DEVELOPMENT OF VOLTAGE REGULATOR FOR 3-PHASE SELF-EXCITED INDUCTION GENERATOR USING SATURABLE CORE REACTOR

A DISSERTATION

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requirements for the award of the degree
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MASTER OF ENGINEERING
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By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled, "DEVELOPMENT OF VOLTAGE REGULATOR FOR 3-PHASE SELF-EXCITED INDUCTION GENERATOR USING SATURABLE CORE REACTOR", in partial fulfilment of the degree of MASTER OF ENGINEERING IN ELECTRICAL ENGINEERING with specialization in POWER APPARATUS AND ELECTRIC DRIVES, submitted in the Department of Electrical Engineering, University of Roorkee, Roorkee is an authentic record of my own work carried out for a period of about six months, from January 1987 to March 1987 and from September 1988 to October 1988 and in August 1989 under the supervision of Sri M.K. Vasantha, Reader and Dr. Bhim Singh, Reader, Department of Electrical Engineering, University of Roorkee, Roorkee, India.

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

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Dated: September 20, 1989.

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ABSTRACT

The dissertation concerns the design, fabrication and performance of voltage regulator for three-phase self excited induction generator using saturable core reactor. The performance of three phase self excited induction generator is experimentally investigated to study the effect of various parameters such as speed, load, capacitors etc. For the development of voltage regulating system, saturable core reactors with its feedback circuits are designed and fabricated. A voltage regulating system for three phase self excited induction generator is realised by using saturable core reactors in parallel with fixed valued capacitor bank.

The steady state and transient performance of self excited induction generator with the developed voltage regulating system under different loading conditions is investigated. It is found that the induction generator with its voltage regulating system is capable of starting as well as running a three-phase cage induction motor alongwith other static loads. From the experimental investigations, it is concluded that the developed voltage regulator works satisfactorily under steady state and dynamic loading conditions.

CONTENTS

CHAPTER - 1

INTRODUCTION

1.1 GENERAL

As a consequence of increasing fuel cost, greater attention is being given to renewable sources of energy and its economical utilization. To utilize non-conventional energy sources such as wind energy, biogas, small hydro heads etc., attempts have been made to develop small systems to supply electrical power for domestic use or for farm premises at remote areas. Induction generators driven by hydro-turbines or wind-turbines are finding wide spread applications as an isolated power generating unit.

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

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

The self excited induction generator can provide reliable and relatively inexpensive means to generate electricity compared to synchronous generators for the applications where small frequency variations are allowed. Self excited induction generators can be used to generate power from hydro-turbines or wind/aero-turbines.

The utility of self excited induction generators is tremendously increasing because of its various advantages over the conventional synchronous generators as a source of power supply in isolated and remote areas. An squirrel cage induction machine is very robust in construction and hence it is reliable which requires minimum maintenance. In isolated systems, the excitation can be obtained from a suitable valued capacitor bank connected across armature terminals and hence a separate d.c. source is not required for excitation by induction generators as it is required by synchronous generators. It has almost maintenance free operation due to the absence of brushes and separate d.c. source. On external short circuit too, the excitation of induction generator collapses giving automatic protection to it.

Induction generator can be used as an isolated or standby power source driven by either constant speed primemovers such as diesel engines, hydro turbines, or variable speed primemovers like wind turbines etc. . The variable speed primemover need not to be governed, although generator must be able to sustain overspeed upto 2 or 3 p.u. . A distinct advantage of such generators is much lower unit cost as compared to the conventional synchronous generators.

Self excited induction generators can also be operated in parallel in several advantageous ways. During parallel operation of induction generators, synchronisation is not necessary and generators are not required to be run at a common synchronous speed. Moreover, the absence of synchronising torque and absence of problems due to hunting are some of the other advantages of induction generators.

The disadvantages of the induction generator are its poor inherent frequency and voltage regulation. The induction generators have also moderate efficiency. The terminal voltage waveform is likely to be distorted because of the need for a saturated condition to stabilize the excitation. Dangerous voltages may occur with induction generators working over long transmission lines, if synchronous machine at the far end becomes disconnected and the line capacitance excites the induction machine. This phenomenon is known as "accidental self-excitation".

In most of the applications, a voltage source of fixed terminal voltage and independent of load is required. To cope with varying load and/or speed variation of self excited induction generator, the voltage control can be suitably based on adjustable reactive power generators connected to the terminals of the induction machine. These reactive power generators connected at the terminals of the induction generator have also to supply magnetic energy to inductive loads on the generator. Static VAR compensators provide a continuously varying reactive power to achieve desired voltage regulation at different loads and speed conditions.

In order to maintain the terminal voltage constant, synchronous condenser can be used to supply continuously varying reactive power to the induction machine. As the synchronous condenser is a rotating device, its efficiency is moderate and requires routine maintenance and above all it will increase the cost of the system. Switched capacitors scheme may be a cheap and simple solution, if the variation of the terminal voltage is within a tolerable limit. Controlled rectifier-inverter scheme with fixed value of capacitors can also be used to obtain constant terminal voltage and frequency. It is a two stage static conversion and it may be ideal solution for variable speed primemovers. However, it is costly and complicated alternative for constant speed primemovers. For a constant speed primemovers, the system using thyristor controlled variable inductor in parallel to a fixed capacitor may be an alternative, but it also suffers from the switching transients and harmonics. The saturable core reactor in parallel to the fixed capacitors can also maintain the terminal voltage constant. Absence of switching operation will provide smooth waveform of the terminal voltage of the induction generator.

Wind driven self excited induction generators are used as an isolated source of power supply in remote areas for domestic and agricultural work or in space heating situations such as glass houses heating where high heat losses occur in windy weather. Electrical or thermal energy storage system can be used in conjunction with these generators. The self excited induction generator can also be used to generate power from small remote hydro plants to meet out the local requirements. The machine can also utilize waste heat of process system in chemical works.

1.2 SCOPE OF PRESENT WORK

In the present work the performance of three phase capacitor self excited induction generator is experimentally investigated to study the effect of various parameters such as speed, load, capacitors etc. A voltage regulating system for three-phase self excited induction generator is developed by using saturable core reactors in parallel with fixed valued capacitor bank. For this purpose, saturable core reactors with its feedback circuit are designed and fabricated. The steady state and transient performance of this voltage regulating system with self excited induction generator under different loading conditions is also investigated.

In the present work, the following objectives are made:

1. To study the performance of three-phase self excited induction generator under different operating conditions.

2. Development of voltage regulator for three-phase self excited induction generator using saturable core reactors with proper feedback and bias circuits.
3. To study the steady state and transient behaviour of induction generator with voltage regulating system for resistive, inductive (static load) and induction motor (dynamic load) loads.

Steady state performance of three_phase self excited induction generator under different operating conditions is investigated. A voltage regulator for three phase self excited induction generator is designed and fabricated. The steady state performance of self excited induction generator with its developed voltage regulating system in terms of variation in terminal voltage with its loading and waveforms of different parameters are given. Transient performance of the generator with voltage regulator in terms of system parameters for sudden application and removal of load is also investigated.

Outline of the Chapters

In Chapter 1, an introduction to self excited induction generators with its applications, advantages and disadvantages are discussed.

In Chapter 2, historical development of self excited induction generator is discussed. Exhaustive literature survey on the self excited induction generator is also given.

In Chapter 3, the steady state performance of self excited induction generator including no-load magnetization characteristic as well as variation of terminal voltage for different types of load at fixed capacitor and rated speed are investigated. An idea of switched capacitors scheme to maintain the terminal voltage within a permissible limit is also presented. Variation of capacitance to keep the terminal voltage constant from no-load to full load of the generator is obtained. The optimum output power and corresponding terminal voltage is also obtained for rated stator current and speed of the machine. Requirement of capacitance with speed to keep the terminal voltage constant is also investigated.

Chapter 4,deals with the principle of operation of voltage regulator for three-phase self excited induction generator using saturable core reactors, selection of components of the voltage regulator, fabrication of saturable core reactors and its performance characteristics.

In Chapter 5, steady state and dynamic performance of the induction generator with developed voltage regulating system under different loading conditions are investigated.

In the last chapter, main conclusions along with the salient features of the voltage regulator are discussed and suggestions for further work are enlisted.

CHAPTER - 2

LITERATURE REVIEW

2.1 GENERAL

In this chapter, historical developments of self excited induction generators are given in detail. An exhaustive literature survey provides the idea regarding the work done so far on the feasibility, analysis and performance of self excited induction generators. The reported regulating systems of different types are reviewed and other possible alternatives are also discussed for capacitor excited induction generators.

2.2 HISTORICAL DEVELOPMENT

Although the driving of induction machine connected with synchronous generator, faster than synchronous speed causing it to generate a.c. power is well known since long ago [1-4], but it was unable to get its practical suitability for the long time. Its main reason is that the induction machine draws lagging magnetizing current which is to be supplied by the synchronous machines (alternators) connected on the system. Moreover, the induction generators have moderate efficiency and power factor.

In 1935 Bassett and Potter [1,2] have found that the induction machine can be made to operate as an isolated induction generator by supplying the magnetizing current from static capacitors connected in shunt across the terminals of the machine. This phenomenon is known as "capacitor self excitation". As the terminal voltage and frequency of the self excited induction generator drops with its loading, therefore, the much attention was not given for the practical suitability of self excited induction generator.

In last decade, for the utilization of non-conventional energy sources such as wind, biogas, small hydro heads etc., efforts have been made for the economical utilization of the self excited induction generator as an isolated source of power supply. A considerable number of investigations on feasibility, analysis, design and development of voltage regulating system of self excited induction generators are made for its suitability in different applications.

2.3 LITERATURE SURVEY

The phenomenon of capacitor self excitation occurrence was investigated by Bassett and Potter [1]. The phenomenon of self excitation in induction machines and a physical interpretation of self excitation occurrence is presented by Elder et al. [5]. The predetermination of performance characteristic of three-phase self excited induction generator is given by Wagner [2] under no-load and loaded condition. Terminal voltage was determined by summation of reactive volt amperes equal to zero and slip by the relation that summation of the real power equal to zero.

A derivation for the circle diagram giving the relation between power and VAR output of an induction generator is given by Barkle and Ferguson [6]. For this purpose, method of analysis of self excitation of induction generator using modified synchronous machine transient theory is used. From the power balance analysis and efficiency analysis of induction generator Erdelyi et al. [7] concluded that the induction generators are useful if the speed range is limited.

Vanderway and Inculet [8] have described the induction generator scheme with an attempt to minimise or possible elimination of the excitation power normally provided by a bank of capacitors. The advantages and its performance at variable sppeed have been described by Nagrial and Shami [9].

The steady state analysis of three phase self excited induction generator is done by Murthy et al. [10] by using 'Newton-Raphson method' to identify the saturated magnetising reactance and the generated frequency of self excited induction generator for a given capacitance, speed and load. For the analysis of single phase self excited induction generator Singh [11] has used Newton-Raphson method to compute the capacitance and generated frequency for a desired voltage at given speed and load. Single variable optimization technique along with Newton-Raphson method is used to achieve optimum terminal voltage for maximum output power of the generator at specified current and speed.

Under steady state analysis Murthy et al. [12] have discussed about the leading VAR requirement of self excited induction generator at constant/variable speed. Newton-Raphson method was used to determine the saturated magnetising reactance. Berchten [13] had used current state analysis of self excited induction generator to predict the steady state performance under different loading conditions.

By the method presented by Ouazene and McPherson [14] for the analysis of isolated induction generator, the output voltage and frequency of a three phase squirrel cage induction generator with three phase resistance loading over a wide range of rotor can be predicted, if at normal rated frequency magnetization characteristic and equivalent circuit parameters are known. This method directly uses the speed of prime-mover to determine the frequency, slip and voltage output without actually solving the complete network of the system which is composed of the induction machine, load and excitation capacitors.

A computer algorithm has been developed by Tandon et al. [15] which presents a method for steady state analysis of self excited induction generator using balanced terminal capacitors. Analytical method used by Tandon et al. [16] uses algebraic equations formulated from steady state equivalent circuit of the induction machine by equating the closed loop impedance of phasor equivalent circuit in terms of pu speed and pu frequency to zero. For this a computer programme has been developed to predict performance. A computer programme is also developed by Murthy et al. [17] to calculate the performance of self excited induction generator for resistive and inductive loads. They concluded that the rotor heating is the limiting factor on the power that can be obtained from the self-excited induction machine.

A computer method for steady state performance of a self excited induction generator is presented by Yegna Narayanan and Johnny [18]. This paper also presents capability chart of a wind turbine driven induction generator to observe the location of any operating point relative to a region bounded by curves representing loci of the operating point corresponding to prescribed limiting values of terminal voltage, frequency, maximum line current and maximum induction generator shaft input power respectively.

