STEADY STATE ANALYSIS OF SELF-EXCITED INDUCTION GENERATOR FOR BALANCED AND UNBALANCED CONDITIONS

Thesis submitted towards the partial fulfillment of the requirements for the award of degree of

Master of Engineering
in
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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, **"Steady State Analysis of Self-Excited Induction Generator for Balanced and Unbalanced Conditions"**, in partial fulfilment of the requirements for the award of degree of Master of Engineering in *Power Systems and Electrical 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 Kumar Chauhan, Sr. Lecturer, EIED.

The matter in this project report has not submitted for the award of any other degree of this you 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 self-excited induction generator is becoming popular for the harnessing the renewable energy resources such as small hydro and wind. The poor voltage regulation under varying load is the major drawbacks of the induction generator. The steady state analysis is paramount as far as the running conditions of machine are concerned. To study the steady state aspects, methods are required by which the generator performance is predicted by using the induction motor data so that the effect of the parameters can be assessed. Different methods are available to identify the steady state operating point under saturation for a given set of speed, load and excitation capacitor.

The steady-state analysis of self-excited induction generators (SEIG) under balanced conditions using an iterative method is presented. MATLAB programming is used to predict the steady state behaviour of self-excited induction generator. By considering the conductance connected across the air gap node in the equivalent circuit, an iteration procedure is developed for the determination of the per unit frequency. The main advantage of the method as compared with other methods of analysis is that it involves only simple algebraic calculations with good accuracy and rapid convergence.

The steady state analysis of three-phase self-excited induction generator for unbalanced conditions is also presented. Symmetrical components theory is used to obtain relevant performance equations through sequence quantities. While the analysis of the system is inherently complicated due to unbalance and magnetic saturation. Valid simplifications incorporated in the equivalent circuit for both forward and backward fields results in manageable equations suitable for computer simulation. Newton-Rhapson method is employed to solve these equations in order to determine the generated frequency and magnetizing reactance. Computer program in MATLAB environment is developed to determine the performance under any unbalanced external network at the given speed of the prime mover.

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R_s		pu stator resistance
R_r		rotor resistance
X_s		pu stator reactance
X_r		pu rotor reactance
R_L		load resistance
X_L		pu load reactance
C, X_c		pu excitation capacitance and reactance
F		pu generated frequency
v		pu speed
V_s		pu stator voltage
Is		pu stator current
V_L		pu load voltage
I_L		pu load current
V_g		pu air gap voltage
X_m		pu magnetizing reactance
V_0, V_1, V_2		symmetrical (0, +, - sequence) components of voltage
I_0, I_1, I_2		symmetrical (0, +, - sequence) components of current
j		pu imaginary operator
ω		angular frequency
s	-	Slip
ω_s	-	Synchronous speed
ω_r	-	Rotor speed

CHAPTER – 1

INTRODUCTION

1.1 GENERAL

The increasing concern to the environment and fast depleting conventional resources have motivated the researchers towards rationalizing the use of conventional energy resources and exploring the non-conventional energy resources to meet the ever-increasing energy demand. A number of renewable energy sources like small hydro, wind, solar, industrial waste, geothermal, etc. are explored. Since small hydro and wind energy sources are available in plenty, their utilization is felt quite promising to accomplish the future energy requirements. Harnessing mini-hydro and wind energy for electric power generation is an area of research interest and at present, the emphasis is being given to the cost-effective utilization of these energy resources for quality and reliable power supply. Induction generators are often used in wind turbines and some micro hydro installations due to their ability to produce useful power at varying speeds [1].

Usually, synchronous generators are being used for power generation but induction generators are increasingly being used these days because of their relative advantageous features over conventional synchronous generators. Induction generators require an external supply to produce a rotating magnetic flux. The external reactive supply can be supplied from the electrical grid or from the externally connected capacitor bank, once it starts producing power. Induction generators are mechanically and electrically simpler than other generator types. Induction generators are rugged in construction, requiring no brushes or commutators, low cost & low maintenance, operational simplicity, self-protection against faults, good dynamic response, and capability to generate power at varying speed. These features facilitates the induction generator operation in stand-alone/isolated mode to supply far flung and remote areas where extension of grid is not economically viable; in conjunction with the synchronous generator to fulfill the increased local power requirement, and in grid-connected mode to supplement the real power demand to the grid by integrating power from resources located at different sites [2, 3].

Several types of generators are available; DC and AC types, parallel and compound DC generators, with permanent magnetic, synchronous and asynchronous (induction generators). Induction generators are widely used in non-conventional power generation. Self-excited or stand-alone self-excited induction generator can be used with conventional as well as non-conventional energy sources available at semi-isolated and isolated locations, and can feed remote families, village community, etc [4].

A detailed study of the performance of the induction generator operating in the above referred modes during steady-state and various transient conditions is important for the optimum utilization. The steady-state performance is important for ensuring good quality power and assessing the suitability of the configuration for a particular application, while the transient condition performance helps in determining the insulation strength, suitability of winding, shaft strength, value of capacitor, and devising the protection strategy.

1.2 INDUCTION GENERATOR

1.2.1 Concept

An induction generator is a type of electrical generator that is mechanically and electrically similar to an induction motor. Induction generators produce electrical power when their shaft is rotated faster than the synchronous speed of the equivalent induction motor. Induction generators are often used in wind turbines and some micro hydro installations due to their ability to produce useful power at varying speeds. Induction generators are mechanically and electrically simpler than other generator types.

To excite the generator, external reactive supply can be supplied from the electrical grid or from the externally connected capacitor bank, once it starts producing power. The rotating magnetic flux from the stator induces currents in the rotor, which also produces a magnetic field. If the rotor rotates slower than the rate of the rotating flux, the machine acts like an induction motor. If the rotor rotates faster, it acts like a generator, producing power at the synchronous frequency [4].

In stand alone induction generators, the magnetizing flux is established by a capacitor bank connected to the machine and in case of grid connected, it draws magnetizing current from the grid. It is mostly suitable for wind generating stations as in this case speed is always a variable factor.

1.2.2 Advantages and Disadvantages of Induction Generator

Several types of generators are available. 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.

- **Advantages**
  - Simple and robust construction
  - Run independently
  - Inexpensive as compared to the conventional synchronous generator.
  - Minimal maintenance
  - Inherent overload protection
  - Stand-alone applications, no fixed frequency
  - Less material costs because of the use of electromagnets rather than permanent magnets.

- **Disadvantages**
  - Requires significant reactive energy
  - Poor power factor.
  - Poor voltage and frequency regulation.

Therefore, the wider acceptance of the SEIG is dependent on the methodology to be adopted to overcome the poor voltage and frequency regulation, its capability to handle dynamic loading, and its performance under unbalanced conditions [5].

The induction generator can also be operated in parallel with synchronous generator to supplement the increased local power demand. The configuration may exploit the advantages of both the machines, i.e. improved power factor from the synchronous generator and low power generation cost from the induction generator. The dynamic performance of the configuration with load controller should be thoroughly investigated to assess the feasibility of dispensing costly governors.

1.2.3 Classification of Induction Generators

Induction generators can be classified by different ways as rotor construction, excitation process, and prime movers [1, 6].

➢ **Classification on the basis of their rotor construction:**

- Squirrel cage induction generator
- Wound rotor induction generator

1.2.3.1 Squirrel Cage Induction Generator

For the squirrel cage type induction generator, the rotor winding consists of un-insulated conductors, in the form of copper and aluminum bars embedded in the semi closed slots. These solid bars are short circuited at both ends by end rings of the same material. Without the rotor core, the rotor bars and end rings look like the cage of a squirrel. The rotor bars form a uniformly distributed winding in the rotor slots.

1.2.3.2 Wound Rotor Induction Generator

In the wound rotor type induction generator, the rotor slots accommodate an insulated distributed winding similar to that used on the stator. The wound rotor type of induction generator costs more and requires increased maintenance [1].

➢ **Classification on the basis of their excitement process:**

- Grid connected induction generator
- Self-excited induction generator

1.2.3.3 Grid Connected Induction Generator

The grid-connected induction generator (GCIG) takes the reactive power from the grid, and generates real power via slip control when driven above the synchronous speed, so it is called grid connected induction generator. It is also called autonomous system. Fig. 1.1 shows a grid connected induction generator. The operation is relatively simple as voltage and frequency are governed by the grid voltage and grid frequency respectively.

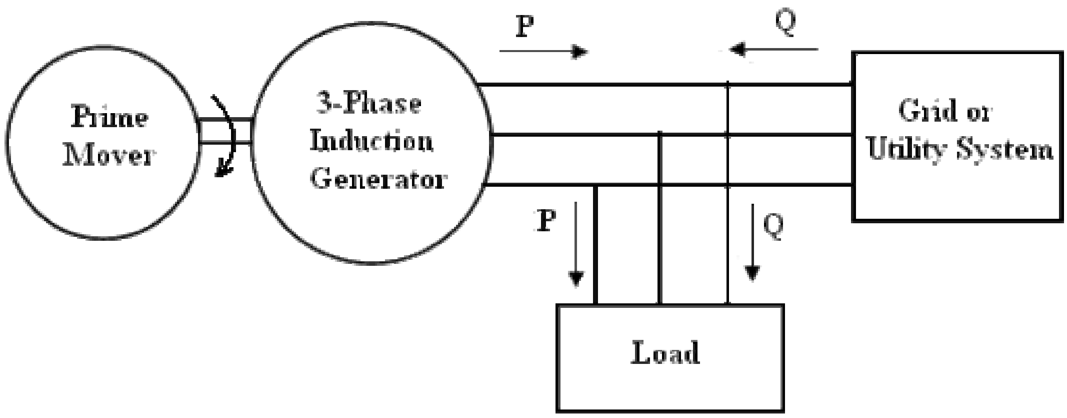


Fig. 1.1: Grid connected induction generator

The GCIG results in large inrush and voltage drop at the time of connection, and its operation makes the grid weak. The excessive VAR drain from the grid can be compensated by the shunt capacitors, but it cause large over voltage during disconnection. Therefore, the operation of GCIG should be carefully chalked out from the planning stage itself. The performance of the GCIG under balanced and unbalanced faults should be thoroughly investigated to ensure good quality and reliable power supply [1].

1.2.3.4 Self-Excited Induction Generator (SEIG)

The self excited induction generator takes the power for excitation process from a capacitor bank, connected across the stator terminals of the induction generator. This capacitor bank also supplies the reactive power to the load. Fig. 1.2 shows a self-excited induction generator.

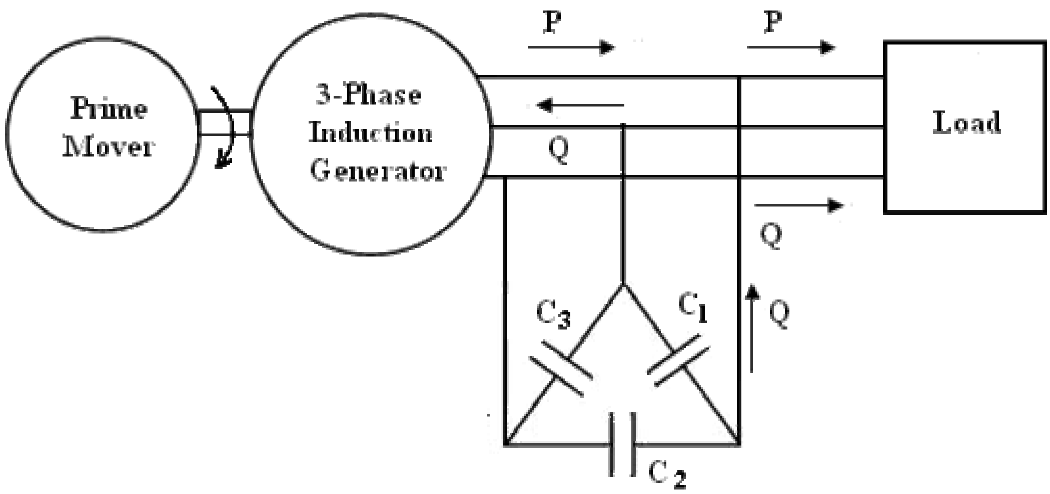


Fig. 1.2: Self-excited induction generator

The excitation capacitance serves a dual purpose for stand alone induction generator: first ringing with the machine inductance in a negatively damped, resonant circuit to build up the terminal voltage from zero using only the permanent magnetism of the machine, and then correcting the power factor of the machine by supplying the generator reactive power [1-6].

➢ **Classification on the basis of prime movers used, and their locations:**

- Constant speed constant frequency (CSCF)
- Variable speed constant frequency (VSCF)
- Variable speed variable frequency (VSVF)

1.2.3.5 Constant-Speed Constant Frequency

In this scheme, the prime mover speed is held constant by continuously adjusting the blade pitch. 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 [7].

1.2.3.6 Variable-Speed Constant Frequency

Variable speed constant frequency (VSCF) energy conversion schemes generally use synchronous or wound rotor induction machines to obtain constant frequency power generation, even in presence of prime mover speed fluctuations [6]. Further, on account of its simplicity, ease of implementation, and low cost, the self-excited induction generator finds wide application in power generation using non-conventional energy sources such as wind. The variable-speed operation of wind electric system yields higher output for both low and high wind speeds. 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. There are two popular schemes to obtain constant frequency output from variable speed as discussed [10, 11].

- **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.

- **Double Output Induction Generator (DOIG)**

The DOIG consists of a three-phase wound rotor induction machine, mechanically coupled to either a wind or hydro turbine, whose stator terminals are connected to a constant voltage and constant frequency utility grid. 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 high maintenance requirements, low power factor, and poor reliability are the few disadvantages due to the sliding mechanical contacts in the rotor. This scheme is not suitable for isolated power generations because it needs grid supply to maintain excitation [6].

1.2.3.7 Variable-Speed Variable Frequency

This scheme is the only one known where the generator gives more than its rated power without being overheated. Since the proposed concept is to be used for heating purposes, a constant voltage and a constant frequency is irrelevant. Thus, the model will be of interest for frequency and voltage insensitive applications especially in remote areas. 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 [2, 3].

1.2.4 Application of Induction Generator

Induction generators, generally, have the application in the wind, solar and micro hydro power plants to generate power for various critical situations as given below [1, 96-102].

- **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 centers
  - Hospitals
  - Telephone exchange
  - Cinema Hall
  - Auditorium
  - Marketing complex

- **As a portable source of power supply**
  - Decorative lighting
  - Lightings for projects and constructional site

1.3 LITERATURE SURVEY

Induction generator is the most common generator in wind energy systems because of its simplicity, ruggedness, little maintenance, price and etc. The main drawback in induction generator its need of reactive power to build up the terminal voltage and to maintain the voltage. Using terminal capacitor across generator terminals can generate this leading reactive power. 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. So it is desirable to maintain a high level of residual magnetism, as it does ease the process of machine excitation [17-33].

J. M. Elder *et al.* [17] have presented the process of self excitation in induction generators. The capacitance value of the terminal capacitor is not constant but it is varying with many system parameters like shaft speed, load power and its power factor. If the proper value of capacitance is selected, the generator will operate in self-excited mode. The capacitance of the excitation capacitor can be changed by many techniques like switching capacitor bank [l, 2], thyristor controlled reactor [3] and thyristor controlled DC voltage regulator [12].

