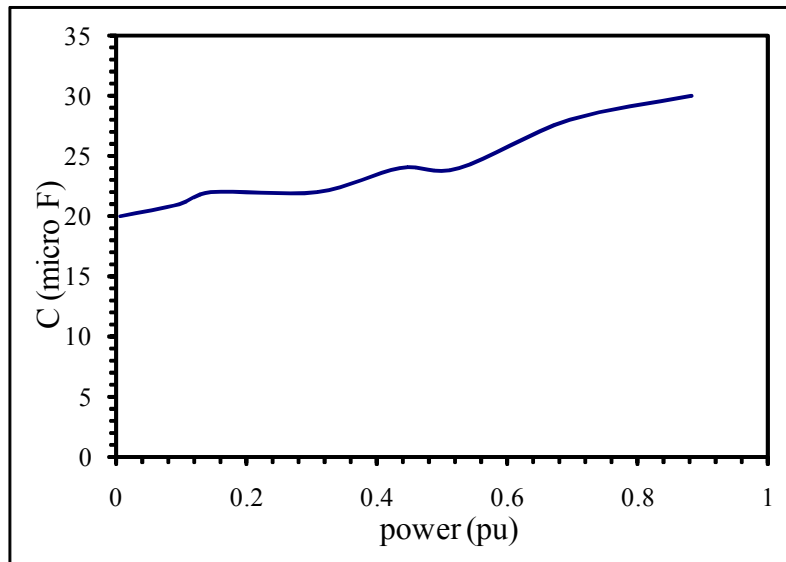
### Induction Machine Magnetizing Characteristic (Experimental)

The magnetizing characteristic obtained by performing synchronous speed test on induction machine.



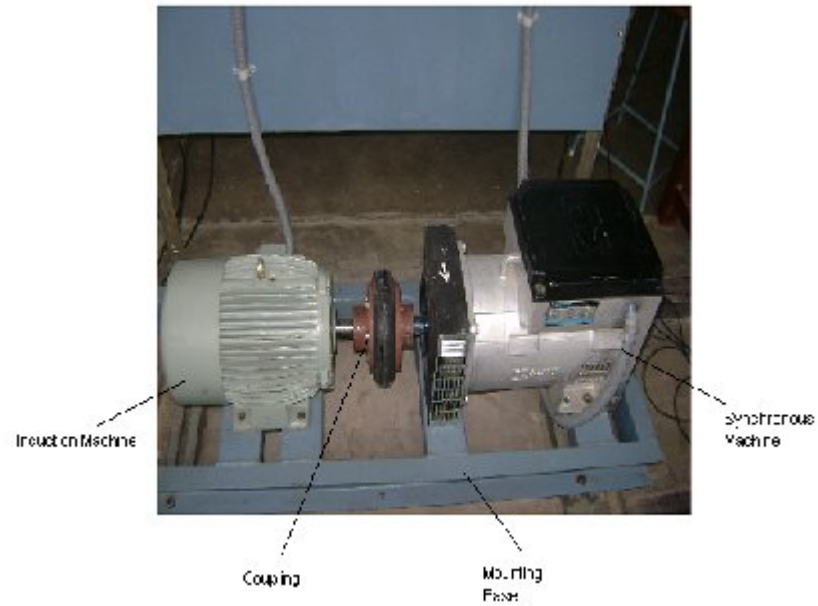
$$V_g = -0.0664X_m^3 + 0.4447X_m^2 - 1.1404X_m + 2.0272$$

### Constant voltage curve (Experimental)



## Appendix – D

### Setup Photographs



Setup view of induction machine coupled with synchronous machine



Capacitor bank and lamp load