A simple method for steady state analysis of self excited induction generator for a general impedance load using only quadratic equation has been developed by Ammasaigounden et al. [19]. This method requires much less computation effort than the earlier methods [10,14-16] which involve higher order polynomials and numerical techniques for their solution. A direct relationship between P.U. frequency and speed leading to an expression for operating slip, applicable for both no-load and loaded conditions is obtained.

Though generally for the steady state analysis of self excited induction generator, core losses have been neglected [1,2,10-19] but for stable operation machine has to be operated in the region of magnetic saturation and hence in any accurate analysis such losses must be included. Considering the effect of machine core losses, steady state analysis and performance of an isolated self excited induction generator is presented by Malik and Haque [20].

Murthy et al. [21] have explained the computer algorithm in order to determine the performance of capacitor self excited induction generator taking the machine design details as the input data.

The behaviour of the generator under balanced and unbalanced condition is analysed by Elder et al. [22]. For this purpose machine equations are transformed to the equivalent two phase machine equations, with the two phase stator axis (D,Q) fixed to the stator and rotating axis. Steady state and transient analysis of self excited induction generators using D-Q axis is done by Granthmam [23].

Melkebeck [24] describes the application of saturated model for the stability behaviour of voltage feed induction motor and self excited induction generator. The necessity of improved model has also been pointed out due to the unrealistic predictions of classical model. The small signal stability and dynamic response for six modes of induction generator operation including both voltage and current inverter system have been examined and compared by Melkebeck and Novotony [25]. They have introduced an improved small signal model, considering main flux saturation to study the stability properties of all six modes. The capacitive self excited case is shown to require special treatment because of the phase freedom is inherent in this mode.

The method of analysis for autonomous and parallel operated self excited induction generators had been presented by Watson and Milner [26]. This method uses simplified expression for magnetising current to determine characteristics of induction generator and division of load.

To get constant voltage and frequency a number of schemes have been proposed by Erdelyi et al. [7] involving two induction generators on a common shaft with interconnected windings. But in these schemes either power circulates between both machines and no net power is supplied to the line or power proportional to slip must be dissipated in the rotor circuitry at severe efficiency panalities.

It was seen by Novotny et al. [27] that the self excitation in inverter driven induction generator is practicable when the rotor speed exceeds the synchronous speed of the inverter switching frequency. The magnetisation current in this case comes from the circulating currents in the inverter.

Constant voltage with varying load and/or speed variation can be maintained by using adjustable power generators connected at the terminals of the induction machine. A simple switched capacitor scheme has been discussed by Singh et al. [28] to maintain terminal voltage within a fixed limit. A voltage regulator has been developed by Brenner and Abbondanti [29] using fixed capacitor connected in parallel to a thyristor controlled inductor. George Konotos and Lytsikas [30] describe about the effects of the harmonics currents and minimisation under the steady state operation of three phase induction generator with a three phase voltage fed autonomous inverter.

Feasibility of Scherbius drive as voltage regulator for induction generator with synchronous condenser is presented by Ooi and David [4]. The scherbius drive is suggested, not only for the purpose of slip power recovery, but also for the ease and fast response in control by electronic signals.

Arrillage and Watson [31] have described the characteristic of self excitation and controlled rectification for constant speed source and its prospective applications to HVDC transmission. Further controlled rectifier for induction generator has been developed by Watson et al. [32] to maintain constant terminal voltage at variable speed and to generate optimum power by delay angle control of rectifier.

A voltage regulator using a 6-pulse naturally commutated converter feading VAR to an inductor has been developed by Murthy et al. [33]. A diode bridge with an appropriate smoothing reactor connected across the induction machine terminals was suggested by Raina and Malik [34] to give a constant D.C. output voltage which is free from frequency variation at generator terminals. An inverter can supply constant voltage and constant frequency A.C. power.

Malik et al. [35] collectively describe a solid state voltage regulator for self excited induction generator by using fully controlled converter to compensate the capacitive VARs of fixed capacitors across the generator terminals. A D.C. power supply system based on a three phase self excited induction generator coupled to a forced commutated rectifier has been developed by Watanabe and Barreto [36]. This system provides good voltage regulation with respect to the variation of load and speed.

Elder et al. [22] had described inductively loaded AC/DC converter, thyristor controlled inductors and switched capacitors, their relative merits and demerits as voltage regulators for induction generators. Microprocessor controlled resistance is used by Watson and Watson [37]. This resistance absorbs power excess of consumers requirements to maintain a constant loading on the generator, thereby maintaining constant frequency and voltage. But this method is satisfactory only when the consumer load is purely resistive. A control scheme using INTEL 8086 for the d.c. linked inverter of double output wound rotor induction generator has been developed by Ziyad Salameh and Sunway Wang [38].

The characteristics and corresponding protections of induction generator up to 1500 KW are discussed by Bailly [39]. The difference in synchronous generator and induction generator's protection under several electrical system configuration is also presented.

John R. Parsons [40] describes the suitability of induction generator for many industrial cogeneration application. The application of 3000 KW induction generator is compared to that of a comparably sized synchronous machine considering their relative costs, equipment protective relaying, utility tie-in and synchronising, maintenance and operating procedures.

Saturable core reactor [41-44] with various control windings serves the purpose of controlled inductor. Itsuse as auto-excited magnetic amplifier is also presented.

2.4 CONCLUSIONS

From the exhaustive literature survey it is found that a good amount of work has been done on the feasibility, exploitation, analysis and design of the self excited induction generator. A number of efforts has been made to develop the voltage regulating system using thyristor controlled circuits for constant speed and variable speed prime-movers. But not a single attempt is made to develop a voltage regulator for three-phase self excited induction generator using saturable core reactor. Here, an attempt has been made to develop a voltage regulator using saturable core reactor for 3-phase self excited induction generator.

CHAPTER - 3

EXPERIMENTAL INVESTIGATIONS O THE STEADY STATE PERFORMANCE OF SELF EXCITEX INDUCTION GENERATOR

3.1 GENERAL

In this chapter, basic principle of three-phase self excited induction generator is explained. Steady state performance of a three-phase self excited induction generator is investigated on a commercial three-phase, 3.7 KW, 7.1 A, 50 Hz, 4 pole, 415 V, delta connected cage induction machine. The extensive tests are conducted on cage generator to find the few discrete capacitor steps to keep the terminal voltage within specified limits at different loads and at constant speed. Tests are also performed to determine capacitance requirements of the generator to maintain constant terminal voltage under different loading conditions at constant (synchronous) speed and for different speeds at no-load. The optimum output power and corresponding terminal voltage is also obtained for the given specific electric loading i.e. rated stator current of the machine.

3.2 BASIC PRINCIPLE

When the rotor of an induction machine is being driven by a primemover, the residual magnetism in the rotor core induces a small emf in the stator winding at a frequency proportional to the rotor speed. If the static capacitors are connected across the terminals of the induction machine, a leading current flows in the capacitor, the same current passing through the stator winding of the machine and producing an armature reaction flux assisting the original residual flux. If the capacitors are of sufficient value, the voltage builds up and its final being limited by the magnetic saturation of the induction machine. The machine is then self excited and can operate as an induction generator in isolation from an active power source.

The terminal voltage of the self excited induction generator depends upon the value of capacitors, speed of primemover and the nature and amount of load. If the self excited induction generator is loaded with resistive or reactive load, its terminal voltage drops by a considerable amount. However, in most of the applications, a constant terminal voltage irrespective of load is requested. The constant terminal voltage of the generator with varying loads can be maintained by using a suitable leading VAR generator. The variable leading reactive power requirements of the cage generator to maintain constant terminal voltage can easily be met by a fixed valued capacitor bank and a variable inductor. The variable induction can be realised either by using thyristor controlled reactor or using saturable core reactor. However, the few discrete capacitor steps can also allow to load the generator with its full capacity by maintaining its terminal voltage within tolerable limits.

3.3 EXPERIMENTAL MACHINE AND TEST SET-UP

Basic block diagram of self excited induction generator is shown in Fig. 3.1. In this investigation, entire experimentation

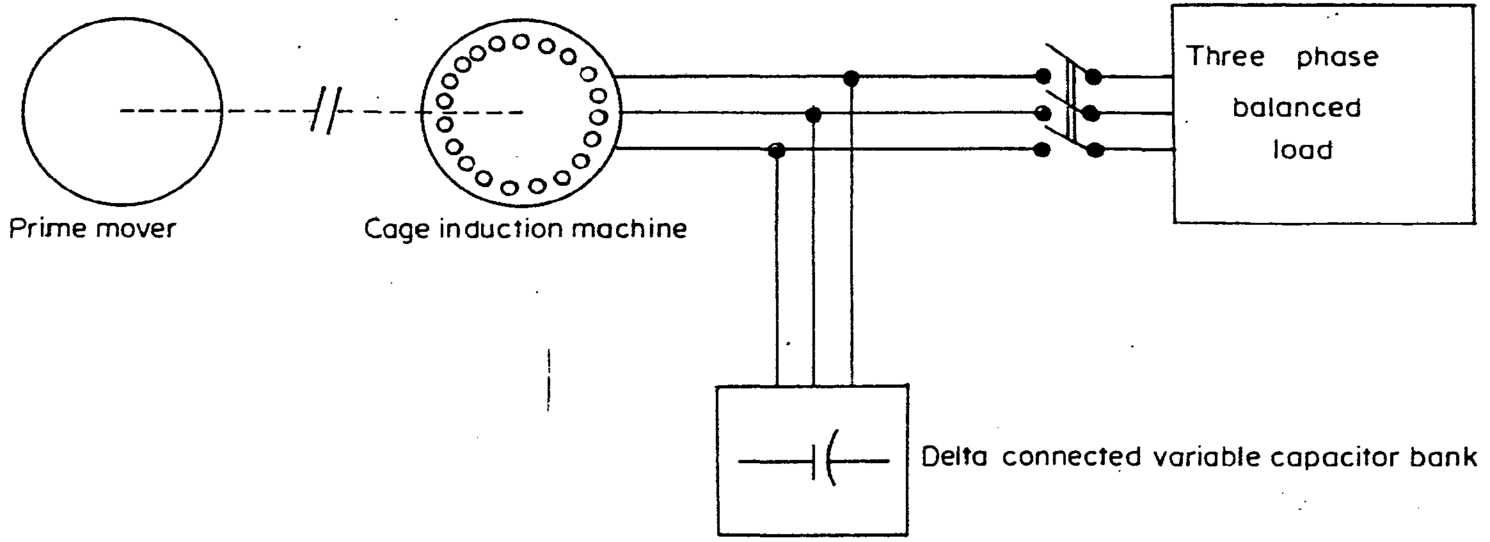


FIG.3.1 BLOCK DIAGRAM OF SELF EXITED THREE PHASE CAGE INDUTION GENERATOR.

is carried out on a commercial three-phase, 3.7 KW, 7.1 A, 4 pole, 50 Hz, 415 V delta connected squirrel cage induction machine used as an isolated self excited induction generator. To obtain desired speed under different loading conditions, the induction machine under test was coupled to a 7.5 HP, 220 V compound d.c. motor. To adjust the speed of primemover at any desired value, a rheostate of 2.8 A, 200 ohm rating was connected in series of the field circuit of the d.c. motor. To get the desired terminal voltage, a three-phase variable capacitor bank was connected at the terminals of induction machine. A variable three phase resistance of proper value and a three-phase, 3 H.P., 4 pole, 50 Hz induction motor is used as resistive and dynamic load on the induction generator.

3.4 RESULTS AND DISCUSSIONS

Using test results the steady state performance characteristics of three-phase self excited induction generator are obtained and are shown in Figs. 3.2 to 3.7. The test results include the no load characteristic, load characteristic for resistive and motor load, reactive power requirements in terms of capacitance for different loads and the variation of output power with terminal voltage at rated stator current of generator. At no-load, requirement of capacitance with speed to keep the terminal voltage constant is also obtained.