Many researches have determined the minimum capacitor for self-excited induction generator [17, 19, 25-33]. Most of these researches use loop equations in the analysis of induction generator equivalent circuit [18, 19]. Most of these researches have much difficulty and it needs numerical iterative techniques to obtain the minimum capacitance required. Some of these researches require large computational time to obtain accurate value for the minimum capacitor required. D. Sutanto et al. described a method for accurately predicting the minimum value of capacitance necessary to initiate self-excitation with stand alone induction generator [23]. G. K. Singh [24] presents a paper for 6-phase induction generator using capacitive self-excitation. Décio Bispo [25] 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 which improves balance overall and maximizes the allowable power output of a particular machine [26].

A.I. Alolah *et al.* [27] present an optimization method to determine the excitation requirements of three-phase SEIG under single phase mode of operation. A single phase load is connected to the generator through two excitation capacitors. The values of these capacitors are chosen to ensure minimum self-excitation of the machine in addition to minimization of the unbalance between the stator voltages. A.M. Eltamaly, [28] presents a new formula to determine the minimum capacitance required for self-excited induction generator, which uses nodal analysis instead of loop analysis. T. Ahmed [29] present a paper for variable speed prime mover for minimum capacitance required for self excitation, he used a nodal admittance approach to find it. L. Wang [30, 31] 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.

Usually there are two types of useful studies to describe the performance of induction generator.

- Steady State analysis
- Transient Analysis

Steady-state analysis of SEIG is of interest, both from the design and operational points of view. In a capacitor-excited generator used as an isolated power source, 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 the SEIG [1, 6, 22, 34-50].

T.F. Chan *et al.* [34] have proposed two solution technique for the steady state analysis of SEIG. The first technique is based on the loop impedance method and the second technique is based on the nodal admittance method. The iterative technique by assuming some initial value for f and then solving for a new value considering a small increment until the result converges. This technique, however, lacks in making a judicious choice of an initial value and number of iterations required. Rajakaruna *et al.* [35] have used an iterative technique which uses an approximate equivalent circuit and a mathematical model. S. P. Singh *et al.* [36] tried an optimization technique by formulating as a multivariate unconstrained nonlinear optimization problem. The impedance of the machine is taken as an objective function. The f and X_m are selected as independent variables, which are allowed to vary within their upper and lower limits so as to achieve practically acceptable values of the variables. The Rosenbrock's method of rotating coordinates has been used for solving the problem. Murthy *et al.* [37] developed a mathematical model to obtain the steady-state performance of SEIG using the equivalent circuit impedance of the machine. Two nonlinear equations, which are real and imaginary parts of the impedance, are solved for two unknowns and using Newton–Raphson method. Quazene et al. [38] used a nodal admittance technique to obtain a nodal equation and then separated it into its real and imaginary parts to solve for 'f' and then for 'X_m'.

L. Shridhar *et al*. [39] applied an algorithm for dynamic load as induction motor. Based upon per phase equivalent circuit of SEIG, find out the unknown values of magnetizing reactance and frequency, while solving two non linear equations. S.M.

Alghuwainem *et al.* presented the steady-state analysis including transformer saturation, the system equations are formulated using nodal analysis of the SEIG's equivalent circuit. A.L. Alolah *et al.* [41] have 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 SEIG. D.K. Jain *et al.* [42] have proposed a method in which the algebraic equation is solved for the initial value of and then the Secant method is used for the exact solution.

A.H. Al-Bahrani *et al.* [43] discussed steady state and performance characteristics of a three-phase star or delta connected induction generator employing a single excitation capacitor supplying a single phase load. References [43], [46-50] have used phase sequence equivalent circuit to study the performance of the SEIG under unbalanced conditions. In general symmetrical component and phase sequence equivalent circuit are suitable only in steady state analysis. T.F. Chan *et al.* [48] considered symmetrical component technique has been in analyzing the steady state operation of the SEIG under general unbalance load and excitation conditions. S. S. Murthy *et al.* [45] have presents a Matlab based generalized algorithm to predict the dynamic and steady state performance of self-excited induction generators (SEIG) under a 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. Yaw-Juen Wang *et al.* [46] analyzed the steady-state performance of a self-excited induction generator whose electrical loads are unbalanced by using the symmetrical component theory. An equivalent circuit of the induction generator taking into account unbalanced voltages and currents caused by load unbalance are developed. Analysis of the proposed equivalent circuit allows the performance of the induction generator under unbalanced electrical loads to be investigated.

The transient analysis 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 stress and shaft vibrations. The various dynamic models have been proposed to study the dynamic and transient behavior of SEIG. Many articles have been reported on the transient studies of SEIG [1, 6, 51-64].

L. Wang *et al.* [54] described the dynamic performances of an isolated self-excited induction generator for various loading conditions. L. Shridhar *et al.* [55] presented the transient analysis of short shunt self-excited induction generator. It is reported that it can sustain severe switching transients, has good overload capacity, and can re-excite over no load after loss of excitation. It is also observed that except for the most unusual circumstances (the short circuit across the machine terminals across the series capacitor), the short-shunt SEIG supplies adequate fault current to enable over current protective device operation. Hallenius *et al.* [56] have described analytical models to predict transient behavior of the SEIG self regulated short shunt SEIG. But scope of these papers is limited to applicability of respective model equations to the SEIG. In [57], B. Singh *et al.* transient analysis of SEIG feeding an induction motor (IM) has been investigated to analyze the suitability of the SEIG to sudden switching, such as starting of the induction motor. It is seen that reliable starting of an induction motor on SEIG is achievable with the value of capacitance determined through steady-state investigation; however, the capacitance should be applied in two steps: first to self-excite the generator, and second along with the motor or after switching on the motor.

Transient performance of three-phase SEIG during balanced and unbalanced faults is presented in [59], considering the effects of main and cross flux saturation for load perturbation, three-phase, and line-to-line short circuit, opening of one capacitor, two capacitors and a single line at the capacitor bank, opening of single-phase load, two-phase load, etc. Wang *et al.* [60] have presented a comparative study of long-shunt and short-shunt configurations on dynamic performance of an isolated SEIG feeding an induction motor load. Results show that the long shunt configurations may lead to unwanted oscillations while the short shunt provides the better voltage regulation. Matlab based generalized algorithm to predict the dynamic performance of self excited induction generator (SEIG) is discussed by using an iterative technique [61]. L.B. Shilpakar *et al.* [63] present the transient operation performances for parallel operated self excited induction generator. Avinash Kishore *et al*. [64] proposed the transient analysis by using dynamic modeling of a three phase SEIG developed using d-q variables in stationary reference frame. The proposed model for induction generator, load and excitation using state space approach can handle variable prime mover speed, and various transient conditions.

Induction generators have some drawbacks like the need of reactive power support and poor voltage regulation [1]. To get better voltage regulation the reactive current need to be changed suitably during load variation from no load to full load. In stand alone induction generator the required reactive power is supplied by capacitor bank and reactive power supplied is controlled by various voltage regulating schemes [6]. By using the short/long-shunt configurations, SEIG gives better performance by improving the voltage regulation, but the compensation used in these configurations causes the problem of sub-synchronous resonance while supplying power to dynamic loads. 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 [65-82].

H.C. Rai *et al*. [66] proposed a scheme which used passive element such as capacitors, saturable reactors, and constant voltage regulator for improvement of performance of SEIG. In [67-70] voltage and frequency control is achieved using PWM voltage source converter with a capacitor and a chopper in the DC side. The control objective is to maintain the DC voltage constant by changing the effective value of the DC resistance to consume the excessive generated power. By maintaining a constant modulation index, the AC voltage can be maintained constant. T. F. Chan [71] proposed the control of voltage and frequency of slip-ring induction generator by varying the effective rotor resistance using a DC chopper. But this introduces current harmonics in the rotor circuit and the slip-ring machine is more expensive and requires more maintenance. Bhim Singh *et al*. [74] present 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.

S.P. Singh *et al.* [75] present a steady-state model of short-shunt SEIG with induction motor load and static resistive load is presented. The steady-state analysis is directed to find the values of capacitances resulting in optimum voltage regulation for various loading conditions. T. Chandra Sekhar *et al.* [76] proposed different voltage regulation schemes like power electronic controller, electronic load controller and magnetic amplifier. He proposed to use inverter based VAR compensator (STATCOM) or Magnetic amplifier. Dheeraj Joshi *et al.* [77] applied genetic algorithm for constant voltage and constant frequency operation. B. Singh *et al.* [78] present a procedure for the design and selection of STATCOM components is developed for regulating the terminal voltage of SEIG. The VAR requirements of five different rating machines at no load and full load at different power factors are obtained to decide the STATCOM component ratings with a view to develop a generalized design procedure. Karim H. Youssef *et al.* [80] introduces a new and simple method for voltage and frequency control of three-phase unregulated speed induction generators in the islanding mode. The method uses a constant voltage constant frequency (CVCF) PWM converter without regulating the DC capacitor voltage. The capacitor voltage is left changing with the loading conditions and the AC side voltage is regulated by controlling the modulation index. This eliminates the need of an auxiliary switch in the DC side which reduces the high frequency current components flowing in the DC capacitor.

Hamid R. Karshenas [81] proposed a current type converter (CTC), based on STATCOM, to regulate the output voltage of a SEIG. G. V. Jayaramaiah *et al.* [82] present the analysis of a voltage regulator for a 3-Phase Self-Excited Induction Generator (SEIG) using a current controlled voltage source inverter (CC-VSI). The control scheme consists of two PI controllers, which are used to regulate the stator terminal voltage of the induction generator (IC).

There are certain locations, where natural resources are available in abundance. Usually SEIGs operate in parallel [1, 83-90] to utilize the full potential of natural resources. Parallel operation of SEIG requires extensive investigation with regard to different aspects of parallel operation, such as influence of parameter variations on parallel operation, VAR control, etc. C. Chakrabort *et al.* [85, 89] presented an iterative solution for the problems related to steady state performance of self-excited induction generators operating in parallel based on voltage and current balance equations derived from an inverse model for steady state equivalent circuit of SEIG. L. Wang *et al.* [86] present the minimum start value of capacitance required for self excitation of parallel operated induction generators feeding an induction motor based on eigen value method. S. P. Das *et al.* [88] presented analyses to study the performances of parallel SEIG with common excitation capacitance under steady state balanced conditions. F. A. Farret [90] discussed approach for steady-state and transient analysis of any number of SEIGs operating in parallel, by classical state space modeling.

Steady-state analysis of induction generators is of interest, both from the design and performance characteristic point of view [2]. The performance of this type of induction generator is undesirable. The reason for the poor performance is that, the designer optimized the performance operating as motor rather than generator. Moreover, it will have poor voltage regulation [91-95]. S.S. Murthy *et al.* [92] have reported the effect of variation of parameters on its performance using design based procedure. P.G. Casielles *et al.* [93] present the design of SEIG by analyzing the steady state condition. By computing the required external capacitance, the minimum and maximum values of speed, frequency, and voltage and output power can be easily determined. Now it is possible to design a system that should be able to maintain output voltage and frequency within some predefined range of values for any feasible load conditions. J. Faiz *et al.* [94] proposed the design of a three phase self excited induction generator but the factors like rotor skewing was not considered in the design. B. Sawetsakulanond *et al.* [95] proposed the new design method of three phase self-exited induction generator (SEIG). The designed SEIG has been analyzed by using a finite element method and tested and compared with a standard SEIG under various operating conditions such as no-load and on-load.

In the field of small renewable energy resources to generate electrical power, the squirrel cage induction generator is a good option due to its robustness, reduced costs and low maintenance [1-8]. Standalone generator systems are used in a wide variety of situations such as remote area power supplies, lighting, transportation, life support systems, communications etc [1]. Several papers have been presented over the application field of induction generators in wind energy conversion schemes [96-102].

S.S. Murthy *et al.* [99] present a study undertaken by the field experience to assess the suitability of conventional induction motors for the development of micro hydel grid independent power generation scheme [99-101]. T. L. Maguire [102] describes the design and laboratory testing of a novel generation apparatus for supplying an isolated dc load from a self-excited induction generator.

1.4 AIM OF THESIS

The objective of the thesis entitled *"**steady state analysis of self-excited induction generator for balanced and unbalanced conditions**"* is to analyze the steady state performance of SEIG for balanced and unbalanced conditions under various loading conditions. The obtained results are experimentally validated to prove the effectiveness of the proposed procedure. For unbalanced conditions, the symmetrical component approach has been used. The positive sequence and negative sequence circuits have been directed to take care of unbalance. The problem has been solved with loop impedance and node admittance method.

1.5 ORGANIZATION OF THESIS

For better understanding of induction generator behavior during unbalanced conditions, the work in the thesis entitled "steady state analysis of induction generator for balanced and unbalanced conditions" is carried out. The complete thesis work is divided into six chapters.

Chapter 1: This chapter, entitled as "Introduction", includes the concept of the induction generator, updated classification of induction generator, advantage & disadvantage and its application. The updated literature survey on various aspects is also included in this chapter.

Chapter 2: This chapter, entitled as "Steady state analysis of SEIG for balanced condition", includes the steady state analysis of the SEIG for balanced condition using iterative method. The simulated results are validated with experimental results.

Chapter 3: This chapter, entitled as "Theory of symmetrical components", includes the basic theory and operators of symmetrical components. This chapter also includes the advantages and applications of symmetrical components.

Chapter 4: This chapter, entitled as "Steady state analysis of SEIG for unbalanced condition", includes the steady state analysis of the SEIG for unbalanced condition using N-R method. The results obtained are validated with the experimental results.

Chapter 6: This chapter, entitled as "Main conclusion and further future scope", mainly includes the conclusion and future scope of this thesis work.

1.6 CONCLUSION

The investigations carried out since three decades indicate that the use of an 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 offers many advantages over a synchronous generator. It is desirable that the cost of an isolated system should be very low so that the cost of power produced from it can be afforded to community residing in an isolated area. Use of the SEIG compared to the synchronous generator can reduce the system cost considerably.

This chapter has presented not only a comprehensive literature review on important aspects of SEIG such as the process of self-excitation, modeling, steady-state and transient analysis, reactive power/voltage control, parallel operation, and applications, but also concept of induction generator, classification etc. 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 FOR BALANCED CONDITIONS

2.1 INTRODUCTION

Steady-state analysis of SEIG is of interest, both from the design and operational points of view. In an isolated system, both the terminal voltage and frequency are unknown and by knowing the parameters of the machine, it should be possible to determine its performance for given capacitance, speed and load conditions. If the terminal voltage and frequency are known, as in the case of a machine connected to an infinite bus bar, the prediction of performance is straightforward. However, in a capacitor-excited generator used as an isolated power source, both the terminal voltage and frequency are unknown and have to be computed for a given speed, capacitance and load impedance. The analysis is complicated owing to the magnetic saturation in the machine and the need to choose suitable parameters corresponding to this saturated condition.

For the Steady-state analysis, the following assumptions are made:

(a) Only the magnetizing reactance is assumed to be affected by magnetic saturation, and all other parameters of the equivalent circuit are assumed to be constant. Self excitation results in the saturation of the main flux. As the value of the magnetizing reactance X_m reflects the magnitude of the main flux, it is essential to incorporate in the analysis the variation of X_m with the saturation level of the main flux.

(b) Leakage reactance of stator and rotor, in per unit, are taken to be equal. This assumption is normally valid in induction-machine analysis.

(c) Core loss in the machine is neglected, although the analysis can be easily extended to account for core loss.

(d) MMF space harmonics and time harmonics in the induced voltage and current waveforms are ignored. This assumption is valid in well designed machines.

The characteristics for steady-state operation can be derived using the conventional equivalent circuit of the induction machine, with the exception that the magnetizing branch contains only the magnetizing reactance X_m. This circuit is shown in Fig. 2.1.

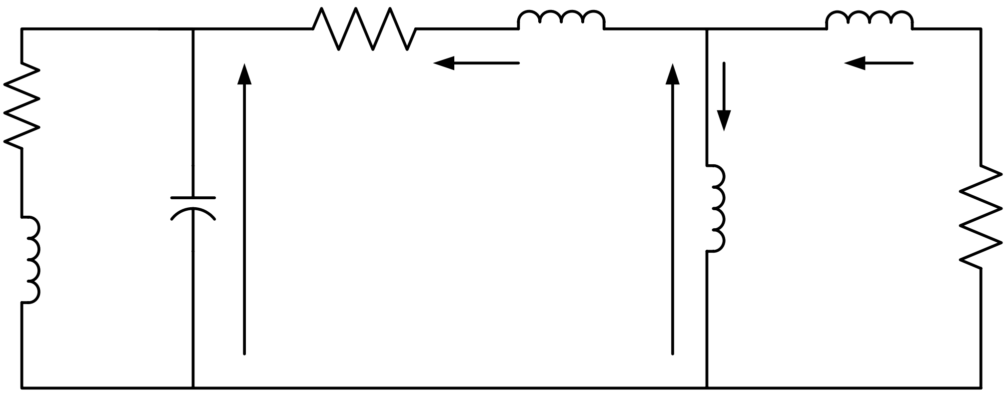


Fig. 2.1: Single-phase equivalent circuit of SEIG at stator frequency 'ω'

The slip, expressed as a fraction of synchronous speed (s = (ω_s- ω_r)/ ω_s) is of course negative for generator action. It should be emphasized that both ω_s and ω_r vary, since the generator is isolated from any electrical supply. One can expect that the slip would be small, because rated loads correspond to low slips when R_2 is small.

2.2 STEADY STATE MODEL OF INDUCTION MACHINE

An equivalent circuit of the induction machine, also known as the per-phase equivalent model is represented in Fig. 2.2, which will be used further for steady state analysis of SEIG.

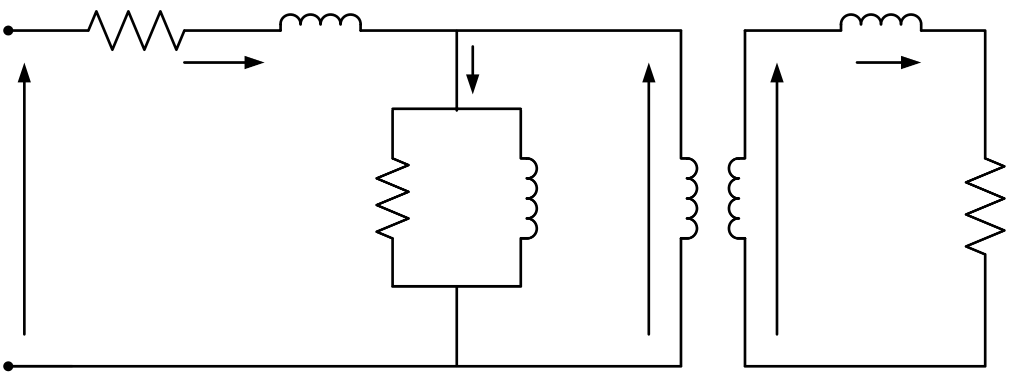


Fig. 2.2: Equivalent model of induction machine

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

$$E_r = sE_{r0} \qquad \text{...... (2.1)}$$

where s is the slip factor

$$X_r = sX_{r0} \qquad \text{...... (2.2)}$$

where X_{r0} is the blocked rotor reactance.

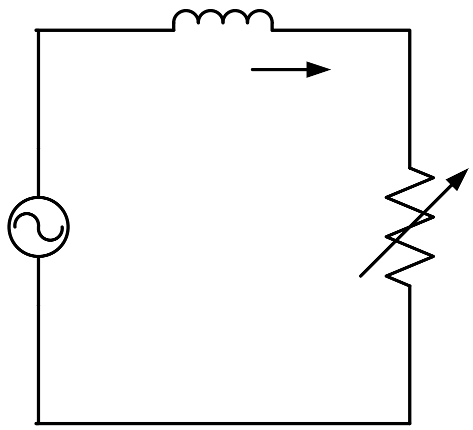


Fig. 2.3: Rotor side equivalent model of induction machine

Fig. 2.3 displays the equivalent circuit of the rotor impedance $Z_{r0}=R_{r0}+jX_{r0}$ as a function of slip factor given by

$$I_r = \frac{E_r}{Z_r} = \frac{sE_{r0}}{R_r + jsX_{r0}} = \frac{E_{r0}}{\frac{R_r}{s} + jX_{r0}} \qquad \text{...... (2.3)}$$

$$Z_r = \frac{E_{r0}}{I_r} = \frac{R_r}{2} + jX_{r0} \qquad \text{...... (2.4)}$$

2.3 NO-LOAD CHARACTERISTICS

The no-load saturation curve of the machine is obtained at normal rated frequency f=50 Hz. The no load condition of operation is realized by using a synchronous motor as prime mover and a variable sinusoidal voltage source at 50 Hz.

The voltage source is applied to the stator of the induction machine while its rotor is driven by the synchronous motor at synchronous speed of the machine at 50 Hz. It is known that the magnetizing current is-the difference between stator current and rotor current referred to the stator. In the present case the slip is very small (practically zero), which implies that the branch corresponding to the rotor in the equivalent circuit can be considered as open as shown in Fig. 2.4. Therefore the magnetizing branch current is essentially the measured stator no-load current.

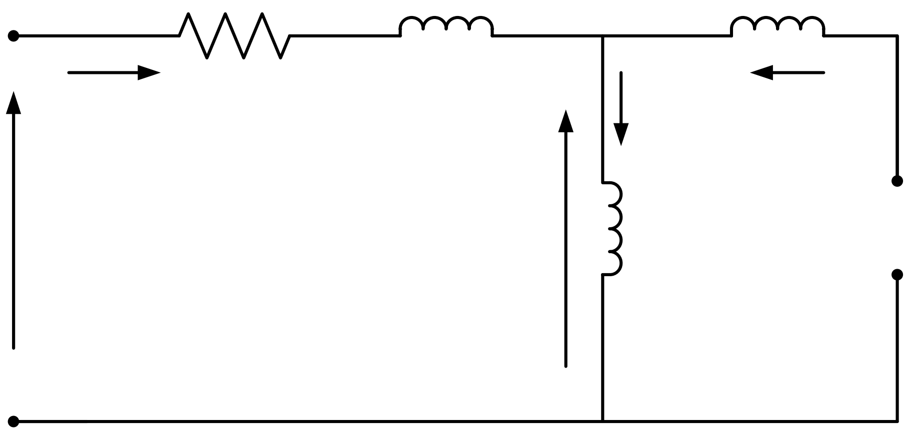


Fig. 2.4: No-load test single phase equivalent circuit

The rms magnetizing branch voltage

R_s

$$V_g = X_m I_0,$$

$$I_0 = I_m$$

The no-load current (in absolute value) is equal to

+

I_{nl}

$$I_0 = \left(V_0 \big/ \sqrt{3} \right) \big/ Z_0$$

Where Z_0 is the absolute value of the total impedance Z_0 of the equivalent circuit of Fig. 2.4, given by:

$$Z_0 = R_s + j(X_s + X_m)$$

V_0

$$Z_0^2 = R_s^{\,2} + (X_s + X_m)^2$$

The magnetizing reactance is

$$X_m = \left(Z_0^{\,2} - R_s^{\,2} \right)^{1/2} - X_s$$

–

Now

$$V_g = [(Z_0{}^2 - R_s{}^2)^{1/2} - X_s] I_0$$

or
$$V_g = [(\frac{V_0}{3I_0^2} - R_s{}^2)^{1/2} - X_s] I_0$$

A plot of V_g v/s I_m is shown in Fig. 2.5 and the voltage-current characteristic of a capacitor bank plotted on the same figure.

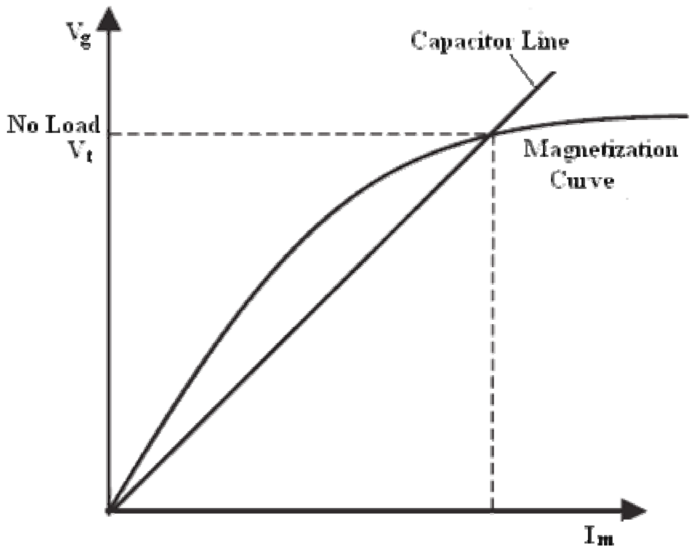


Fig. 2.5: Magnetization characteristic of induction generator

The intersection of the two curves is the point at which the capacitor bank exactly supplies the reactive power demanded by the generator. As shown in the figure the no-load terminal voltage of the generator may be determined from this point.

When a SEIG is loaded, both the magnitude and frequency of the induced e.m.f. are affected by the prime mover speed, the capacitance of the capacitor bank and the load impedance. To simplify the discussion, we assume that all losses in the generator are ignored ($P_{in} = P_{out}$), the connected load is purely resistive and the rotor speed is kept constant. In this case, the decrease in the load resistance (increase in P_{out}) will result in a drop in the stator frequency to provide higher torque to match the increment in the power demand. This circumstance is illustrated in Fig. 2.6.

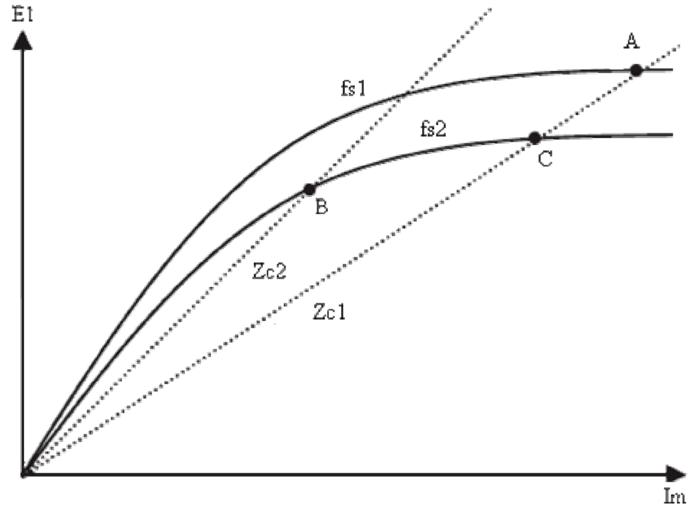


Fig. 2.6: Magnetization characteristic of induction generator at load

2.4 PROBLEM FORMULATION

Self excitation in an induction machine occurs when the rotor is driven by a prime mover and a suitable capacitance is connected across the stator terminals. Both the frequency and the magnetizing reactance (which depends upon magnetic saturation) of the SEIG vary with load even when the rotor speed is maintained constant. Therefore, a crucial step in the steady-state analysis of the SEIG is, given the machine parameters, speed, excitation capacitance and load impedance, to determine the value of the per-unit frequency a and the magnetizing reactance X_m which result in exact balance of active and reactive power across the air gap.

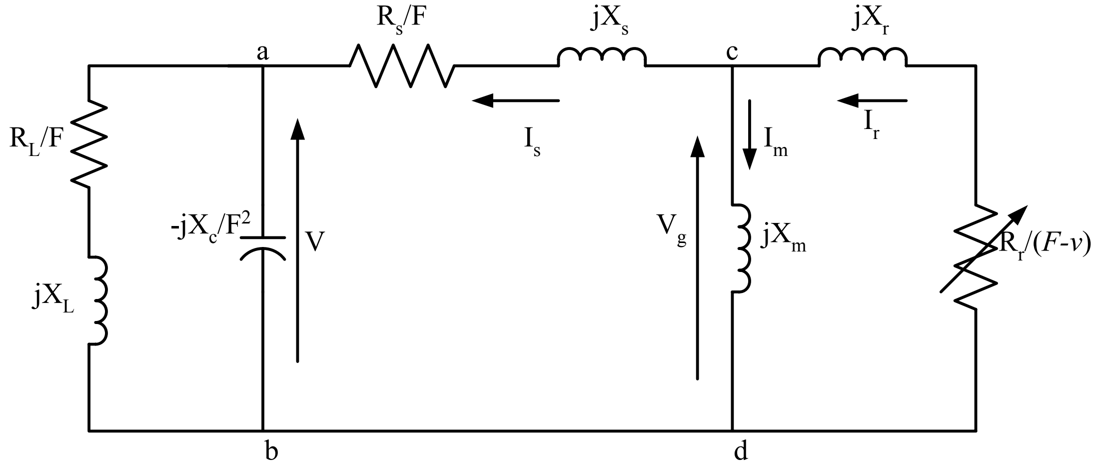


Fig. 2.7: Per-phase equivalent circuit of SEIG

Following two solution techniques based on the steady-state equivalent circuit are:

- **Nodal Admittance Method**

  This method considers the admittances connected across the nodes which define the air gap. By equating the sum of real parts to zero (which is equivalent to active power balance), a polynomial in '*F*' is obtained. 'X_m' can be determined upon equating the sum of imaginary parts to zero, using the value of '*F*' obtained after solving the polynomial by any method among various methods as iterative method, secant method etc.

- **Loop Impedance Method**

  For a given load and speed, two non-linear simultaneous equations in '*F*' and X_m are obtained by equating the real and imaginary terms of the complex loop impedances respectively to zero. These equations are then solved by using an optimization method. Knowing '*F*' and X_m and with the aid of the magnetization curve, the equivalent circuit is completely solved and the steady-state performance of the SEIG can be determined.

While both the above methods are effective in the determination of machine performance, they have the common disadvantage that lengthy algebraic manipulations are required in deriving the coefficients of the simultaneous equations or a high order polynomial. Moreover, the values of these coefficients vary with the equivalent circuit configuration. For example, inclusion of the addition of series compensation capacitive reactance will change the order of the equations or the polynomial. Here second method, nodal admittance method is used by an iterative technique for the performance analysis of the SEIG.