Fig. 3.2 shows the variation of the generated voltage of the machine with capacitance at no-load and rated speed. The developed induced emf increases with increase in the value of

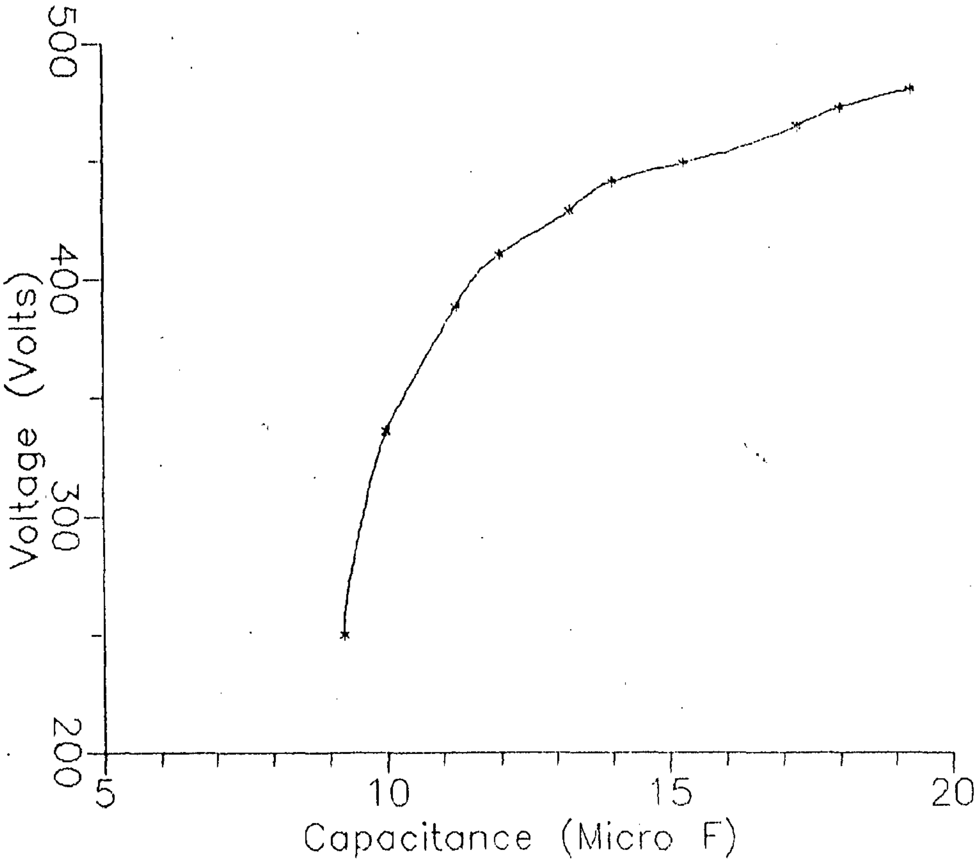


FIG. 3.2 VARIATION OF TERMINAL VOLTAGE WITH CAPACITANCE AT NO-LOAD AND RATED SPEED.

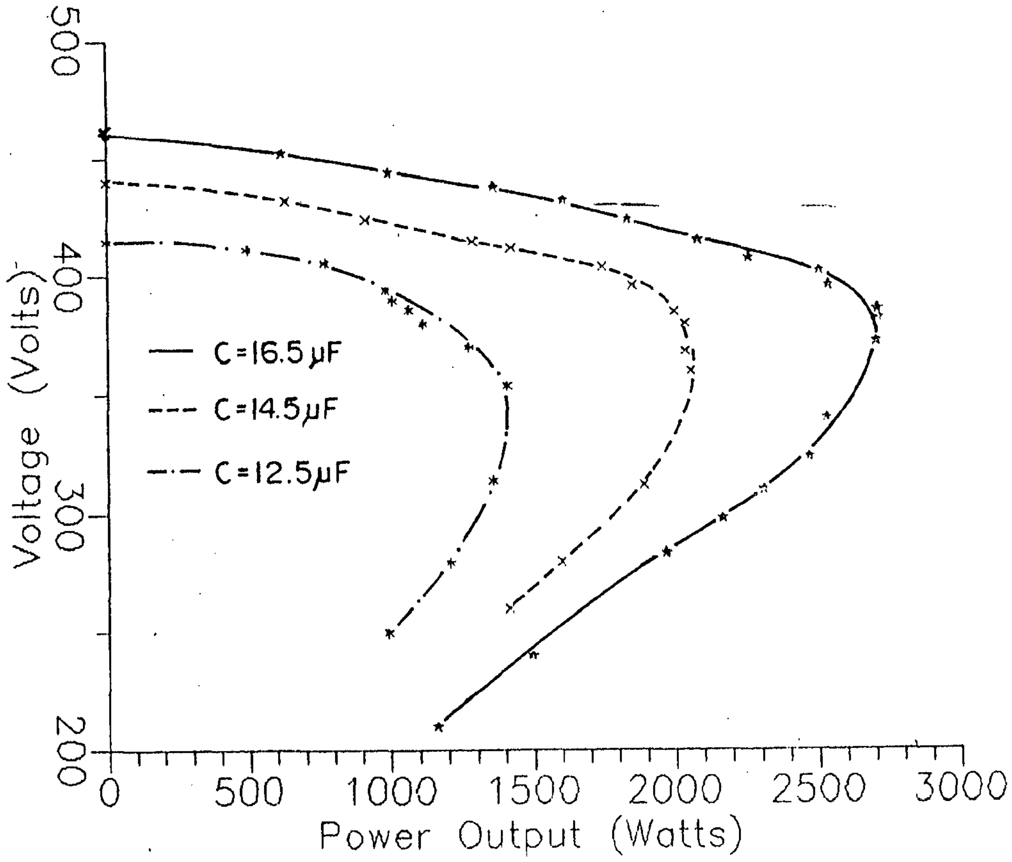


FIG 3.3 LOAD CHARACTERISTICS OF INDUCTION GENERATOR AT RATED SPEED.

the capacitance. The rise of the terminal voltage with capacitance is, however, limited by the saturation of the magnetic circuit of the machine. The minimum value of the capacitance at which the machine starts building up the voltage by increasing the capacitance from a lower value to this value, or by reducing the capacitance from a higher value to the value at which the machine looses self-excitation, is known as 'critical capacitance' for self-excitation and for machine under test it is found to be 9.5 microfarads per phase. This characteristic is also known as no-load characteristic or magnetization characteristic of the machine.

Fig. 3.3 shows the load characteristic of induction generator indicating the variation of terminal voltage with output power for different values of capacitance (12.5 μF, 14.5 μF and 16.5 μF) at rated speed and unity power factor load. Due to the effect of armature reaction, impedance drop and its dependent excitation, a considerable drop in the terminal voltage of the generator with the increased load is observed. The general pattern of the load characteristic is same for all the values of capacitance, but the terminal voltage as well as maximum power output that can be delivered to the load increases with increased capacitance. From this figure, it can be observed that, it is possible to control the terminal voltage within ± 5% at 400 V with only a few capacitors steps (4) upto rated output power of the machine. Therefore, a simple switching scheme may be developed for the control of additional capacitors on the basis of under-and over-voltage operating relays for cutting and connecting these stepped capacitors at the machine terminals for its variable loading.

It would result in a cheap and simple regulating scheme of the self-excited induction generators for the applications where a small variation in the terminal voltage is permissible.

For a constant value of the capacitance, Fig. 3.4 shows the variation of the terminal voltage with power output of the generator for dynamic (induction motor) load. It is seen that for the dynamic load, induction generator is able to give output only of 580 W. More loading of the induction generator results the collapse of self-excitation by reducing the terminal voltage to zero. Hence it is evident from this figure that additional loading of generator may only be done by providing the higher valued capacitor bank at generator terminals.

Fig. 3.5 shows the variation of reactive power in terms of capacitance with output power to keep the terminal voltage constant at the rated speed of the primemover. To maintain the terminal voltage constant, the required value of the capacitance increases with output power. For an output power the required value of capacitance is reduced for lower terminal voltage due to the reduced requirement of excitation at lower flux caused by the decreased value of the voltage. However, it may be concluded that for maintaining the constant terminal voltage, a variable capacitor from 12.5 μF to 24 μF is required to load the generator from no-load to full load for resistive load. These datas provide the guidelines for the design of a voltage regulating system of an induction generator.

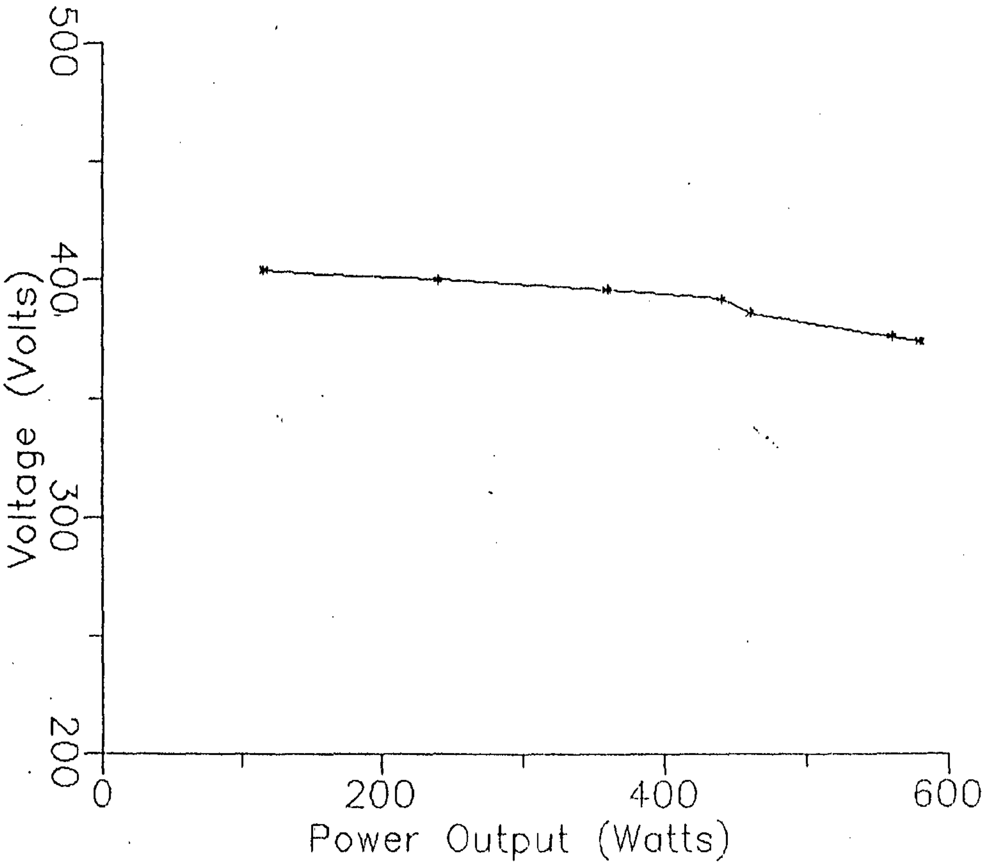


FIG. 3.4 LOAD CHARACTERISTIC OF INDUCTION GENERATOR FOR INDUCTION MOTOR LOAD AT RATED SPEED.

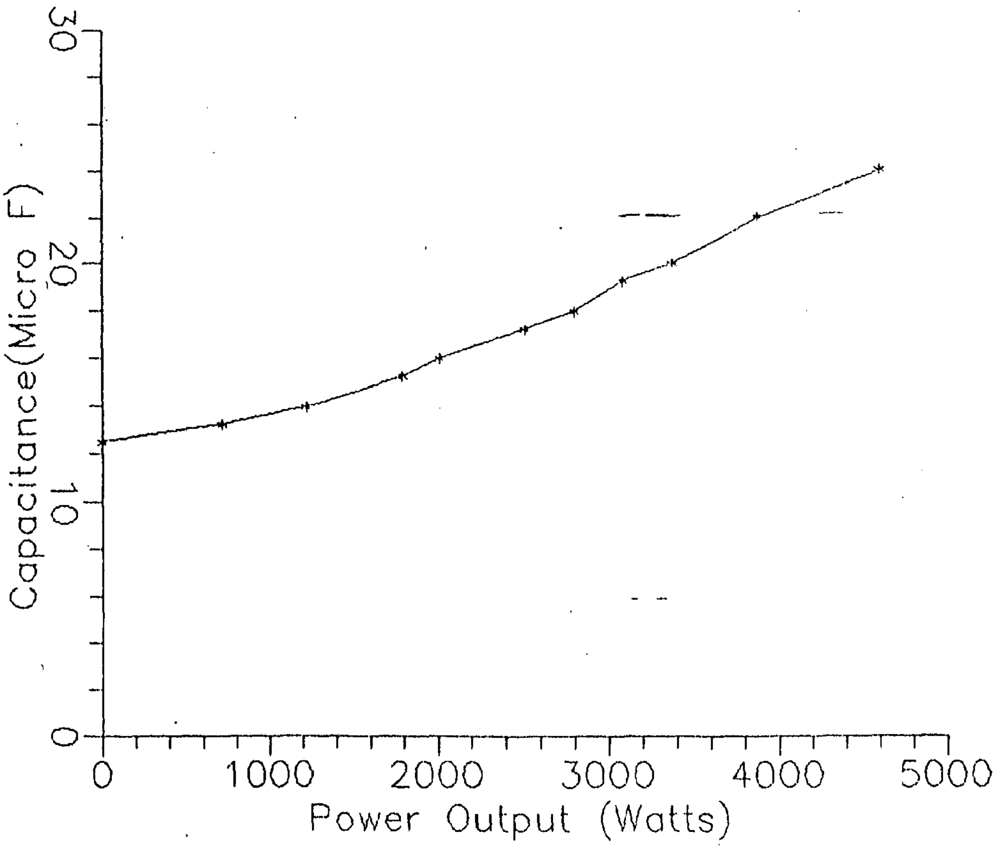


FIG. 3.5 VARIATION OF CAPACITANCE WITH POWER OUTPUT TO KEEP Vt CONSTANT AT RATED SPEED.