2.4.1 Nodal Admittance Method

The formulation of conservation of real and reactive power, in terms of network quantities is equivalent to writing that the sum of the admittances of the branches in the circuit must be zero, as it is seen that this circuit does not contain any e.m.f. source or current source.

$$V_g (Y_{bc} + Y_m + Y_r) = 0 \qquad \text{…... (2.5)}$$

Where,

$$Y_{bc} = \frac{1}{R_t - jX_t} = G_t + jB_t \qquad \text{...... (2.6)}$$

$$G_t = \frac{R_t}{R_t^2 + X_t^2} \qquad \& \qquad B_t = \frac{X_t}{R_t^2 + X_t^2} \qquad \text{...... (2.7)}$$

$$R_t = \left(R_{ab} + \frac{R_s}{F} \right) \qquad \& \qquad X_t = \left(X_{ab} - X_s \right) \qquad \text{...... (2.8)}$$

$$R_{ab} = \frac{R_L X_c^2}{F\left[F^2 R_L^2 + \left(X_L F^2 - X_c^2\right)^2\right]} \qquad \text{...... (2.9)}$$

$$X_{ab} = \frac{(X_L X_c^2 - F^2 X_L^2 X_c - R_L^2 X_c)}{\left[F^2 R_L^2 + (X_L F^2 - X_c^2)^2\right]} \qquad \text{...... (2.10)}$$

$$Y_m = \frac{1}{jX_m} = -j\frac{1}{X_m} \qquad \text{...... (2.11)}$$

$$Y_r = \frac{1}{\frac{R_r}{(F-v)} + jX_r} = \frac{(\frac{R_r}{F-v}) - jX_r}{\left(\frac{R_r}{F-v}\right)^2 + X_r^2} \qquad \text{...... (2.12)}$$

For voltage build-up, $V_g \neq 0$, hence equation (2.5) becomes

$$Y_{bc} + Y_m + Y_r = 0 \qquad \text{...... (2.13)}$$

Equating the real and imaginary parts in equation (2.13) to zero, we have

$$G_t + \frac{(\frac{R_r}{F-v})}{(\frac{R_r}{F-v})^2 + X_r^2} = 0 \qquad \text{...... (2.14)}$$

$$\& \qquad B_t - \frac{1}{X_m} - \frac{X_r}{(\frac{R_r}{F-v})^2 + X_r^2} = 0 \qquad \text{...... (2.15)}$$

Let $\gamma = F - v$ …… (2.16)

Equation (2.14) can be rewritten as a quadratic equation in γ as:

$$G_t X_r^2 \gamma^2 + R_r \gamma + G_t R_r^2 = 0 \qquad \text{…… (2.17)}$$

Solving equation (2.17), we get

$$\gamma = -\frac{R_r}{2G_t X_r^2}\left\{1 \mp \sqrt{1 - 4G_t^2 X_r^2}\right\} \qquad \text{…… (2.18)}$$

In practice, γ is a small negative number for generator operation; hence the negative sign in the brackets of equation (2.18) should be taken.

$$\gamma = -\frac{R_r}{2G_t X_r^2}\left(1 - \sqrt{1 - 4G_t^2 X_r^2}\right) \qquad \text{…… (2.19)}$$

For a given rotor speed, load impedance and excitation capacitance, equation (2.14) may be used to determine 'F'. By using equation (2.15), we calculate the value of X_m as by given equation (2.20).

$$X_m = \frac{\left(R_L + \frac{R_s}{F}\right)\left[\left(\frac{R_r}{F - v}\right)^2 + X_r^2\right]}{\left[\left(\frac{R_r}{F - v}\right)\left(X_s - X_L\right) - X_r\left(R_L + \frac{R_s}{F}\right)\right]} \qquad \text{…… (2.20)}$$

After getting the value of X_m and F, find the air-gap voltage (V_g) by using the magnetization curve (plot of V_g v/s X_m), and solve the equivalent circuit for the performance parameters such as V_s, I_s, I_L, output power.

$$I_s = \frac{V_g}{F} Y_{bc} \qquad \text{…… (2.21)}$$

$$V_s = \frac{V_g}{F} - I_s Z_{ac} \qquad \text{…… (2.22)}$$

$$I_c = \frac{V_{ab}}{\left(-jX_c / F^2\right)} \qquad \text{…… (2.23)}$$

$$I_L = I_s - I_c \qquad \text{…… (2.24)}$$

$$P_{out} = V_{ab} I_L \qquad \text{…… (2.25)}$$

2.5 ALGORITHM AND FLOW CHART

The computational procedure of Iterative method for solution of X_m and F and subsequent performance of SEIG is as follows:

Step 1: Read the machine data (R_s, X_s, R_r, X_r), prime mover speed, p.f. of load, synchronous speed test data etc.

Step 2: Assume an initial value of per-unit frequency 'F' and take the value of 'F' is equal to 'v' (F=v).

Step 3: Evaluate G_t using equations (2.7) - (2.10).

Step 4: Determine γ by using equation (2.19); hence obtain the updated value of 'F' using equation (2.16).

Step 5: Repeat steps (2) and (3), each time using the updated value of 'F' for evaluating G_t until the values of 'F' in successive iterations differ by a sufficiently small number ε.

Step 6: By getting the value of 'F', calculate the value of X_m by using equation (2.20).

Step 7: By using the magnetizations curve (V_g v/s X_m), determine V_g and correspondingly find the value of voltage and current across the load branch by using eq. (2.21) to eq. (2.25).

Step 8: Store the relevant data in data file.

Step 9: By using the values of the above calculated parameters, various characteristics that yield to the machine performance are obtained.

Step 10: Stop.

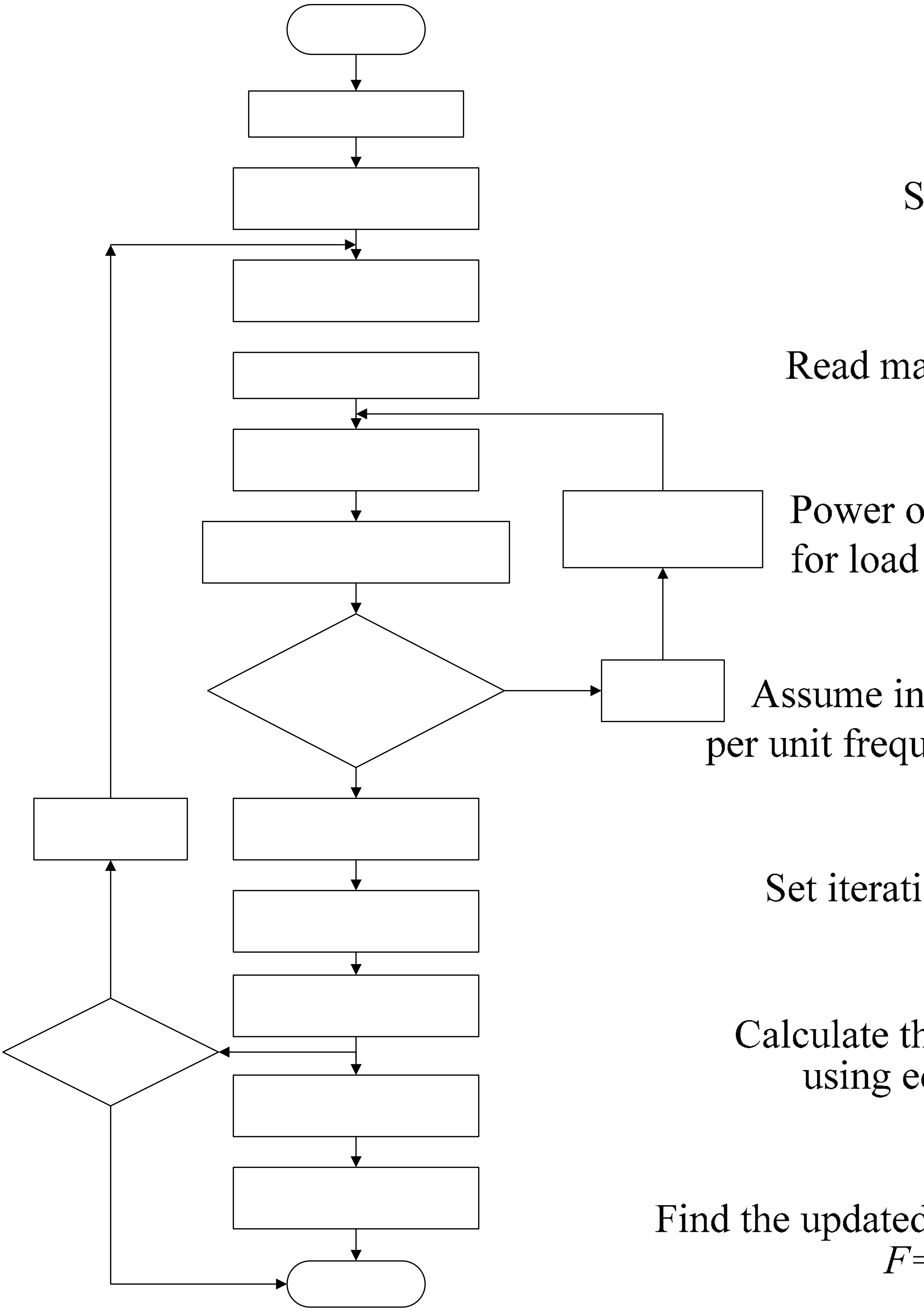


Fig. 2.8: Flow chart of iterative method

2.6 RESULTS AND DISCUSSION

In this section following studies have been carried out for the given data of machine (specification given below) with resistive load and resistive-inductive (R-L) load.

3-phase, 4-pole, 50 Hz, 415 V, 5.83A, 5.5 kW delta-connected squirrel cage induction machine whose per-phase equivalent circuit constants in per unit are: R_s=0.0633; R_r=0.0247; X_s=0.0633; X_r=X_s; pf=0.8; v=1 p.u.

- Variation of magnetizing reactance (X_m) v/s output power for different load power factor.
- Variation of terminal voltage (V_L) v/s output power for different load power factor, different capacitor value and different speed.
- Variation of load current (I_L) v/s output power for different load power factor, different capacitor value and different speed.

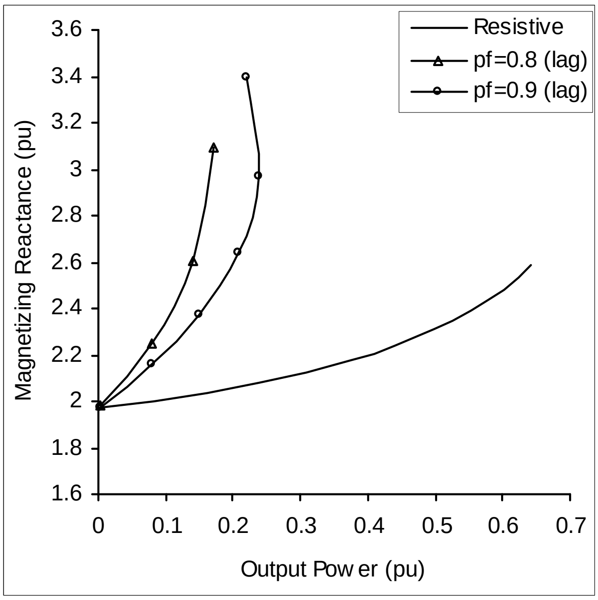


Fig. 2.9: Magnetizing reactance (X_m) v/s output power at 22 μF, v=1 p.u.

Figure 2.9 shows the magnetizing reactance (X_m) v/s output power characteristic for various resistive and resistive-inductive loads. For resistive load the loading is more than resistive-inductive load and magnetizing reactance is varying slowly-slowly (nearly constant) for resistive load. Power output for resistive-inductive load depends upon power factor and for p.f. =0.9 (lagging) output loading is more as compared to p.f. = 0.8 (lagging). Variation in X_m for p.f. = 0.9 (lagging) and p.f. = 0.8 (lagging) is almost same. These characteristics are calculated at 22μF value of per phase capacitance of capacitor bank connected in shunt for excitation purpose.

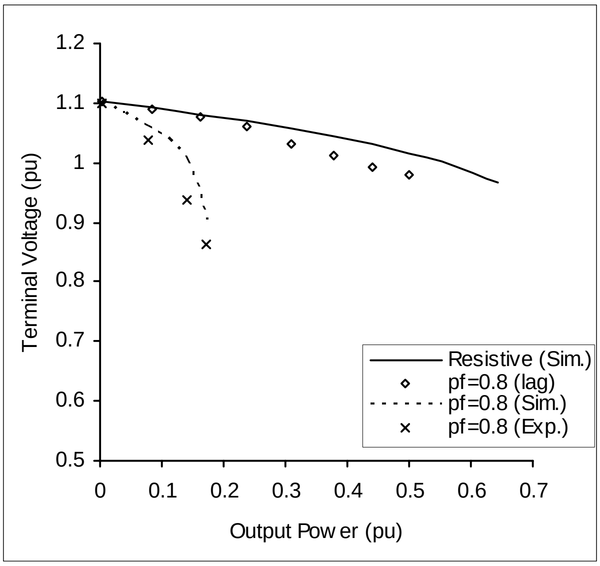


Fig. 2.10: Terminal voltage (V_L) v/s output power at 22 μF, v=1 p.u.

Figure 2.10 shows the terminal voltage v/s output power characteristic for purely resistive load and resistive-inductive load. For resistive load, the terminal voltage decreases gradually while for resistive-inductive load the terminal voltage decreases rapidly.

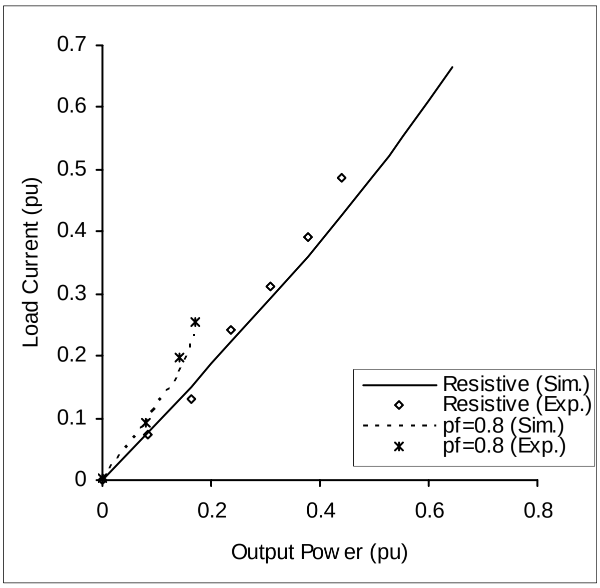


Fig. 2.11: Load current (I_L) v/s output power at 22 μF, v=1 p.u.

Figure 2.11 shows the simulated results for load current v/s output power. For the resistive load, SEIG draw the more current and the output loading is also more as compare to resistive-inductive loading. These characteristics show that loading capacity is more for resistive load as compared to inductive loading.

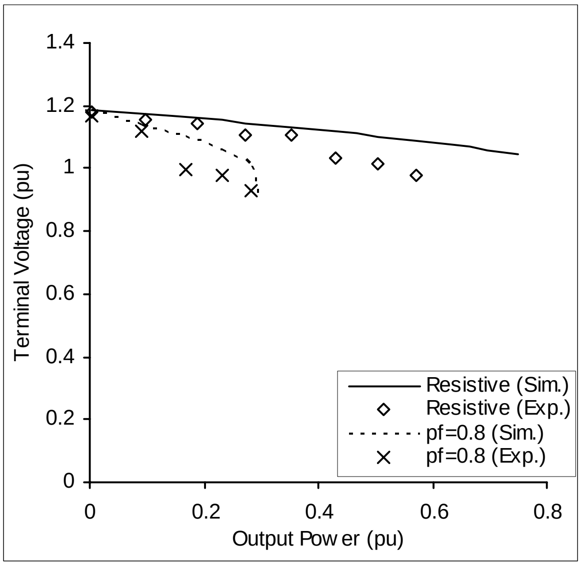


Fig. 2.12: Terminal voltage (V_L) v/s output power at 28μF, v=1 p.u.

Figure 2.12 shows the terminal voltage v/s output power characteristic with the shunt capacitance value of 28μF for various loading condition. Output loading increased in this case, compared with earlier case and the terminal voltage is also more as compare to 22μF case.