Fig. 3.6 shows the variation of output power with terminal voltage for rated value of stator current and speed. The maximum output power 3.8 KW is observed at 416 volts and much sharp fall in power is seen at higher voltages. It may be observed from this figure that the machine is capable of developing maximum power more than rated value at optimum voltage of 416 volts, while it may deliver output power more than the rated power for the terminal voltage between 400 voltls to 425 volts for rated speed and current.

The variation of the speed of the induction generator wwith required capacitance to keep the terminal voltage constant at no-load is presented in Fig. 3.7. It may be observed from the figure that for maintaining a fixed terminal voltage, the capacitance required at higher speed is less than the capacitance required at lower speed of the generator. At higher speeds the required value of capacitance reduces due to the reduced requirement of excitation at lower value of flux caused by the increase in frequency.

From the above results it is seen that at the rated terminal voltage and speed, the reactive power requirement (12.5 μF) of the generator is minimum at no-load and the reactive poweer requirement (24 μF) is maximum at full load. As a self excited induction generator is not able to generate loading VAR, the reactive power requirement of the load is also supplied by the capacitor bank connected at the terminals of the generator. Considering the maximum reactive power requirement to be 10 μF of the load, a leading VAR generator capable of supplying variable reactive

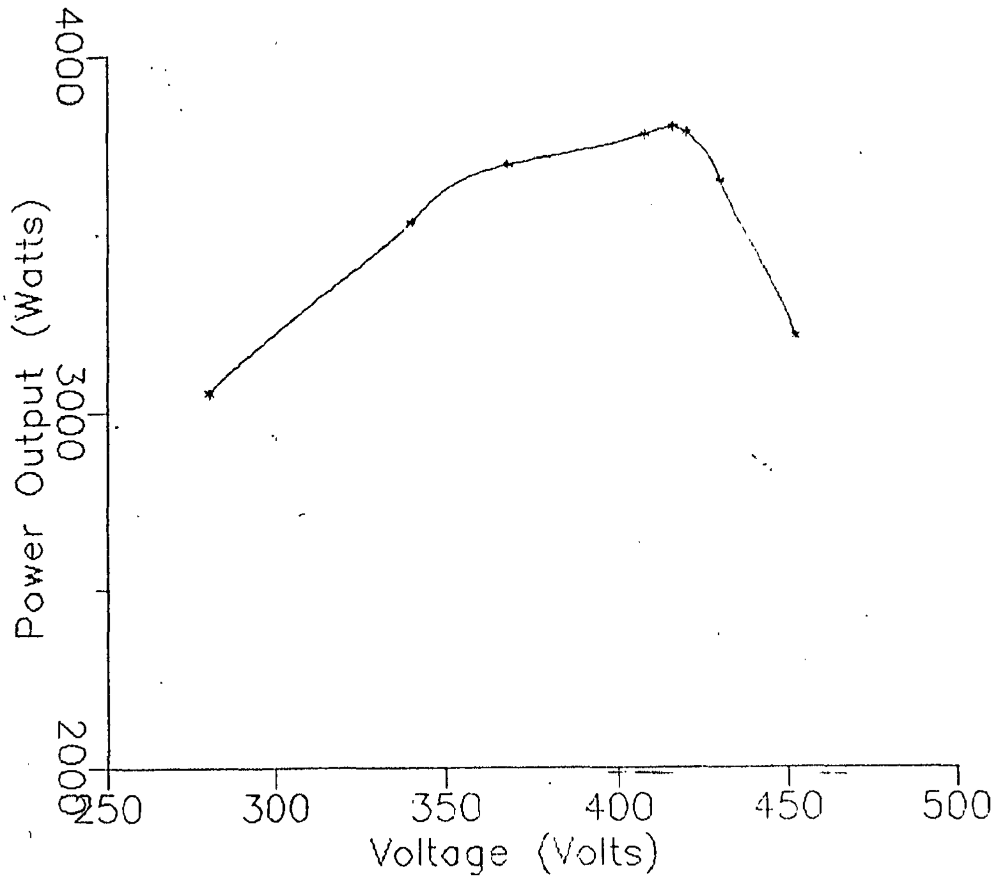


FIG. 3.6 VARIATION OF POWER OUTPUT WITH TERMINAL VOLTAGE AT RATED SPEED AND STATOR CURRENT.

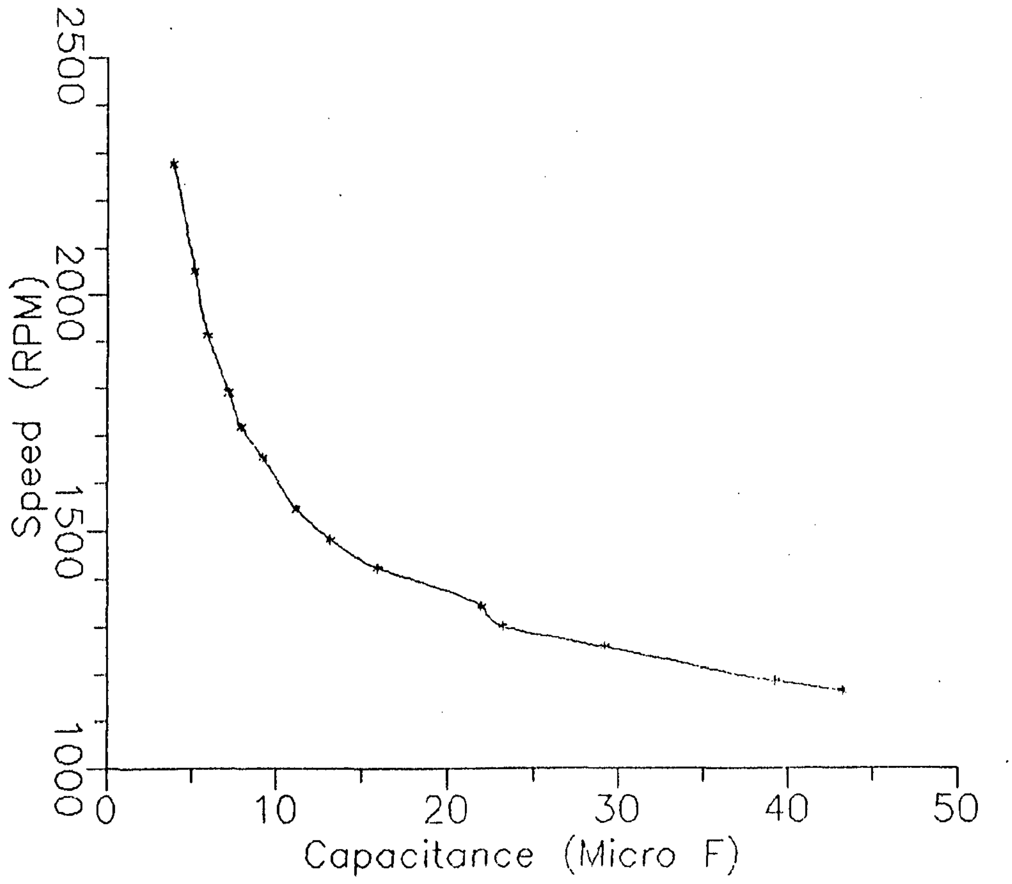


FIG. 3.7 VARIATION OF SPEED WITH CAPACITANCE TO KEEP THE TERMINAL VOLTAGE CONSTANT AT NO-LOAD.

power from 12.5 μF at no-load to any value up to 34 μF at load as required by the induction generator and load to keep the terminal voltage constant is needed. Saturable core reactor of 400 volts, 2.7 A capacity connected in parallel to 34 μF capacitor bank may easily serve the purpose of desired VAR generator. This system with proper feedback signals to the saturable core reactor may work as a voltage regulator for the self excited induction generator.

3.5 CONCLUSIONS

The steady state performance of the self excited cage induction generator has been studied in detail. From the test results it is observed that machine starts building up the voltage at no-load and rated speed by connecting a capacitor bank of 9.5 μF per phase respectively. It is concluded that with the four number of capacitor steps, the machine can be loaded upto its rated capacity at rated speed while maintaining its terminal voltage within ± 5% of rated value. It is observed that the reactive power requirement of the machine under test may be met by a variable capacitor bank of 12.5 μF per phase to 24 μF per phase to maintain constant terminal voltage from no-load to full load for resistive load. It is also concluded that machine is capable of developing more than rated output power for a wide range of voltage at rated stator current and speed with appropriate required capacitor. It is also observed that the requirement of capacitor reduces with rise in speed of primemover for a given voltage of the generator.

CHAPTER - 4

DEVELOPMENT OF THE VOLTAGE REGULATOR

4.1 GENERAL

When a suitable capacitor bank is connected across the terminals of the induction machine driven by a primemover at a particular speed, it gets excited to buildup the voltage which is restricted by the magnetic saturation of the machine. If the induction machine is self excited with a particular value of capacitor and loaded with resistive or inductive load, the terminal voltage drops by a considerable amount. However, in most of the applications constant terminal voltage is needed at different loads. Constant terminal voltage can be maintained by using suitable voltage regulator consisting VAR generators for self excited induction generators. Generally variable VAR generators are using either switched capacitors or thyristor controlled reactors. Switched capacitor scheme can be used in applications where the variation in the terminal voltage is permitted within a spacified limit. In the thyristor controlled schemes terminal voltage and I_1 contains switching transients and harmonics. Hence in this work to maintain the terminal voltage constant with varying loads, a static VAR generator using saturable core reactor is developed. Fig. 4.1 shows the basic block diagram of the induction generator with voltage regulating system.

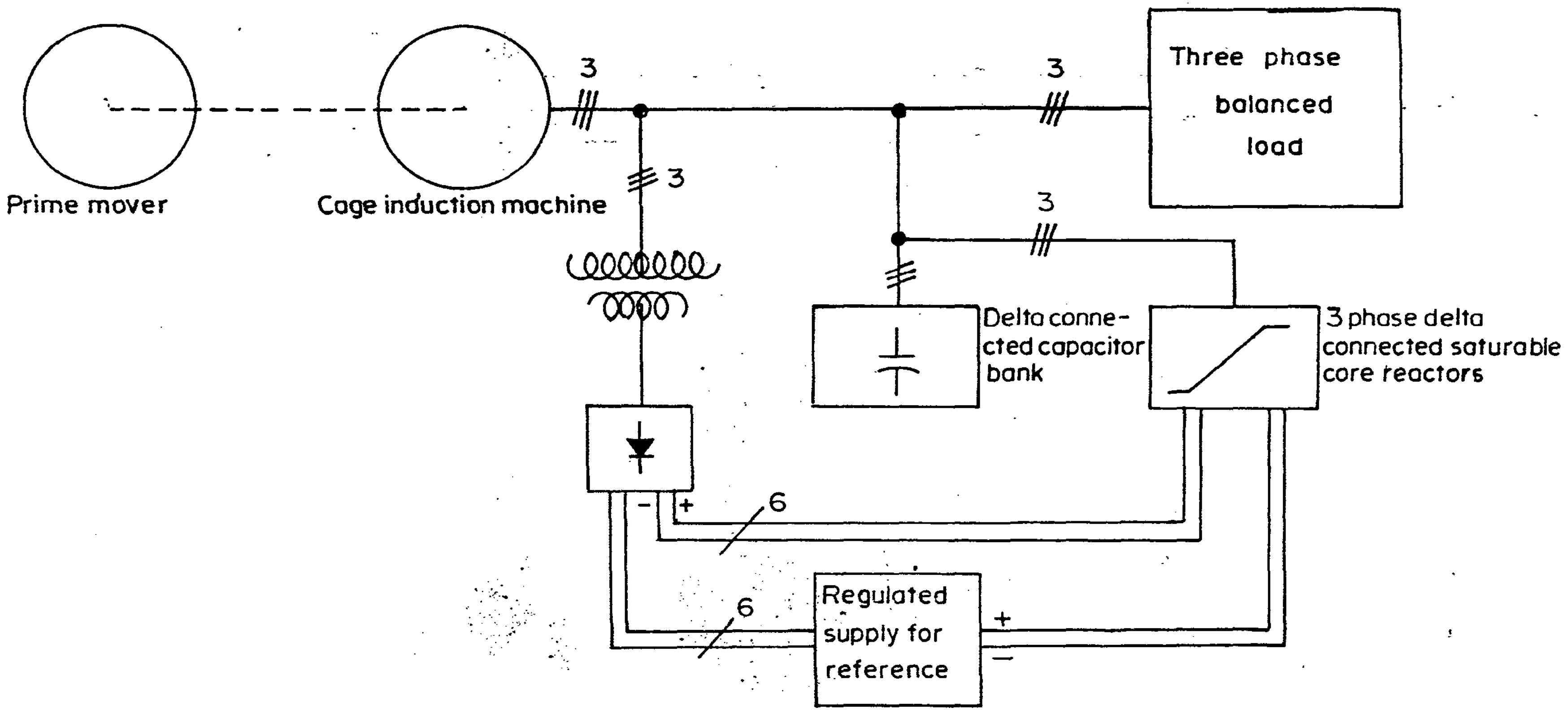


FIG.4.1 BLOCK DIAGRAM OF THREE PHASE SELF EXCITED INDUCTION GENERATOR WITH VOLTAGE REGULATOR.