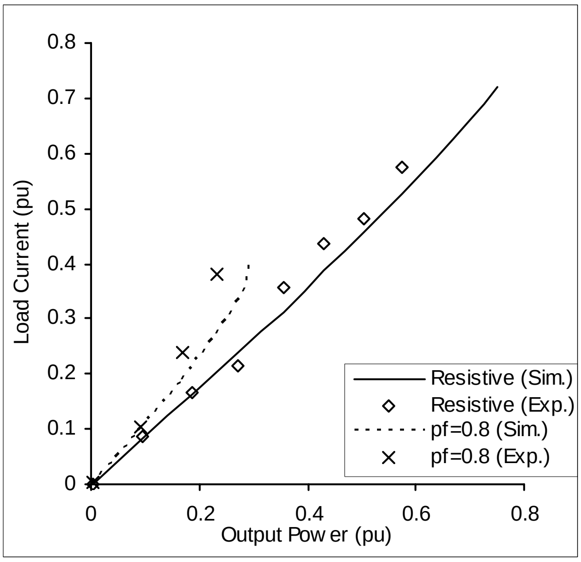


Fig. 2.13: Load current (I_L) v/s output power at 28μF, v=1 p.u.

Figure 2.13 shows the load current v/s output power characteristic. It shows that current is increased at 28μF than the 22 μF, which make the machine to handle more loading.

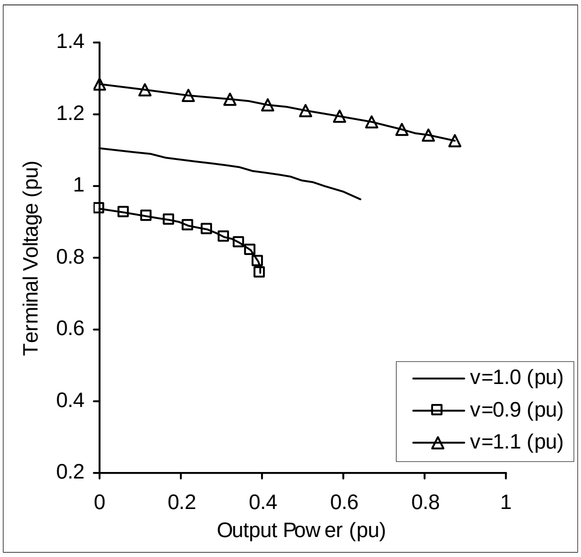


Fig. 2.14: Terminal voltage (V_L) v/s output power output at 22μF for different speed

Speed of prime mover play an important role in performance of induction generator, speed of prime mover affects the slip of induction generator which further affects the stator terminal voltage. Terminal voltage decrease if speed decrease, it changes from 1.3 pu to 0.95 pu when speed changes from 1.1 pu to 0.9 pu. The characteristic also shows that output loading also affected due to changes in speed, output power decreases from 0.7 pu to 0.43 pu when speed changes from 1.0 pu to 0.9 pu.

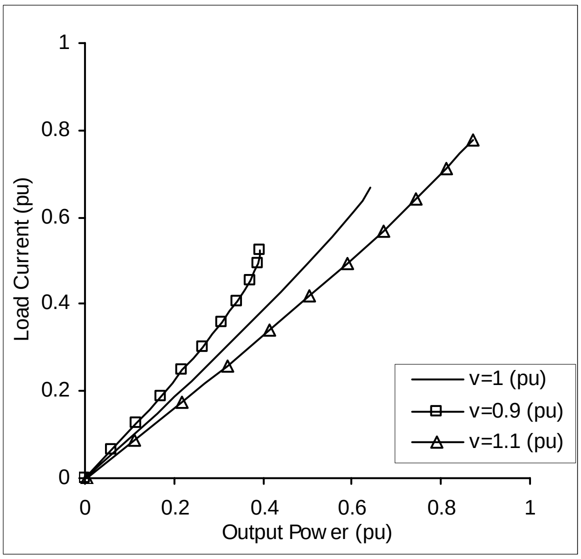


Fig. 2.15: Load current (I_L) v/s output power at 22μF for different speeds

The change in speed affects the load current as shown in figure 2.15, it start increasing when the speed decrease. The current increase from 0.5 pu to 0.75 pu when speed decreases from 1.1 pu to 0.9 pu at output loading 0.5 pu.

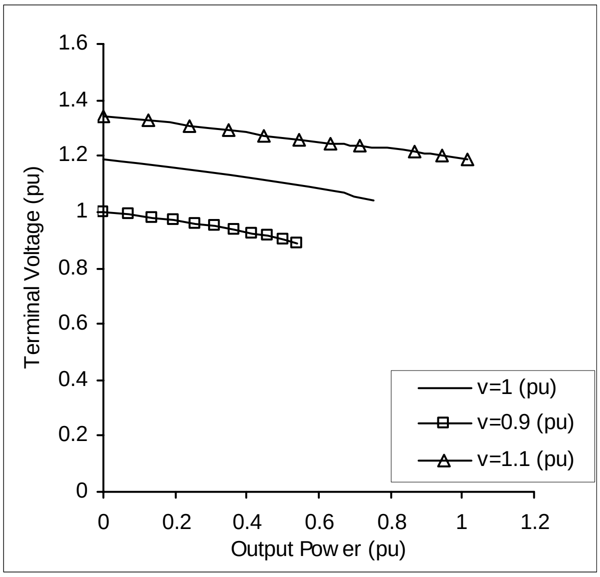


Fig. 2.16: Terminal voltage (V_L) v/s output power at 28μF for different speeds

Figure 2.16 shows that when the capacitance value changes from 22 μF to 28μF, terminal voltage increases from 1.10 pu to 1.20 pu at 1.0 pu speed. When the speed decreases the more value of capacitor will be required to improve the terminal voltage. The loading capability of SEIG also increases from 0.72 to 0.8 pu at speed 1.0 pu.

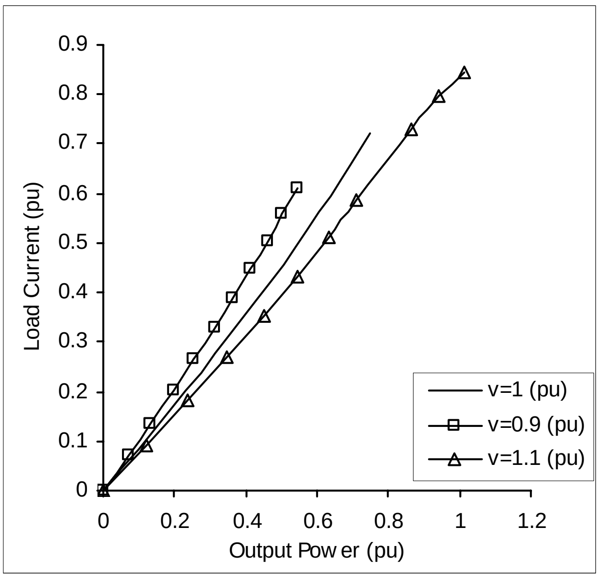


Fig. 2.17: Load current (I_L) v/s output power at 28μF for different speeds

The loading improves when the capacitance value increase. When capacitance is of 22µF the stator current was 0.5 pu if the capacitance value increase to 28µF, the load current decrease to 0.5 pu at 0.9 pu speed as shown in figure 2.17.

2.7 CONCLUSION

The proposed steady state analysis might be helpful to wind generation, can be utilized by the interested users or the normal utility to feed loads where frequency and voltage need not be regulated. The steady-state analysis shows that the characteristics of generation can be predicted with a good accuracy over a wide range of speeds, using the widely adopted conventional equivalent circuit of the induction machine. Because the induction generator is isolated, its stator frequency is free to vary with the rotor speed and the operating slip remains small. This in turn results in high efficiency. The proposed method involves only simple numeric calculations, in contrast to existing methods which require tedious and complicated algebraic derivations, but accuracy is extremely good and convergence is fast.

CHAPTER - 3

THEORY OF SYMMETRICAL COMPONENTS

3.1 INTRODUCTION

In electrical engineering, the symmetrical components are used to simplify analysis of unbalanced three phase systems.

When performing steady-state analysis of induction machine for symmetrical distribution of load and excitation capacitance, we make use of the per-phase equivalent circuit. But for the analysis of unsymmetrical conditions induction generator (single phase load, unbalancing in capacitance employed for self excitation), the three phases no longer see the same impedance, which violates the basic requirement of per-phase analysis (phases must be balanced).

There is a very elegant approach available for analyzing asymmetric three-phase circuits. The approach was developed by an American scientist, named C. L. Fortescue and reported in a paper in 1918. It is now called the method of symmetrical components.

3.2 FORTESCUE'S THEOREM

An American scientist, C. L. Fortescue states that, we can represent any unsymmetrical set of three phasors as the sum of three constituent sets; each is having 3-phasors:

- A positive (a-b-c) sequence set and
- A negative (a-c-b) sequence set and
- An equal set

These three sets we will call, respectively,

- Positive V_a^+, V_b^+, V_c^+
- Negative V_a^-, V_b^-, V_c^-
- Zero $\left(V_a^0, V_b^0, V_c^0\right)$ sequence components.

The implication of this theorem is that any unsymmetrical set of 3-phasors V_a, V_b, V_c can be written in terms of the above sequence components in the following way:

$$V_a = V_a^0 + V_a^+ + V_a^-$$
$$V_b = V_b^0 + V_b^+ + V_b^- \qquad \ldots\ldots (3.1)$$
$$V_c = V_c^0 + V_c^+ + V_c^-$$

We can write the equations of (3.1) in a more compact fashion, but first, we must describe a mathematical operator that is essential.

3.3 THE α - OPERATOR

To begin on familiar ground, we are all conversant with the operator '*j*' which is used in complex numbers.

Remember that '*j*' is actually a vector with a magnitude and an angle:

$$j = 1\angle 90° \qquad \ldots\ldots (3.2)$$

In the same way, we are going to define the 'α' operator as:

$$\alpha = 1\angle 120° = -0.5000 + j0.8666 \qquad \ldots\ldots (3.3)$$

It is easy to show the following relations:

$$\alpha^2 = 1\angle -120°$$
$$\alpha^3 = 1\angle 0° \qquad \ldots\ldots (3.4)$$
$$\alpha^4 = 1\angle 120° = \alpha$$

We also have that

$$1 + \alpha = -\alpha^2 = 1\angle 60° \qquad \ldots\ldots (3.5)$$

Note that

$$-\alpha^2 = -1\angle 240° = 1\angle 60° \qquad \ldots\ldots (3.6)$$

As illustrated in Fig. 3.1.

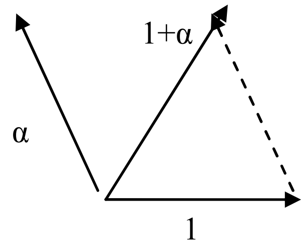


Fig. 3.1: Illustration of 1+α

Similarly, we may show that:

$$1+\alpha^2 = -\alpha = 1\angle -60° \qquad \text{...... (3.7)}$$

$$1-\alpha = \sqrt{3}\angle -30° \qquad \text{...... (3.8)}$$

$$1-\alpha^2 = \sqrt{3}\angle 30° \qquad \text{...... (3.9)}$$

$$\alpha - 1 = \sqrt{3}\angle 150° \qquad \text{...... (3.10)}$$

$$\alpha^2 - 1 = \sqrt{3}\angle -150° \qquad \text{...... (3.11)}$$

3.4 SYMMETRICAL COMPONENTS THEORY

We repeat equations (3.1) below for convenience:

$$V_a = V_a^0 + V_a^+ + V_a^-$$

$$V_b = V_b^0 + V_b^+ + V_b^- \qquad \text{...... (3.12)}$$

$$V_c = V_c^0 + V_c^+ + V_c^-$$

We can relate the three different quantities having the same superscript.

- **<u>Zero Sequence Quantities</u>:**

These quantities are all equal, i.e.

$$V_a^0 = V_b^0 = V_c^0 \qquad \text{...... (3.13)}$$

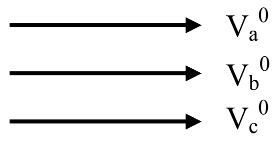


Fig. 3.2: Zero sequence components

➢ **Positive Sequence Quantities:**

The relation between these quantities can be observed immediately from the phasor diagram and can be expressed using the α-operator.

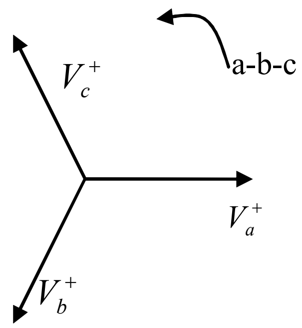


Fig. 3.3: Positive sequence components

$$V_b^+ = \alpha^2 V_a^+$$
$$V_c^+ = \alpha V_a^+ \quad \text{...... (3.14)}$$

➢ **Negative Sequence Quantities:**

The relation between these quantities can be observed immediately from the phasor diagram and can be expressed using the α-operator.

$$V_b^- = \alpha V_a^-$$
$$V_c^- = \alpha^2 V_a^- \quad \text{...... (3.15)}$$

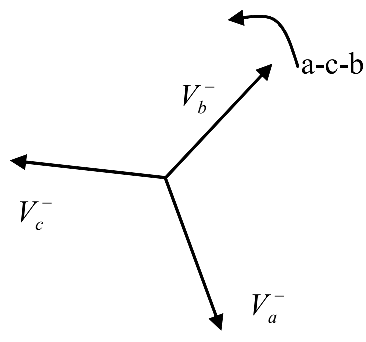


Fig. 3.4: Negative sequence components

Now let's use equations (3.13), (3.14), and (3.15) to express the original phasors V_a, V_b, V_c in terms of only the a-phase components:

$$V_a^0, V_a^+, V_a^-$$

i.e., we will eliminate the b-phase components

$$V_b^0, V_b^+, V_b^-$$

and the c-phase components

$$V_c^0, V_c^+, V_c^-$$

This results in,

$$V_a = V_a^0 + V_a^+ + V_a^-$$
$$V_b = V_b^0 + V_b^+ + V_b^- \qquad \text{...... (3.16)}$$
$$V_c = V_c^0 + V_c^+ + V_c^-$$

So we have written the *abc* quantities (phase quantities) in terms of the 0, +, - quantities (sequence quantities) of the a-phase. We can write this in matrix form as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix} \qquad \text{...... (3.17)}$$

Defining

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} \qquad \text{...... (3.18)}$$

We see that eq. (3.18) can be written as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = A \begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix} \qquad \text{...... (3.19)}$$

We may also obtain the 0+- (sequence) quantities from the abc (phase) quantities:

$$\begin{bmatrix} V_a^0 \\ V_a^+ \\ V_a^- \end{bmatrix} = A^{-1} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad \text{...... (3.20)}$$

Where

$$A^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \qquad \text{...... (3.21)}$$

3.5 CONCLUSION

The symmetrical component theory played a vital role for the analysis of three phase unbalanced system. The generalized positive sequence, negative sequence and zero sequence components have complete phase symmetry. This implies that the three-phase analysis can be reduced to a single-phase analysis for a balanced three-phase system. Because of the widespread use of unbalanced three phase systems, the developed symmetrical component theory has great advantages for general three phase systems.

CHAPTER - 4

STEADY STATE ANALYSIS OF SEIG FOR UNBALANCED CONDITION

4.1 INTRODUCTION

Since most residential loads are of single-phase type such as lighting, heating loads etc. The unbalanced operating condition of SEIG occurs if these single-phase loads are not uniformly spread among the phases. When the power ratings of the generator and loads are smaller, however, it becomes increasingly difficult to ensure an even distribution of the loads among the phases. This implies that in general, the SEIG has to operate with a certain degree of phase imbalance. Unbalanced operation may also result due to manufacturing tolerances of the excitation capacitances, failure of some excitation capacitance modules.

When the SEIG feeds power to an unbalanced load, both the terminal voltages and stator currents are unbalanced. In general, the degree of unbalanced three-phase voltages can be estimated in terms of voltage unbalanced factor (VUF) which is defined as the ratio of negative sequence voltage to positive sequence voltage. A similar definition of current unbalanced factor (CUF) is used to examine the ratio of negative sequence current to positive sequence current. The unbalanced currents tend to increase the losses, create the unequal heating in the windings, de-rate the generator output capacity and induce the torque pulsation on the shaft of SEIG. On the other hand, if the dynamic load such as induction motor is connected to unbalanced voltages source generated by an isolated SEIG, the same problems as mentioned above also happen in the motor load.

The performance analysis of a three-phase self-excited induction generator (SEIG) feeding a three-phase unbalanced load or single-phase load or unbalanced excitation conditions can be assessed with the help of symmetrical components technique, thereby the input impedance of the generator can be determined. Numerical solution of a simplified equivalent circuit for the machine variables, namely the frequency and magnetizing reactance, enables the generator performance to be evaluated for any load and speed. Symmetrical component theory is used to obtain relevant performance through sequence quantities. While the analysis of the system is inherently complicated due to unbalance and magnetic saturation, valid simplifications incorporated in the equivalent circuit for both forward and backward fields result in manageable equations suitable for computer simulation. A sequence equivalent circuit is required for each field with appropriate saturated parameters.

4.2 STEADY STATE ANALYSIS USING N-R METHOD

When three-phase induction machines feed an unbalanced or asymmetrical external network, the machine is modeled through its positive sequence and negative sequence circuits with appropriate parameters pertaining to forward and backward fields. The unbalanced currents and terminal voltages can be resolved into positive sequence components, negative sequence components and zero sequence components. With asymmetrical external networks encountered here, the terminal relations are written for each phase with generator conventions. The external network consists of unequal excitation capacitors in parallel with unbalanced load impedances. Under self-excitation with no external voltage sources, the equations concerned will simplify to a closed circuit whose impedance has to be equated to zero. Solution of this constraint equation yields two unknown quantities, namely the saturated p.u. magnetizing reactance X_m and the p.u. frequency of generated voltage.

Certain simplifying assumptions in the sequence equivalent circuit make the final equation, to obtain the solution. As in three phases SEIG, X_m can be used to obtain the air-gap voltage using the experimentally obtained magnetization curve by synchronous speed test. The next step would be to solve the circuit equations to obtain currents, terminal voltage and power output. Based on the above procedure, computer program in MATLAB environment has been developed to determine the performance under any unbalanced external network at the given prime mover speed.

4.3 PROBLEM FORMULATION

The schematic diagram of a three-phase delta connected SEIG feeding a three-phase unbalanced load is shown in Fig. 4.1. The delta connection is deliberately used here since a star connected three-phase induction motor has to be reconnected in delta to feed single-phase loads. The excitation elements (capacitors) and load balancing elements are combined with the load admittance.

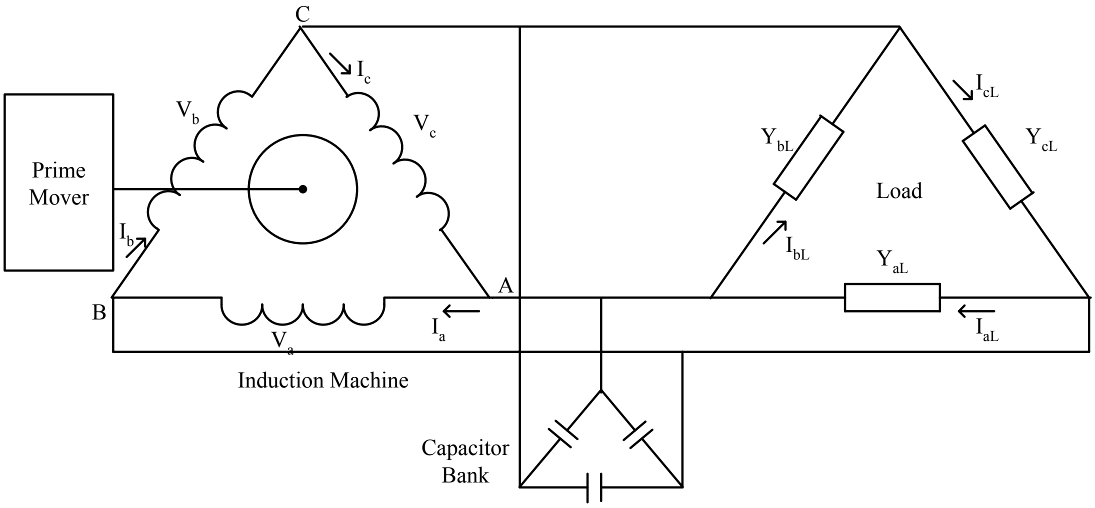


Fig. 4.1: Three-phase SEIG feeding 3-phase load

Assuming an unbalanced three phase lagging power factor load, the net admittance across the three phases would be Y_{aL}, Y_{bL} & Y_{cL}. Admittance Y_{aL} across the phase may be written as:

$$Y_{aL} = jB_a + G_{aL} - jB_{aL}$$
$$Y_{bL} = jB_b + G_{bL} - jB_{bL} \qquad \text{...... (4.1)}$$
$$Y_{cL} = jB_c + G_{cL} - jB_{cL}$$

Where B_a, B_b & B_c are the susceptance due to excitation capacitor and G_{aL}, G_{bL}, G_{cL}, B_{aL}, B_{bL} & B_{cL} are the admittance elements due to load.

The positive sequence and negative sequence equivalent circuit of the induction machine is given in Fig. 4.2(a) and in Fig. 4.2(b) where reactances correspond to the base frequency (50Hz) and X_m is the saturated value corresponding to the forward revolving air-gap flux. The negative sequence circuits would have the term (F+v) in place of (F-v). To simplify the analysis one may assume F=v except in the term (F-v) and also $X_s = X_r = X_l$ (say). The magnetizing reactance appearing in the shunt branch in the negative sequence circuit can be eliminated, as it is very high compared to rotor resistance in parallel.

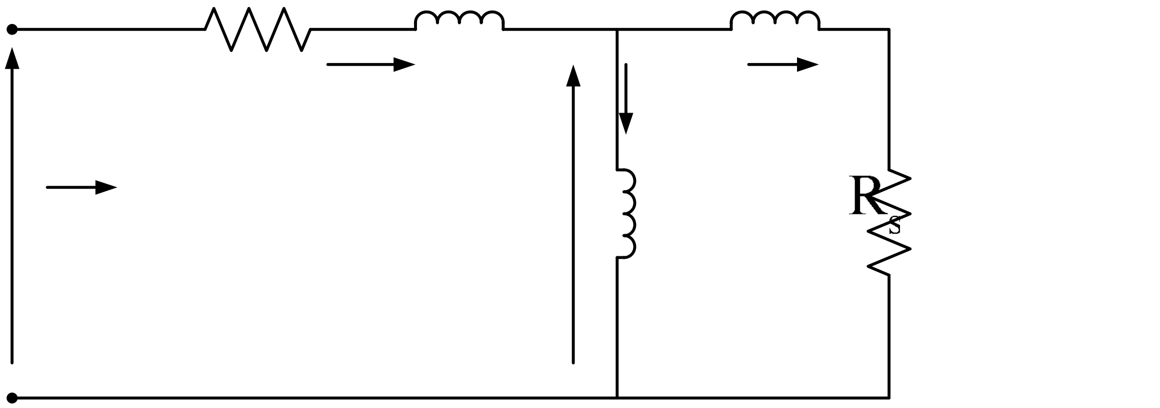


Fig. 4.2 (a): Positive sequence equivalent circuit of SEIG

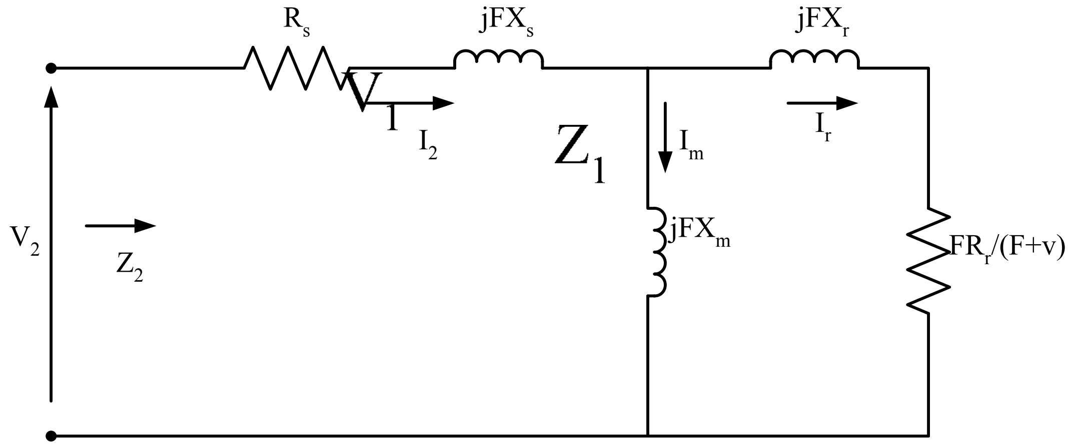


Fig. 4.2 (b): Negative sequence equivalent circuit of SEIG

The generalized objective function of the circuit shown in Fig. 4.1 is obtained as:

$$3+(Z_1+Z_2)(G_4+jB_4)-(K_1-jK_2)Z_1Z_2=0 \qquad \text{...... (4.2)}$$

Where,

$$G_4 = G_{aL} + G_{bL} + G_{cL}$$

$$B_4 = B_a + B_b + B_c - B_{aL} - B_{bL} - B_{cL}$$

$$K_1 = -\{G_{aL}G_{bL} + G_{bL}G_{cL} + G_{aL}G_{cL} - (B_a - B_{aL})(B_b - B_{bL}) \\ - (B_b - B_{bL})(B_c - B_{cL}) - (B_c - B_{cL})(B_a - B_{aL})\}$$

$$K_2 = \{G_{aL}(B_b + B_c - B_{bL} - B_{cL}) + G_{bL}(B_a + B_c - B_{aL} - B_{cL}) \\ + G_{cL}(B_a + b_b - B_{aL} - B_{bL})\}$$

$$Z_1 = R_s + jFX_1 + \frac{jFX_m\left[jFX_1 + \frac{FR_r}{(F-v)}\right]}{\left[\frac{FR_r}{(F-v)} + jF(X_m + X_1)\right]}$$

$$Z_2 = R_s + \frac{R_r}{2} + jF(X_s + X_r)$$

On substituting for Z_1, Z_2, G_4, B_4, K_1 and K_2 and rearranging the following two equations with F and X_m as unknown quantities are obtained by equating real and imaginary parts of equation to zero separately:

$$f_{n1}(X_m, F) = c_1F + c_0 = 0$$

$$f_{n1}(X_m, F) = b_1F + b_0 = 0 \qquad \text{...... (4.3)}$$

Where, constants c_1, c_0, b_1 and b_0 are functions of machine parameters which are given in Appendix-1.

Equation (4.3) is a nonlinear equation with four variables as X_m, X_c, v, and F. If two of these are known then other two variables can be calculated using conventional method such as Newton-Rephson method. After getting the values of X_m and F solve for the symmetrical components (voltage and current) and correspondingly find the performance parameters such as phase currents (I_a, I_b, I_c) and voltages (V_a, V_b, V_c) output power as:

$$V_a = V_0 + V_1 + V_2$$

$$V_b = V_0 + a^2V_1 + aV_2 \qquad \text{...... (4.4)}$$

$$V_c = V_0 + aV_1 + a^2V_2$$

$$I_a = I_0 + I_1 + I_2$$

$$I_b = I_0 + a^2I_1 + aI_2 \qquad \text{...... (4.5)}$$

$$I_c = I_0 + aI_1 + a^2I_2$$

$$I_{a1} = \frac{V_a}{R_a + jFX_a}$$

$$I_{b1} = \frac{V_b}{R_b + jFX_b} \qquad \text{...... (4.6)}$$

$$I_{c1} = \frac{V_c}{R_c + jFX_c}$$

$$P_1 = I_{a1}^2 * R_a$$

$$P_2 = I_{b1}^2 * R_b \qquad \text{...... (4.7)}$$

$$P_3 = I_{c1}^2 * R_c$$

Where,

$$I_1 = \frac{V_g}{jFX_m} + \frac{V_g}{\frac{FR_r}{(F - v)} + jFX_r} \qquad \text{...... (4.8)}$$

$$V_1 = V_g - (R_s + jFX_s)I_1 \qquad \text{...... (4.9)}$$

$$V_2 = K * V_1 \qquad \text{...... (4.10)}$$

The expression for constant '*K*' is given in Appendix-1

$$I_2 = \frac{V_2}{Z_2} \qquad \text{...... (4.11)}$$

Because for delta connected system $V_a + V_b + V_c = 0$ and $I_a + I_b + I_c = 0$, So

$$V_0 = 0 \qquad \text{...... (4.12)}$$

$$I_0 = 0 \qquad \text{...... (4.13)}$$

Here, the Newton-Rephson method is used to calculate the optimized combination per unit value of magnetizing reactance (X_m) and per unit generated frequency (F) by forming the jacobian matrix and using initial values for X_m and F as X_m unsaturated and v respectively. This method gives quite accurate results.

4.4 ALGORITHM AND FLOW CHART

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

Step 1: Read machine data such as R_s, X_s, X_r, R_r, Xc_1, Xc_2, Xc_3, R_l, X_l, R_2, X_2, R_3, X_3, v, p.f. etc.

Step 2: Assume initial values of magnetizing reactance 'X_{m0}' and frequency 'F_0'. For convenience we may take the value of 'F' is equal to v.

Step 3: Calculate Δf_{n1} and Δf_{n2} by using equation (4.3) as

$$\Delta f_{n1} = -f_{n1} \qquad \& \qquad \Delta f_{n2} = -f_{n2}$$

Step 4: Compute the derivative of function with respect to 'F' and 'X_m'.

Step 5: Compute the elements for jacobian matrix $\begin{bmatrix} H & N \\ M & L \end{bmatrix}$, where H, M, N, L are the jacobian elements as:

$$H = \frac{df_{n1}}{dX_m};\ N = \frac{df_{n1}}{dF};\ M = \frac{df_{n2}}{dX_m}\ \&\ L = \frac{df_{n2}}{dF}$$

Step 6: Compute the deviations in results ΔXm & ΔF by

$$\begin{bmatrix} \Delta f_{n1} \\ \Delta f_{n2} \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta X_m \\ \Delta F \end{bmatrix}$$

$$\begin{bmatrix} \Delta X_m \\ \Delta F \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix}^{-1} \begin{bmatrix} \Delta f_{n1} \\ \Delta f_{n2} \end{bmatrix}$$

Step 7: Calculate the modified values of Xm and F as

$$X_m = X_{m0} + \Delta X_m \qquad \text{and} \qquad F = F_0 + \Delta F$$

Step 8: Start the next iteration cycle with these modified results and continue until scheduled error is with in a specified tolerance limit and get the value of X_m and F.

Step 9: After getting the values of 'X_m' and 'F', determine air-gap voltage V_g using the magnetizations curve (V_g v/s X_m).

Step 10: Compute the values of positive sequence, negative sequence and zero sequence voltages and currents and find the phase voltages and currents and the values of power supplied to the load.

Step 11: Store the relevant data in data file and by using these values various characteristics that yield to the machine performance are obtained.