In this chapter the principle of operation of the voltage regulator using saturable core reactors is explained. To realise the voltage regulator, selection of components of voltage regulator and its closed loop system is made for 3.7 KW generator. After fabricating all the components of the voltage regulator, the complete voltage regulator is assembled. Performance characteristics of the saturable core reactors under auto-excited mode is also investigated.

4.2 PRINCIPLE OF OPERATION

For a capacitor self excited induction generator, frequency and voltage is decided by the speed of primemover, capacitance and load across the terminals of the generator. With a fixed value of capacitance, the terminal voltage of the generator drops with its loading. Terminal voltage can be maintained constant by using variable VAR generators as voltage regulator for self excited induction generators. As shown in the block diagram of Fig. 4.1, capacitor bank of higher value and saturable core reactors in parallel to it can serve the purpose of variable VAR generator.

The saturable core reactors, in the present case is to function as auto-excited magnetic amplifier. It consists of several control windings for the purpose of various control signals and biasing. In this scheme only two control windings are used one for the reference setting and is fed from a variable d.c. excitation and the other is used as feedback winding and is excited from derived feedback d.c. signal. For the purpose of feedback, the terminal voltage is stepped down to a low value and is rectified by using a small rating bridge rectifier. Rectified output is connected to the feedback winding having one variable resistance in series of it.

The initial terminal voltage of the system can be adjusted to a desired value by controlling the d.c. signal to feed reference winding. Loading of the generator will cause the terminal voltage to go down, resulting in reduced d.c. signal to feedback winding, which desaturates the core of the reactor and its effective inductance is increased. With this, the current flowing to the saturable core reactor reduces, thus transferring the capacitor current to the induction generator, causing increased excitation to it. It will increase the generated emf across the machine winding, further increasing the excitation to feedback winding and saturation of core of the reactor. From this reactor current will increase and terminal voltage will go down. This process of oscillation will be continued for very short period till final steady state condition is achieved. In this system, the effective gain is of the order of several thousands resulting steady state error of negligible value.

If the load is suddenly removed, the instantaneous terminal voltage will increase and it will cause more excitation to feedback winding which will cause the more saturation of the core. The part of the capacitor current will be transferred to saturable core reactor and results in reduced excitation to the generator will result the decreased in induced emf of the machine. Finally in this case also the terminal voltage will stabilize to the desired preset magnitude of it. This system will regulate the terminal voltage across the generator terminals irrespective of load.

4.3 SELECTION OF COMPONENTS OF VOLTAGE REGULATOR

It is seen that the capacitance required by the induction generator to keep the terminal voltage constant at resistive load varies from 12.5 μF to 24 μF. As a self excited induction generator is not able to supply reactive power to its load, the reactive power required by the load will also be supplied by the capacitor bank connected at the terminals of the induction generator. Hence a delta connected capacitor bank of 34 μF will be sufficient to supply reactive power to the generator and load.

To compensate the excess reactive power from the capacitor bank, saturable core reactors are connected in parallel to the capacitors. At no-load, capacitance required by the induction generator is minimum and is 12.5 μF. Hence, remaining capacitance (34-12.5 = 21.5 μF) will be compensated by saturable core reactor. To compensate this current through the saturable core reactor will be

$$I = V.2\pi fc$$
$$= 400 \times 2\pi \times 50 \times 21.5 \times 10^{-6}$$
$$= 2.7 \text{ Amp.}$$

Saturable core reactor is having two load winding in parallel.

Hence current in each load winding $I_{LW} = \frac{2.7}{2} = 1.35$ Amp.

Assuming current density 1.7 A/mm^2 for air cooled reactor.

Area of copper conductor $= \frac{1.35}{1.7} = 0.7941$ mm^2.

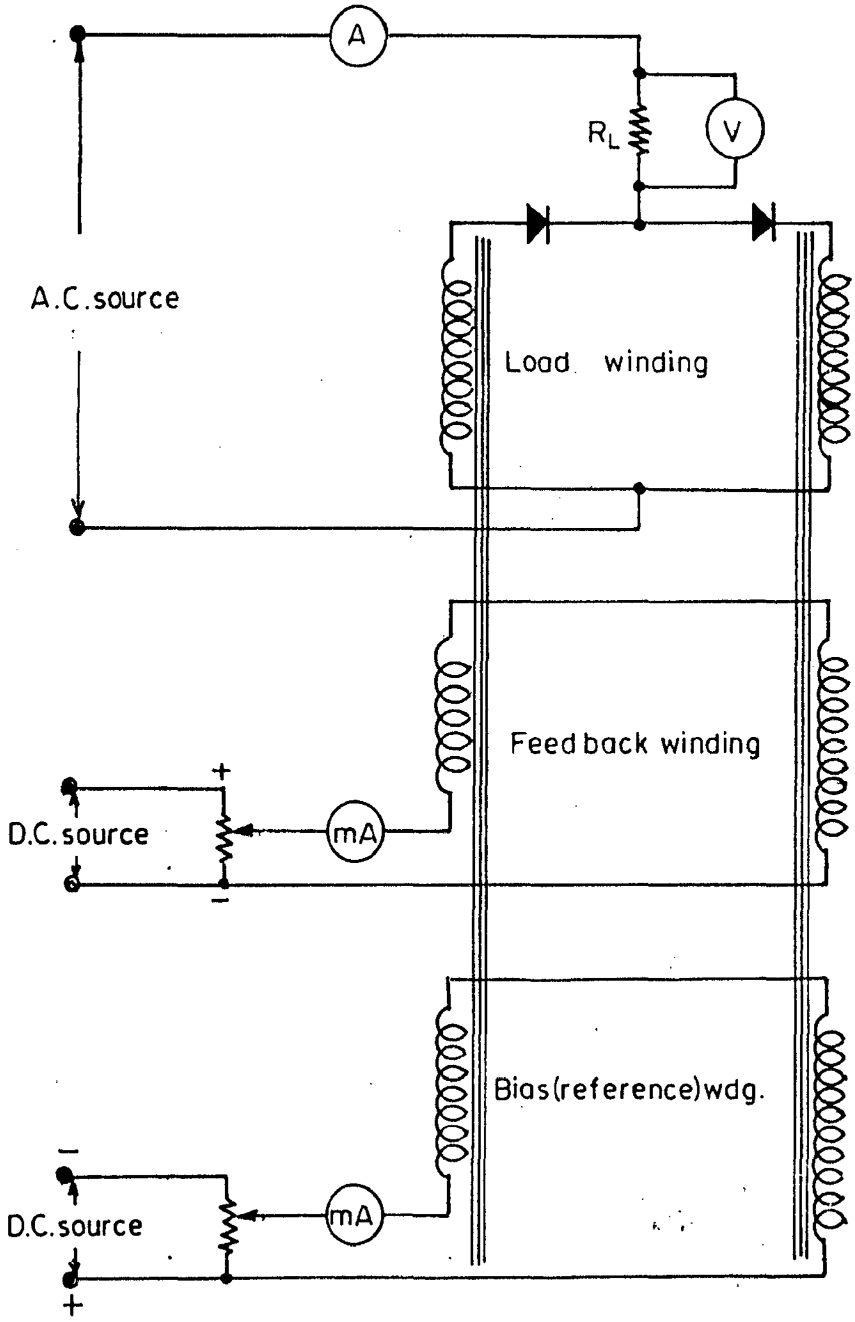


FIG.4.2 SCHEME FOR TESTING THE AUTO-EXCITED SATURABLE CORE REACTOR.

Hence, we can use SWG 19 having nearest copper area=$0.811 mm^2$. diameter of copper conductor = 1.32 mm

Six number of identical toroidal cores are used for the fabrication of saturable core reactors. The cores are having outer diameter = 150 mm, inner diameter = 76 mm and thickness = 39 mm.

Area of cross-section of the core (A) =

$$\frac{(150-76)}{2} \times 39 = 1443 \text{ mm}^2$$

$$= 14.43 \times 10^{-4} \text{ m}^2$$

Taking the flux density of core (B) = 1.4 Wb/m^2

Number of turns in the load winding

$$T = \frac{E}{4.44 \text{ fBA}} = \frac{400}{4.44 \times 50 \times 1.4 \times 14.43 \times 10^{-4}}$$

$$= 892 \approx 900 \text{ turns.}$$

To make the saturable core reactors, auto-excited magnetic amplifiers, diodes are to be connected in each winding as shown in Fig. 4.2. As the current in each winding is 1.4 Amp., and voltage across each winding is 400 V, diodes of 10 A, 1200 V PIV rating are taken with sufficient safety factor for the load winding.

The feedback current required by the control winding is of the order of 100 mA. This can be achieved by using 400 V/6 V step down transformers having secondary current rating equal to 100 mA. At least one number of these transformers should have two secondary windings of 6 V, 100 mA each. One winding is needed for feedback circuit and the other is required for bias winding of saturable core reactors.

For feedback circuit, secondary voltage of the step down transformer is rectified by a bridge rectifier circuit. A small capacitor of 2 μF, 12 V is connected at the output of these rectifier for filtering purpose.

Another 6V winding of the step down transformer is used for biasing circuit. The output of 6V is rectified and capacitor of 12 V, 1000 μF, is connected at the output of the bridge rectifier. This output is connected to the input of IC 7805 voltage regulator. It will provide 5 volts regulated d.c. power supply. To adjust the initial reference voltage, 1K, 3W variable resistance is sufficient in series with bias winding.

4.4 FABRICATION OF SATURABLE CORE REACTOR

To fabricate the saturable core reactors, six identical toroidal cores were insulated by wrapping one layer of cotton tape. After coating with insulating varnish, cores were placed in the oven to dry. Dried cores were covered with one layer of 3 mm thick latheride paper and were again wrapped with one layer of cotton tape. Again applying insulating varnish and getting it dried in the oven, empire tape was wrapped around the core. To make the cores perfectly insulated, one layer of million X tape was wrapped over the core. Now these cores were ready for winding.

According to the design, 900 turns of SWG 19 gauge having enamel covering, were provided uniformly on each core to use as load winding. During the process of winding, million X tape was wrapped between two layers of load winding. Both the end connections of winding conductors were placed into the sleeves and were taken out. To provide proper insulation over load winding, cotton tape was wrapped over the load winding and insulating varnish was applied over it. After getting the insulating varnish dried, two cores having load winding were placed together after placing latheride paper as insulating washer between them. These two combined cores are wrapped with cotton tape. One d.c. control winding of 1000 turns and two d.c. control windings of 500 turns each using SWG 29 gauge with enamel covering were provided over this combined assembly. In these control windings, million X tape was used as inter layer insulation and cotton tape was used as inter coil insulation. End connections of d.c. control windings were taken out after putting the conductors into sleeves. These end connections of load and control windings were connected at connectors terminals.

4.5 PERFORMANCE CHARACTERISTICS OF SATURABLE CORE REACTOR

The circuit of a conventional auto-excited saturable core reactor is shown in Fig. 4.2. In the auto-excited saturable core reactor, the circuit is arranged in such_a_way that the alternating current is prevented from flowing in the coil on the unsaturated core. This removes the possibility of large inducted currents in the coil circuit and makes the saturable core reactor to behave like one with complete self excitation. The effect of constant biasing mmf applied to the auto-excited saturable core reactor is to produce the horizontal shift in the control characteristic due to d.c. ampere-turns provided by the minimum load current through the auto-exciting circuit.