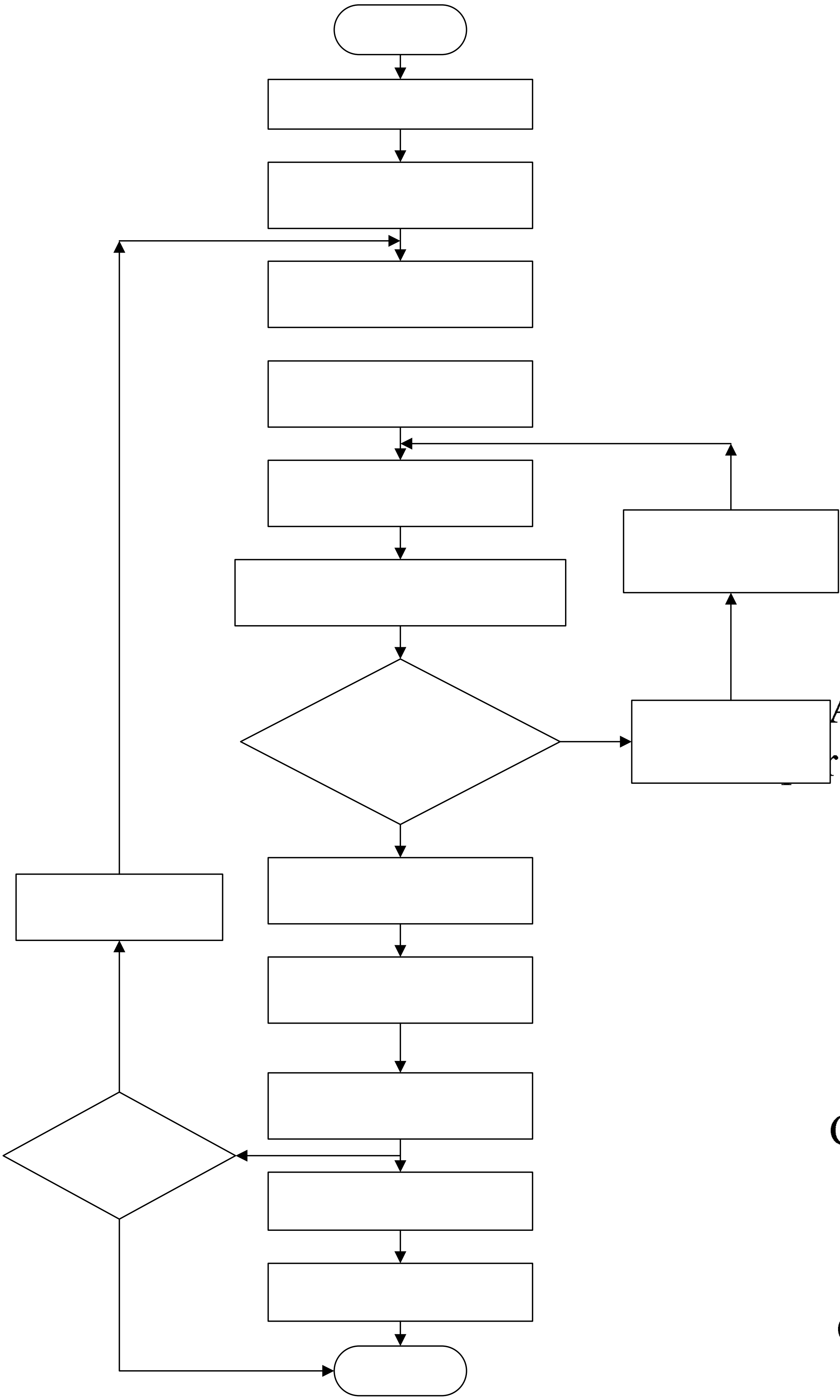


Fig. 4.3: Flow chart of N-R method

4.5 RESULTS AND DISCUSSION

In this section, following studies have been performed for the machine (specification given below) with resistive load and resistive-inductive (R-L) load.

3-phase, 4-pole, 50 Hz, 415 V, 5.83A delta-connected squirrel cage induction machine whose per-phase equivalent circuit constants in per unit are: R_s=0.0633 p.u.; R_r=0.0247 p.u.; X_s=0.0633 p.u.; X_r=X_s; pf=0.8; v=1 p.u.

a) Variation of terminal voltages and load currents v/s output power for unity power factor balanced load, unity speed and unbalanced excitation capacitor bank 22 μF, 18 μF and 18 μF.

b) Variation of terminal voltages v/s output power for different load power factor, balanced load, unity speed and unbalanced excitation capacitor bank 22 μF, 18 μF and 18 μF.

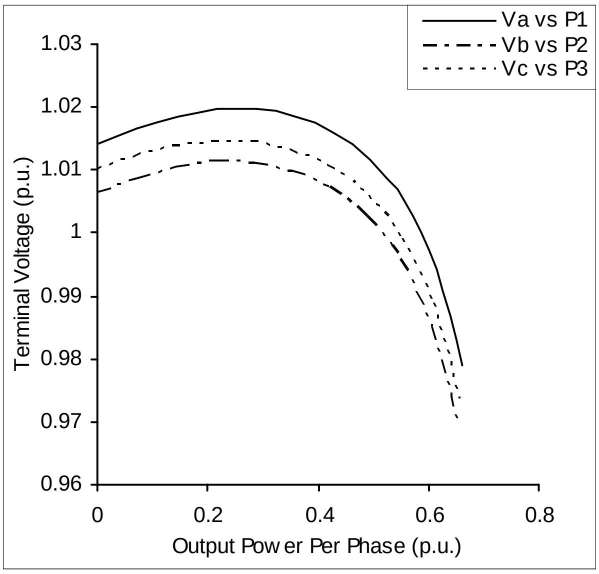
c) Variation of load currents v/s output power for different load power factor, balanced load, unity speed and unbalanced excitation capacitor bank 22 μF, 18 μF and 18 μF.

d) Variation of terminal voltages and load currents v/s output power for unity power factor, balanced load, unity speed and unbalanced excitation capacitor bank 28 μF, 22 μF and 18 μF.

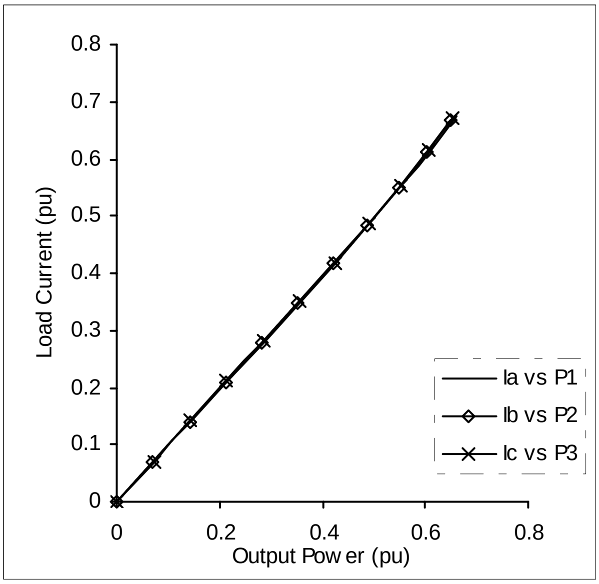
e) Variation of terminal voltages and load currents v/s output power for balanced excitation capacitor bank C_1=C_2=C_3 = 22 μF, unity speed and at unity power factor unbalanced load R_1=R_3, R_2=∞.

f) Variation of terminal voltages v/s output power for unity power factor, balanced load, different speed and unbalanced excitation capacitor bank 28 μF, 22 μF and 18 μF.

a) Unbalancing of per phase terminal voltages and load currents v/s output power for unity power factor balanced load, unity speed and unbalanced excitation capacitor bank 22 µF, 18 µF and 18 µF.



(a)



(b)

Fig. 4.4: Terminal voltages & currents v/s output power for unbalanced excitation 22 µF, 18 µF and 18 µF in capacitor bank

Fig. 4.4(a) and Fig. 4.4(b) shows the effect of the capacitance unbalancing (C_1=22µF, C_2=18 µF, C_3=18 µF) on three-phase voltages and Currents for balanced resistive load varying upto the rated capacity of machine. It is noticed that due to the capacitance unbalancing across the phases, the phase voltages and currents are unbalanced. It is also stated that for the phase having large value of capacitance, the voltage across this phase is large.

b) Variation of per phase terminal voltages v/s output power for different load power factor, balanced load, unity speed and unbalanced excitation capacitor bank 22 μF, 18 μF and 18 μF.

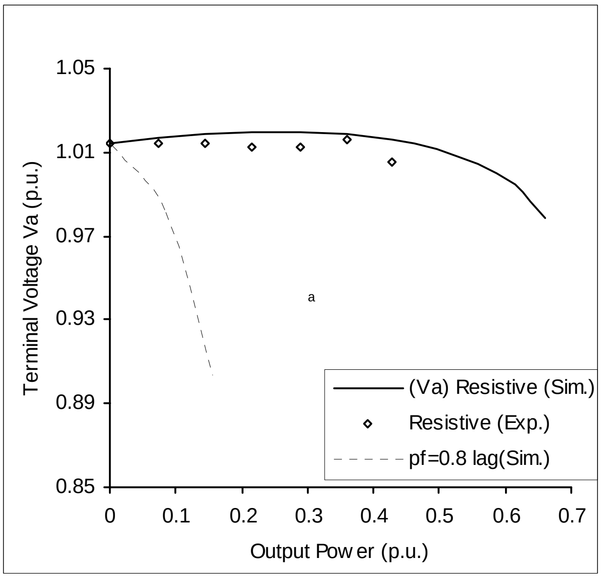


Fig. 4.5(a): Phase voltage (V_a) v/s output power (P_1)

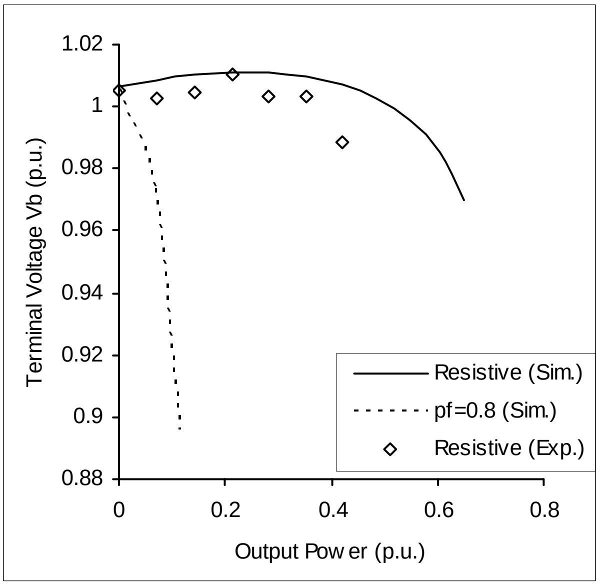


Fig. 4.5(b): Phase voltage (V_b) v/s output power (P_2)

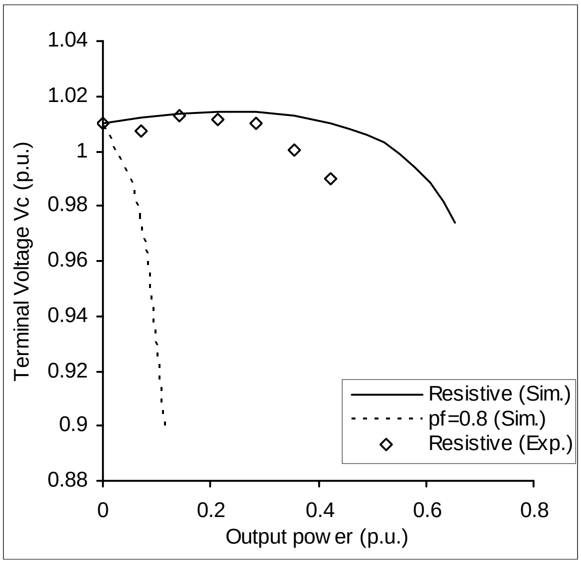


Fig. 4.5(c): Phase voltage (V_c) v/s output power (P_3)

Fig. 4.5(a) to Fig. 4.5(c) shows the variation of phase voltages under unbalanced resistive and resistive-inductive load. For resistive load, the terminal voltage decreases slowly, while for resistive-inductive load, the terminal voltage decreases rapidly. Three-phase voltages of the simulated results are very close to the experimental results, as evident from these figures.

c) Variation of per phase load currents v/s output power for different load power factor, balanced load, unity speed and unbalanced excitation capacitor bank 22 μF, 18 μF and 18 μF.

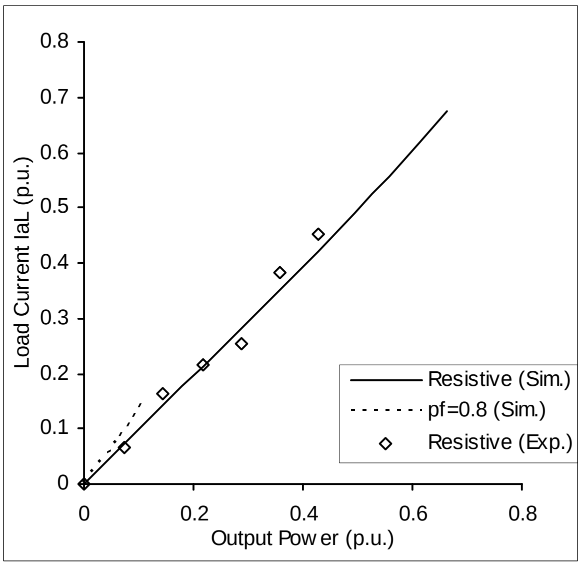


Fig. 4.6(a): Load current (I_a) v/s output power (P_1)

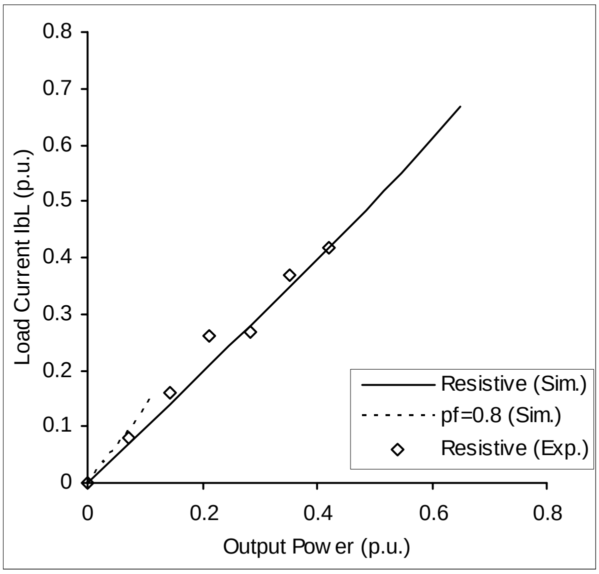


Fig. 4.6(b): Load current (I_b) v/s output power (P_2)