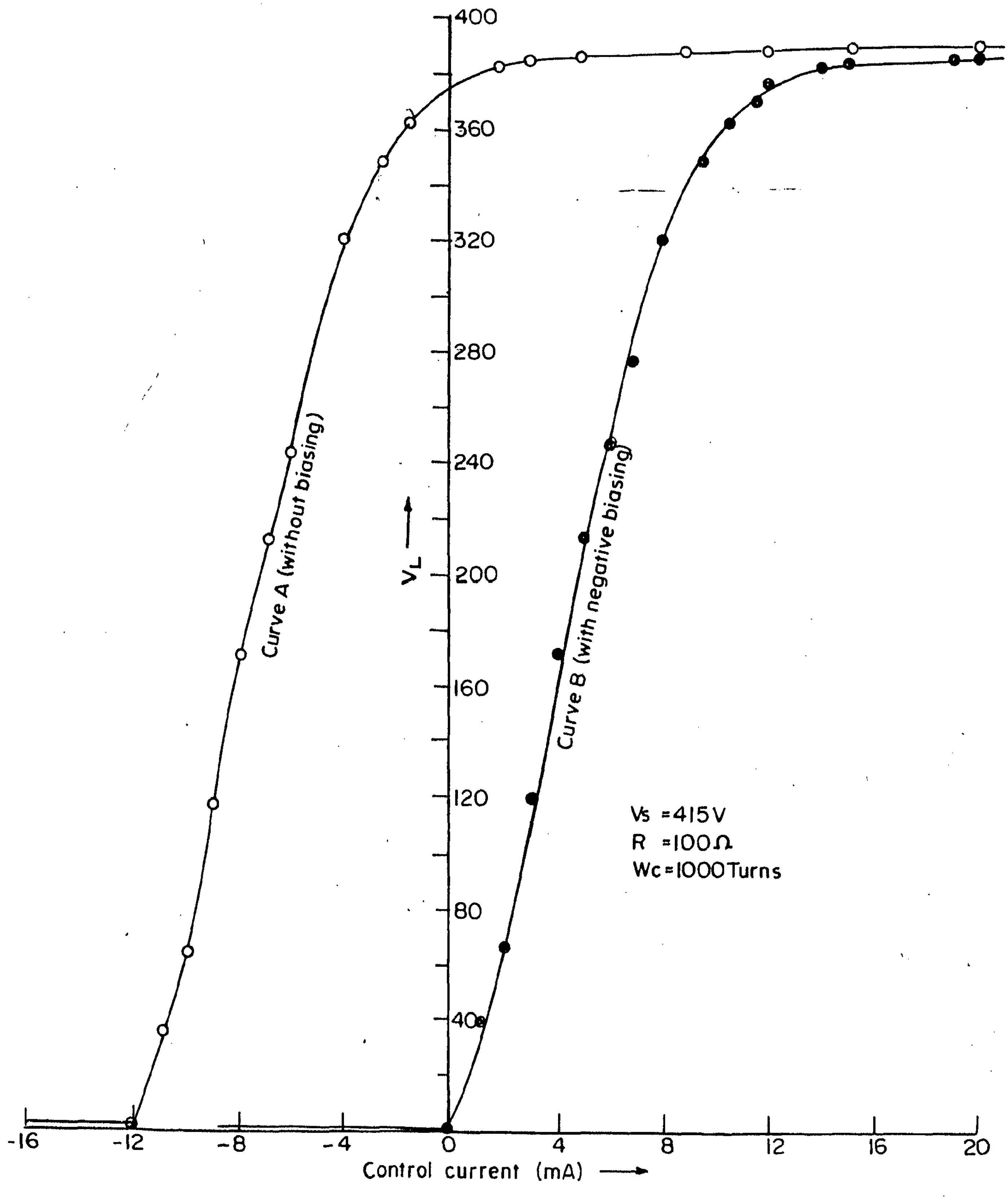


FIG.4.3 CONTROL CHARACTERISTIC OF THE AUTO-EXCITE SATURABLE CORE REACTOR.

To find out the performance characteristic of the auto-excited saturable core reactor, fabricated reactor was connected as shown in Fig. 4.2. Control windings were fed by variable regulated power supplies. Curve-A of Fig. 4.3 shows the performance characteristic of auto excited saturable core reactor without biasing and feding control current to 1000 turns control winding. Curve-B of this figure shows the control characteristic with bias current of 24 mA to 500 turns control winding. Test results show that the load circuit and control circuits are not conductively coupled which makes them more flexible to use.

4.6 CONCLUSIONS

Principle of operation of a voltage regulator for three-phase self excited induction generator has been explained using saturable core reactor. The voltage regulator with its proper feedback circuit has been designed and fabricated. All the three saturable core reactors under auto-excited mode have been tested and results give their satisfactory performance required for the proposed regulator.

CHAPTER - 5

PERFORMANCE OF SELF-EXCITED INDUCTION GENERATOR WITH VOLTAGE REGULATOR

5.1 GENERAL

This chapter includes the experimental investigations on the performance of the self-excited cage induction generator with developed voltage regulating system. The performance of the system is obtained in terms of steady state and the transient response of the parameters such as terminal voltage, load current, generator current and currents of the saturable core reactor. The waveform of three parameters are recorded by using a digital storage cathode ray oscilloscope and four channel recorder for steady state and dynamic behaviour of the induction generator with voltage regulator under different loading conditions.

5.2 EXPERIMENTATION .

The schematic diagram of three-phase self excited induction generator with the developed voltage regulating system is shown in Fig. 5.1. The experimental setup with the metering at appropriate points is arranged according to this schematic diagram. A 7.5 H.P. compound d.c. motor as a primemover is coupled with the induction machine operating as a generator. To obtain the steady state performance at different desired speeds, the speed of the induction generator is set by adjusting the field resistance of the d.c. motor. When, at no load, capacitor bank with voltage

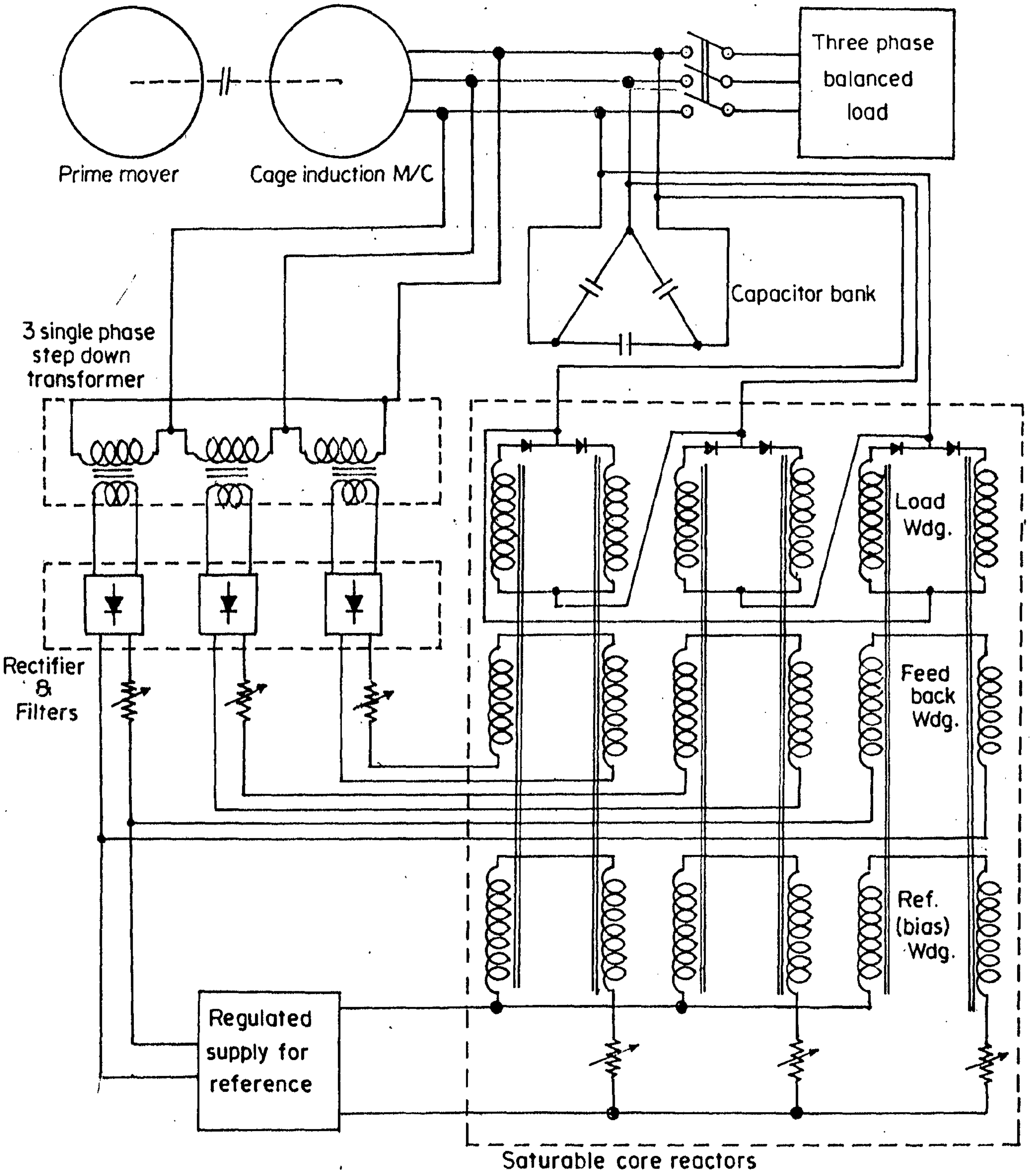


FIG.5.1 SCHEMATIC DIAGRAM OF SELF-EXITED INDUCTION GENERATOR WITH VOLTAGE REGULATOR.

regulator switch is closed, the voltage starts building up due to the large valued capacitor connected at the terminals of the induction machine and the final value of the voltage build up is controlled by the set value of the reference signal. To load the induction generator with voltage regulator, a three-phase resistance bank is used and for reactive load the same is connected in series with three phase variable reactors. A 3 H.P. cage induction motor is used as a dynamic load for loading the system.

To investigate the transient behaviour of self excited induction generator with its voltage regulating system, at constant speed, a 5 H.P., 1500 RPM synchronous motor is used as a primemover and coupled with induction generator. A four channel recorder and a digital storage cathode ray oscilloscope are used to record the transient response of the system at the time of sudden application and removal of different type of loads.

5.3 RESULTS AND DISCUSSIONS

Using test results, the steady state performance characteristics of three-phase self excited induction generator with its developed voltage regulator are shown in Figs. 5.2 to 5.5. The test results shows the variation of terminal terminal voltage of the self-excited induction generator with voltage regulating system under different loading conditions. Figs. 5.6 to 5.8 show the steady state waveforms of load current, capacitor current, saturable core reactor current, generator current alongwith terminal voltage of the generator is presented under different loading conditions of the induction generator.

The phenomenon of the voltage buildup at no-load and loaded condition of the induction generator with voltage regulator is shown in Figs. 5.9(i) to 5.9(ii). In Figs. 5.10 to 5.14, oscillograms of the transient behaviour of this system are shown for sudden application and removal of different types of load and starting of induction motor in terms of different system parameters.

Fig. 5.2 presents the load characteristic of the self-excited induction generator with its voltage regulator, indicating the variation of terminal voltage with output power at rated speed and unity power factor load. From this figure, it may be seen that the developed voltage regulating system is able to maintain constant terminal voltage upto 4.05 KW at unity power factor loads, although, the rated capacity of the generator is only 3.7 KW.

For inductive loads, the variation of terminal voltage with VA output of the induction generator at 0.8 pf and 0.6 pf lagging load is presented in Figs. 5.3 and 5.4 respectively. From these figures, it is observed that for the same VA output of the induction generator, the drop in the terminal voltage at 0.6 pf lagging load is more compaired to the same VA load for 0.8 pf lagging load. A sudden drop in the terminal voltage, above 3.4 KVA in 0.8 pf lagging loads and 3.0 KVA in 0.6 pf lagging loads is observed. It is due to that, the capacitors are required to supply reactive power to induction generator and to load along with the saturable core reactors. But when all the capacitive power is supplied to generator and load, and the saturable core reactor current is almost zero, the voltage regulator looses its control and the system voltage starts dropping beyond its limit.