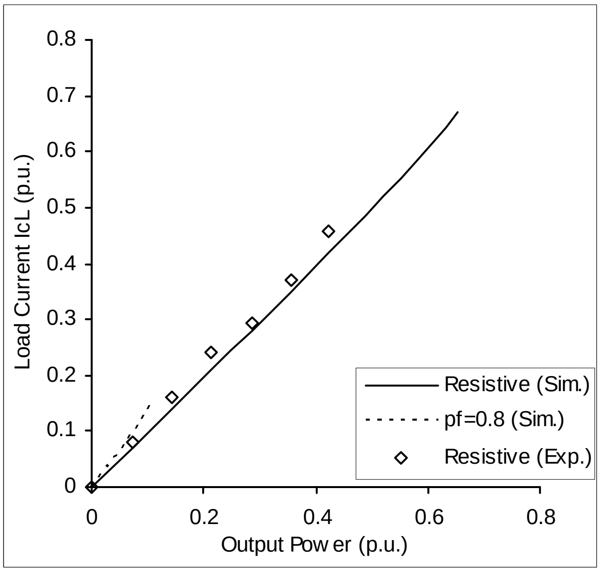
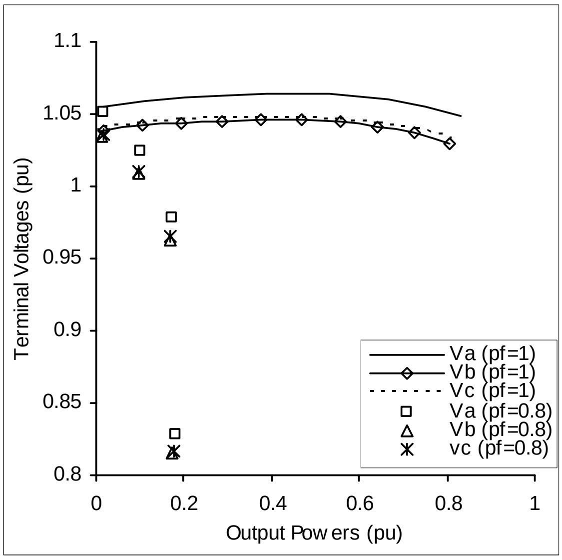


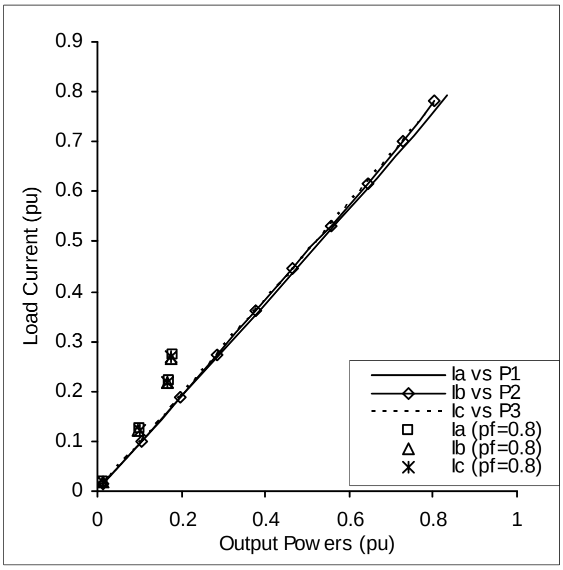
Fig. 4.6(c): Load current (I_c) v/s output power (P_3)

Fig. 4.6(a) to Fig. 4.6(c) shows the simulated and experimental results for load currents versus output power under unbalanced resistive and resistive-inductive load. In the resistive loading SEIG output loading is more as compare to resistive inductive loading. From the characteristics it can be stated that for resistive load, the voltage drop is less as compared to inductive type loading.

d) Unbalancing of per phase terminal voltages and load currents v/s output power for unity power factor, balanced load, unity speed and unbalanced excitation capacitor bank 28 μF, 22 μF and 18 μF.



(a)

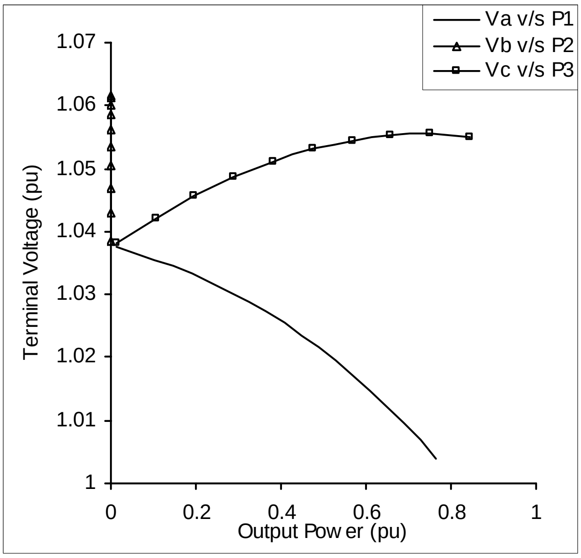


(b)

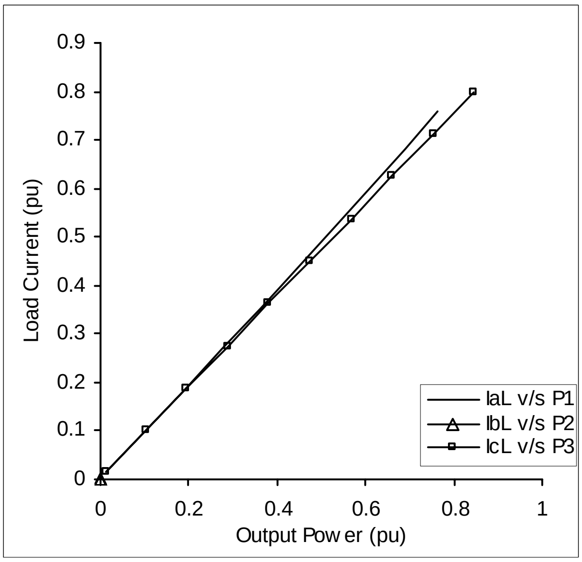
Fig. 4.7: Terminal voltages & currents v/s output power for unbalanced excitation capacitance as 28 μF 22 μF, 18 μF

Fig. 4.7(a) and Fig. 4.7(b) shows the terminal voltages and load currents versus output powers characteristics for unbalanced capacitor bank (C_1=28μF, C_2=22 μF, C_3=18 μF) for balanced resistive load varying from 0no load to rated. It is noticed that the terminal voltages and currents are increased with the increase in capacitor value.

e) **Unbalanced variation of per phase terminal voltages and load currents v/s output power for balanced excitation capacitor bank C_1=C_2=C_3 = 22 µF, unity speed and at unity power factor unbalanced load R_1=R_3, R_2=∞.**



(a)



(b)

Fig. 4.8: Terminal voltages and currents at R_2 = ∞, C_1=C_2 = C_3 = 22µF, v=1

Figure 4.8(a) and 4.8(b) shows the terminal voltages and load currents versus output powers characteristics for one branch of resistive load is open circuited (R_2 =∞) with balanced capacitor bank (C_1=C_2=C_3=22 µF). It is noticed that the terminal voltages across the opened branch is varying upto 1.06 pu instantly and currents through this branch is zero with the increase in three phase load.

f) Variation of per phase terminal voltages v/s output power for unity power factor, balanced load, different speed and unbalanced excitation capacitor bank 28 µF, 22 µF and 18 µF.

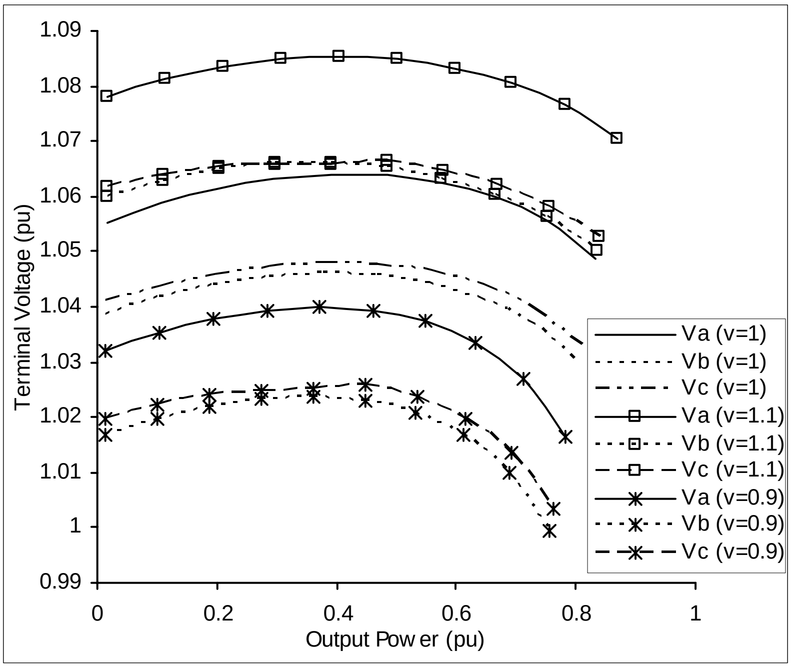


Fig. 4.9: Terminal voltages (V_L) v/s output power output at unbalanced excitation 28 µF, 22 µF &18 µF for different speed

Fig. 4.9 shows the variation in terminal voltage versus output power at different speeds with unbalanced capacitor bank. It shows that if the speed of prime mover decrease it decrease the stator terminal voltage also. The characteristic also shows that output loading also affected due to changes in speed.

4.6 CONCLUSION

The general mathematical model of three phase self-excited induction generator under unbalanced condition is presented here to determine the unknown equivalent circuit variables, namely the excitation frequency and magnetizing reactance, are determined by simplifying and solving the complicated performance equations of SEIG for various conditions. The proposed equivalent circuit, based on the method of symmetrical components, allows the SEIG to be analyzed under any condition of unbalanced loads and unbalanced excitation capacitances. Experiments of unbalanced capacitance have been carried out. In general, good agreement between computed and experimental results has been obtained. A computer program is developed in the MATLAB environment to determine the performance for any condition of operation. The proposed Newton-Raphson method, involves fast and more accurate calculations, in contrast to existing methods which require tedious and complicated algebraic derivations.

CHAPTER 5

CONCLUSION AND FURTHER SCOPE OF WORK

5.1 CONCLUSION

The studies have confirmed that use of an induction machine as a generator becomes popular for the interaction of electrical energy from the renewable energy sources. SEIG has several advantages such as reduced unit cost and size, ruggedness, brushless, absence of separate dc source, ease of maintenance, self-protection against severe overloads and short circuits and that there is no need of reactive power from transmission line as it draws reactive power from capacitor bank connected in shunt. SEIGs have been mainly used in a single system like wind or micro hydro, etc.

Steady state analysis of SEIG is carried out for evaluating running performance. Using the steady state analysis, voltage regulation, frequency regulation, and steady state temperature rise can be assessed. The developed computer algorithm facilitates prediction of performance under the given speed, capacitor and load conditions, which helps in estimating system parameter such as capacitors for a given prime mover and load pattern in the field.

The steady state analysis of SEIG under balanced conditions of operation is carried out. The iterative technique for the steady state analysis of SEIG, for balanced condition, based on nodal admittance method involves only simple numeric calculations, in contrast to other existing methods which require tedious and complicated algebraic derivations. The proposed method has good accuracy and fast convergence. Experimental results obtained on a laboratory machine validate the proposed method.

Under unbalanced condition, steady state analysis of SEIG presented using Newton-Raphson method. The proposed equivalent circuit, based on the method of symmetrical components, facilitates the SEIG to be analyzed under any condition of unbalanced loads and unbalanced excitation capacitances. The effect of variation of various parameters on steady state performance has also been presented. Experiments of several cases of unbalanced load have been carried out. In general, good agreement between calculated and measured results has been obtained.

5.2 FURTHER SCOPE OF WORK

- In the thesis work, the steady state performance of SEIG for balanced and unbalanced conditions has been carried out with conventional Iterative method and N-R method respectively. The results computed for some cases are validated through experimental results.

  Most of the loads in remote and rural areas are single phase loads. The machine operated under this case is unbalanced due to the voltage and current negative sequence components. Unbalanced operation leads to voltage stresses and over heat in the machine and correspondingly leads inefficient operation. To reduce these problems, strategy to be made to minimize the unbalancing by selecting the appropriate size and rating of excitation capacitors.
- Transient analysis can also be made to evaluate the performance and designing of machine parts such as winding and coupling shaft and devising of the protection strategy during unbalanced condition.
- The steady state performance during unbalanced condition is also verified from other simplified methods such as node admittance method to reduce the computational time and fast convergence.
- Power electronics converter such as static compensator (STATCOM) can be simulated and implemented to nullify the effect of unbalance and other related problems.

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Appendix – A

Polynomial coefficients for simple SEIG with R-L load

$$c_1 = -G_4 A_2 (X_m + X_1) - G_4 A_5 X_m - B_4 A_1 (X_m + X_1) - MA_5 (X_m + X_1) - MA_5 X_m \\ - NR_s (X_m + X_1)$$

$$c_0 = 3R_r + G_4 A_1 R_r + G_4 A_2 v(X_m + X_1) + G_4 A_5 v X_m - A_2 R_r + B_4 A_1 v(X_m + X_1) \\ - B_4 A_6 X_m + MR_s R_r + MA_5 v(X_m + X_1) + MA_5 v X_m - NA_5 R_r + NR_s v(X_m + X_1) - NA_6 X_m$$

$$b_1 = 3(X_m + X_1) + G_4 A_1 (X_m + X_1) - B_4 A_2 (X_m + X_1) - NA_5 (X_m + X_1) - NA_5 X_m \\ + MR_s (X_m + X_1)$$

$$b_0 = -3v(X_m + X_1) + G_4 A_2 R_r - G_4 A_1 v(X_m + X_1) + G_4 A_6 X_m + B_4 A_1 R_r + B_4 A_2 v(X_m + X_1) \\ + NR_s R_r + NA_5 v(X_m + X_1) + NA_5 v X_m + MA_5 R_r - MR_s v(X_m + X_1) + MA_6 X_m$$

$$K = -\frac{Y_{aL} + aY_{bL} + a^2 Y_{cL}}{3Y_2 + Y_{aL} + Y_{bL} + Y_{cL}}$$

Where, Y_{aL}, Y_{bL} and Y_{cL} are the admittances of three phase load and ‘a’ is complex operator, its value is:

$$a = -0.5 + j\,0.8666$$

Appendix – B

Induction Machine Experimental Data:

Relevant experiments are carried out on a three-phase, 415 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 p.u.

R_2 = 0.0247 p.u.

X_s = X_r = 0.0633 p.u.

X_m = 1.9588 p.u.

f_{base} = 50 Hz

V_{base} = 415 V

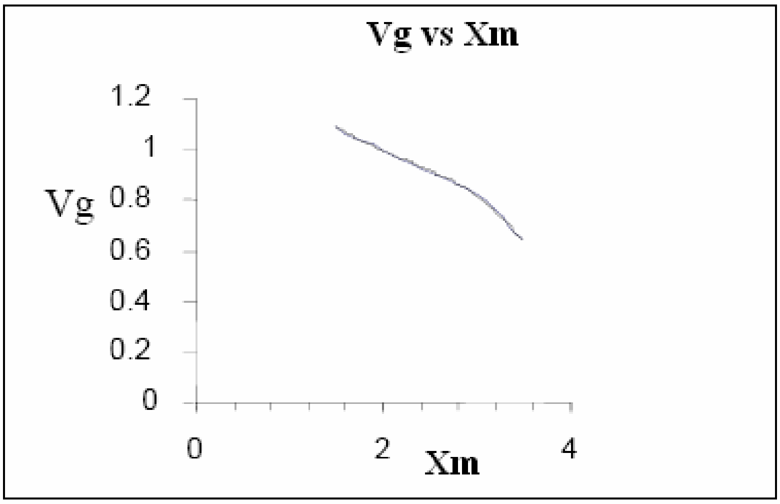
I_{base} = 5.83 A

Z_{base} = 71.168 ohm.

Appendix – C

A. Induction Machine Magnetizing Characteristic (Experimental)

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



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

B. Constant Voltage Curve (Experimental)