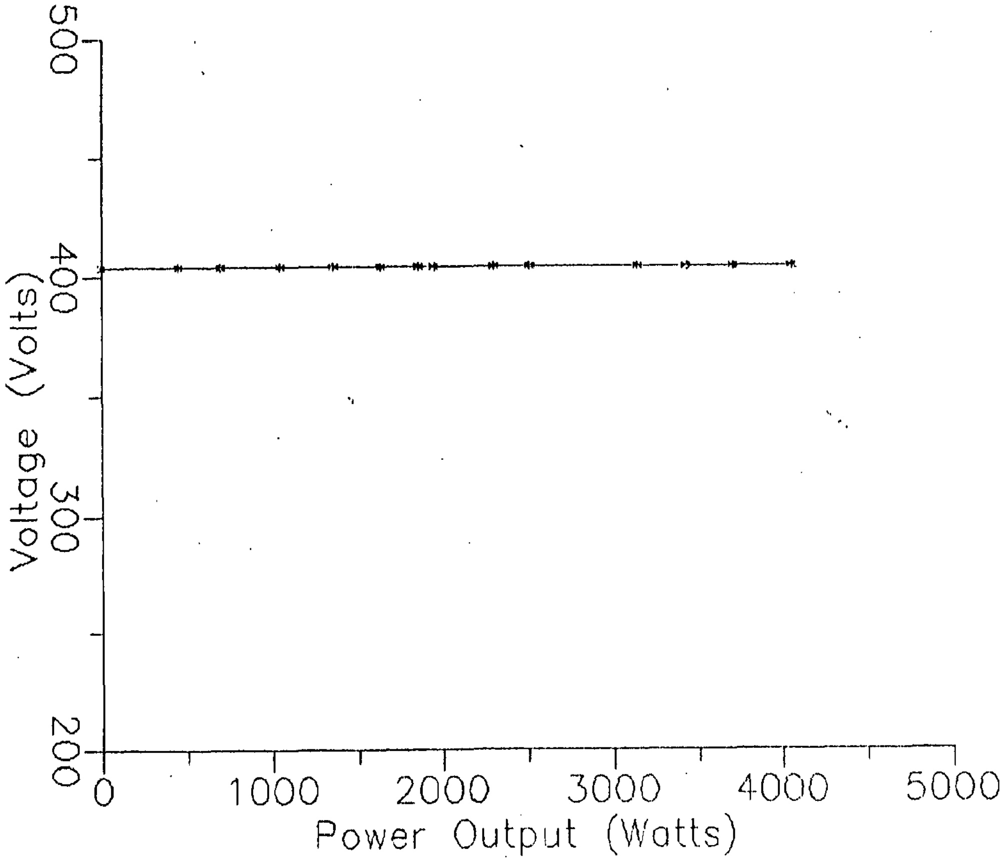


FIG. 5.2 LOAD CHARACTERISTIC OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR RESISTIVE LOADS.

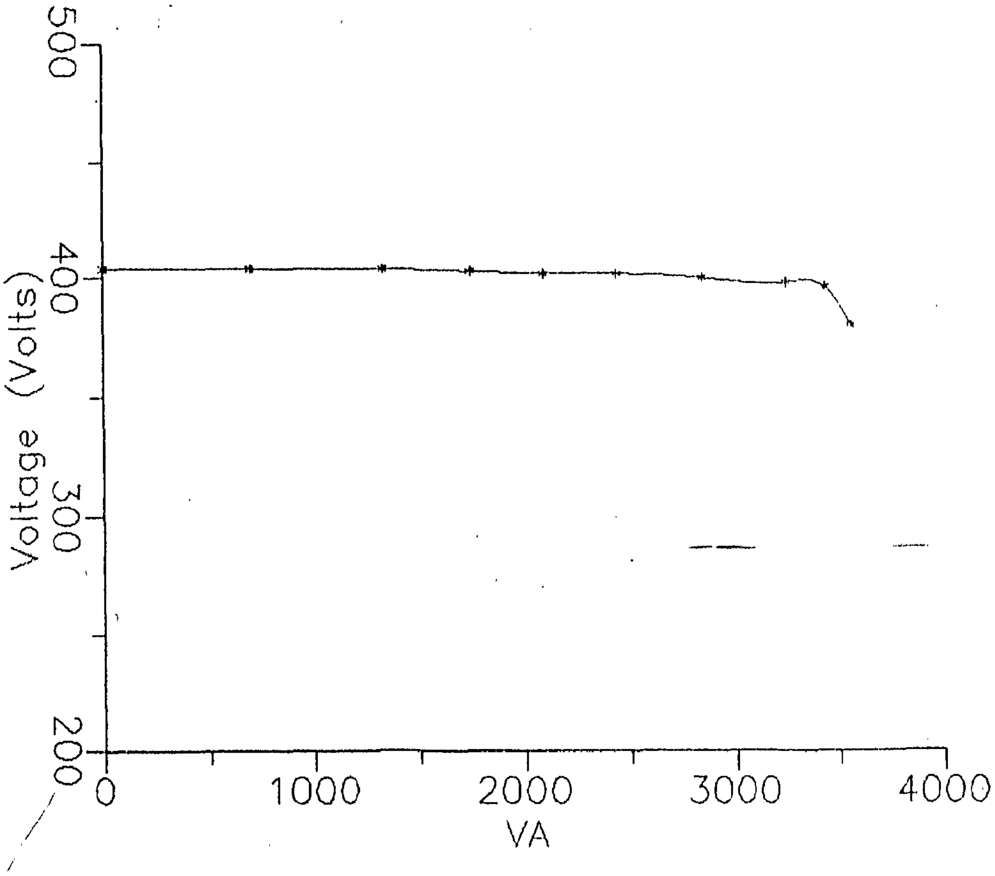


FIG. 5.3 LOAD CHARACTERISTIC OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR 0.8 POWER FACTOR LAGGING LOAD.

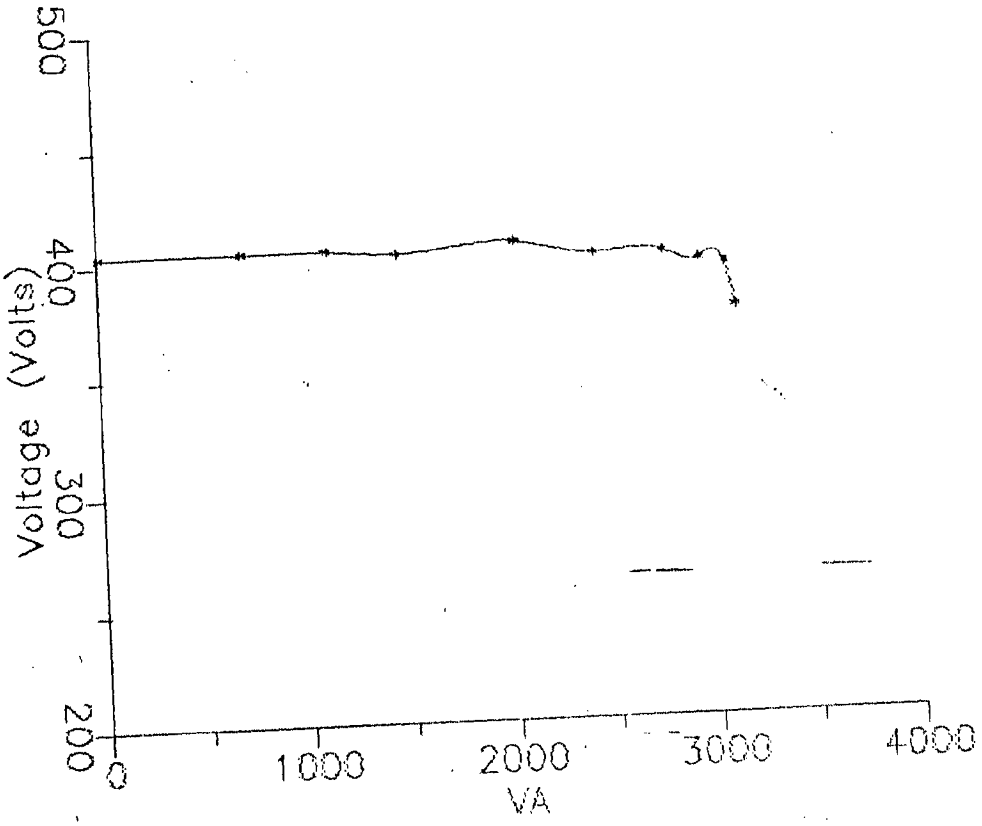


FIG. 5.4 LOAD CHARACTERISTIC OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR 0.6 POWER FACTOR LAGGING LOAD.

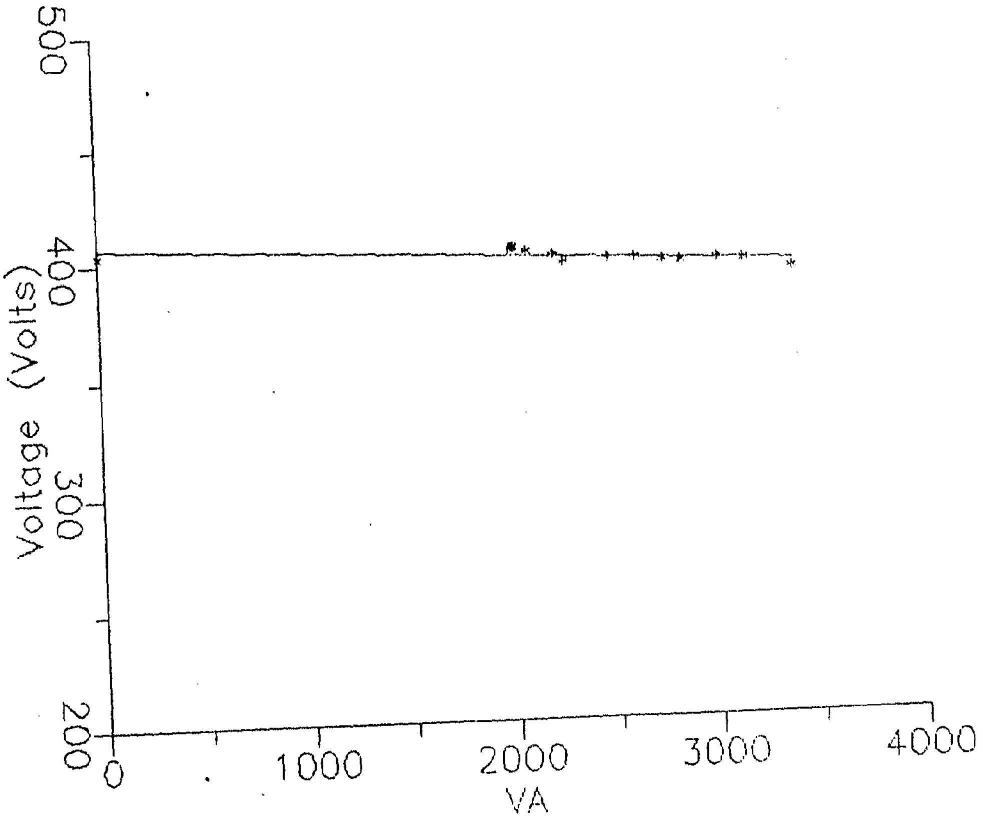


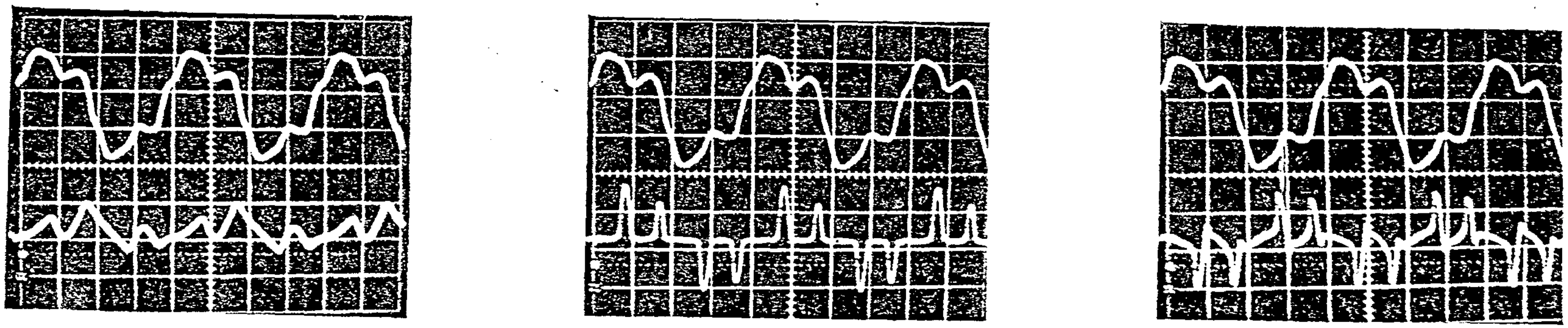
FIG. 5.5 LOAD CHARACTERISTIC OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR INDUCTION MOTOR LOAD.

The variation of terminal voltage with VA output of induction generator for dynamic load (induction motor load) is presented in Fig. 5.5. The induction generator with voltage regulating system is able to start as well as to run a 3 H.P. cage induction motor.

Fig. 5.6 shows the terminal voltage waveform of self excited induction generator with its developed voltage regulator along with stator current (I_G), saturable core reactor current (A_{MA}) and capacitor current (I_C) under steady state at no-load. Steady state terminal voltage of the system along with other system parameters are also presented for resistive and inductive loads in Figs. 5.7 and 5.8, respectively. From these figures it may be observed that the terminal voltage, generator current and loads current under different operating conditions are almost sinusoidal and are free from switching transients.

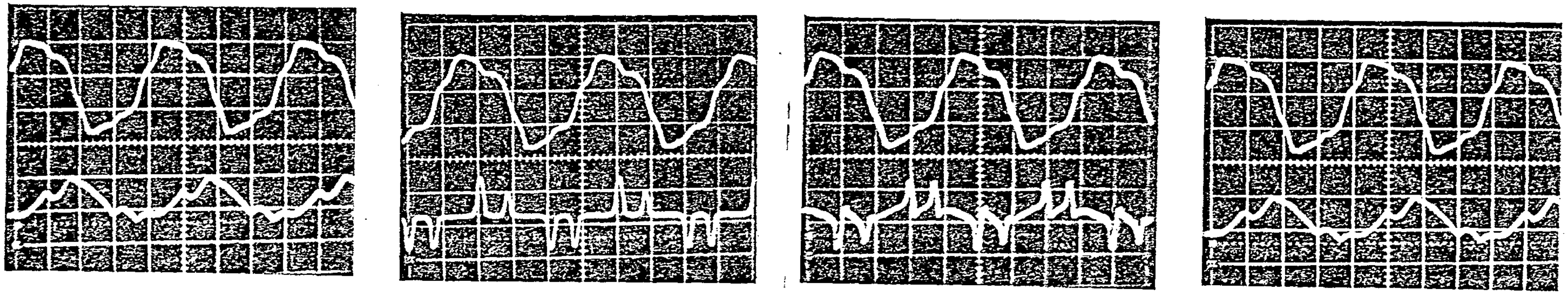
Phenomenon of voltage buildup of induction generator with its voltage regulating system at no-load is shown in Fig. 5.9(i). The same phenomenon of this system having initially resistive load connected is also recorded and shown in Fig. 5.9(ii). It is seen that during the process of building up of voltage, transient rise in the terminal voltage above preset value of the regulator is more in no-load condition compared to loaded condition of the generator.

Transient performance of the induction generator with voltage regulator for sudden application and removal of different types of load is also investigated. Fig. 5.10 shows the variation of terminal voltage (V_t) of the induction generator with voltage



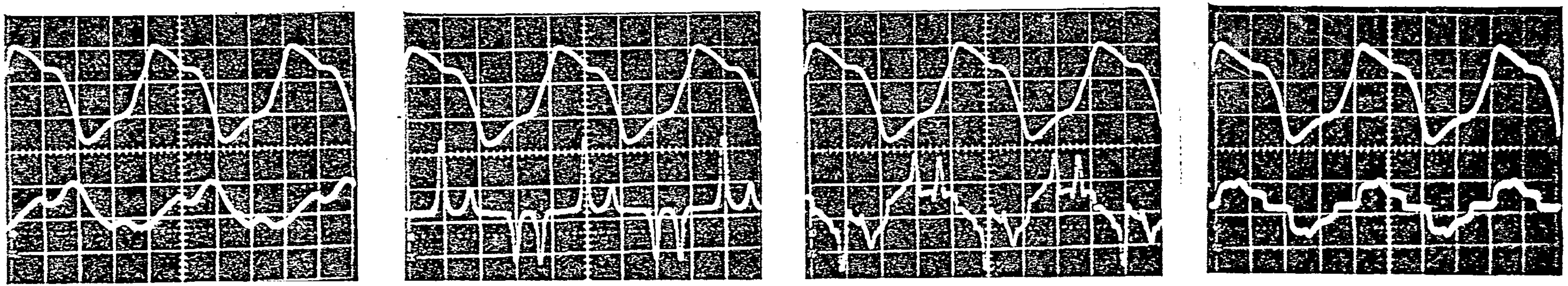
(A) $I_g = 3.7A$ (B) $I_m = 6.9A$ (C) $I_c = 9.9A$

FIG. 5.6 OSCILLOGRAMS OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR AT NO-LOAD OF TERMINAL VOLTAGE (UPPER) AND CURRENT (LOWER) (A) GENERATOR CURRENT (I_g), (B) SATURABLE CORE REACTOR CURRENT (I_m), (C) CAPACITOR CURRENT (I_c).



(A) $I_g = 5.3A$ (B) $I_m = 5.2A$ (C) $I_c = 8.3A$ (D) $I_l = 3A$

FIG. 5.7 OSCILLOGRAMS OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR AT RESISTIVE LOAD OF TERMINAL VOLTAGE ($V_t = 408V$) (UPPER) AND CURRENT (LOWER) (A) GENERATOR CURRENT (I_g), (B) SATURABLE CORE REACTOR CURRENT (I_m), (C) CAPACITOR CURRENT (I_c), (D) LOAD CURRENT (I_l).



(A) $I_g = 6.9A$ (B) $I_m = 2.3A$ (C) $I_c = 7.6A$ (D) $I_l = 2.3A$

FIG. 5.8 OSCILLOGRAMS OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR AT INDUCTIVE LOAD OF TERMINAL VOLTAGE (V_t = 400V) (UPPER) AND CURRENT (LOWER) OF (A) GENERATOR CURRENT (I_g), (B) SATURABLE CORE REACTOR CURRENT (I_m), (C) CAPACITOR CURRENT (I_c), (D) LOAD CURRENT (I_l)

(A) (B)

FIG. 5.9 OSCILLOGRAMS OF BUILDING UP OF TERMINAL VOLTAGE (UPPER) AND GENERATOR CURRENT (LOWER) OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR AT (A) NO LOAD, (B) RESISTIVE LOAD.

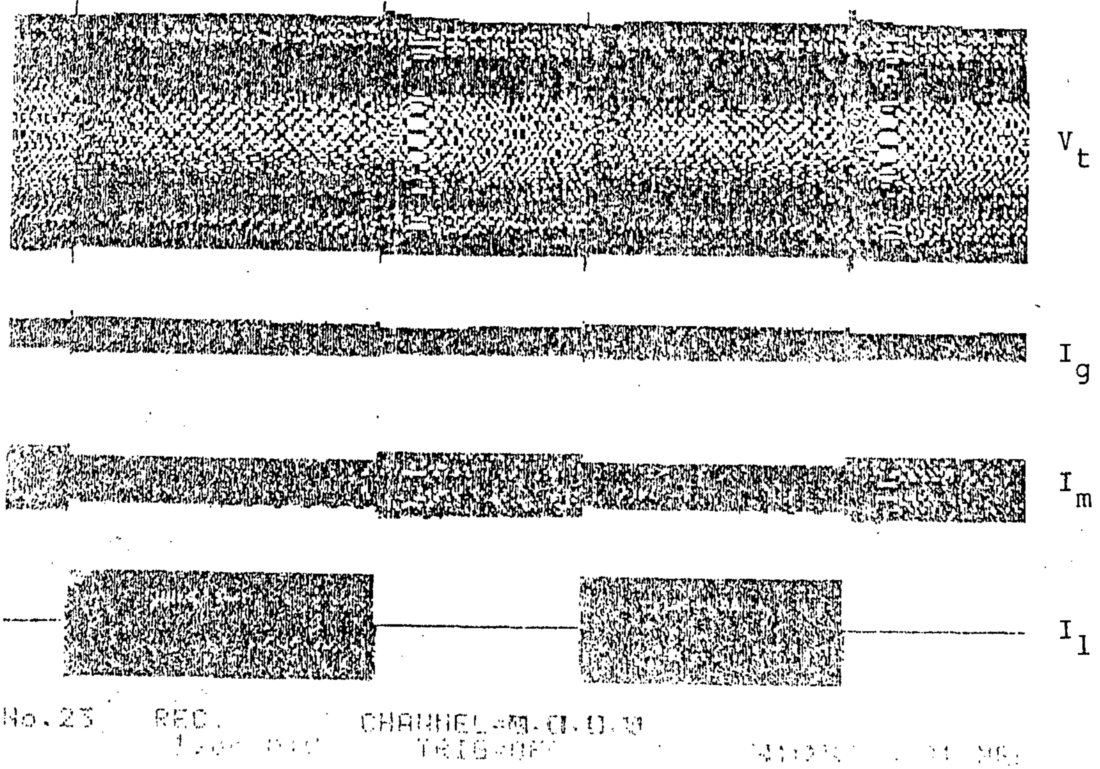


FIG. 5.10 WAVEFORMS OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR SUDDEN APPLICATION AND REMOVAL OF RESISTIVE LOAD (i) TERMINAL VOLTAGE (V_t=408V), (ii) GENERATOR CURRENT (I_g=5.3A), (iii) SATURABLE CORE REACTOR CURRENT (I_m=5.1A), (iv) LOAD CURRENT (I_1=2.9A).

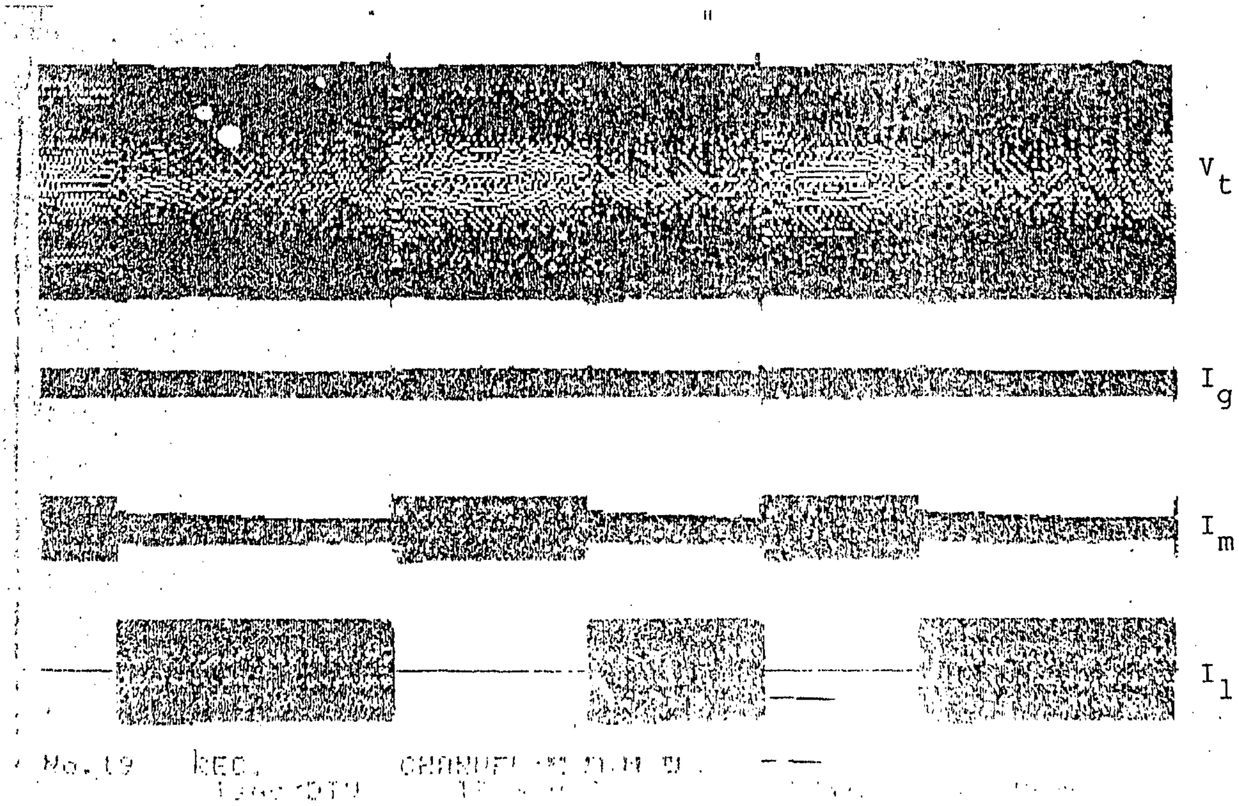


FIG. 5.11 WAVEFORMS OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR SUDDEN APPLICATION AND REMOVAL OF INDUCTIVE LOAD (i) TERMINAL VOLTAGE (V_t), (ii) GENERATOR CURRENT (I_g), (iii) SATURABLE CORE REACTOR CURRENT (I_m), (iv) LOAD CURRENT (I_1).

regulator along with generator current (I_G), saturable core reactor current (I_{MA}) and load current (I_L) for sudden application and removal of 2.05 KW resistive load. At the time of sudden application of load small dip in the terminal voltage and at the time of sudden removal of load small rise in the terminal voltage are observed, but it gets stabilize after a few cycles of generator output supply.

In Fig. 5.11 variation in terminal voltage (V_t), generator current (I_G), saturable core reactor current (I_{MA}) and load current (I_L) of the induction generator with voltage regulator are shown for sudden application and removal of 1.69 KVA inductive load. A sudden change in I_{MA} with the sudden application and removal of inductive load, indicates the shifting of reactive power from saturable core reactor to inductive load and vice-versa respectively.

Starting of 3 H.P. induction motor as dynamic load of induction generator with voltage regulator is shown in Fig. 5.12. At the time of starting of induction motor, required reactive power to the induction motor shifts from saturable core reactors to induction motor, which after starting of induction motor again shifts gradually to saturable core reactors. Though, during this process, terminal voltage remains almost constant.

The starting of 3 H.P. induction motor from the generator with voltage regulator already having 2.05 KW resistive load and 1.7 KW reactive load is showbn in Fig. 5.13 and Fig. 5.14 respectively. In these conditions also, reactive power shifts from the saturable core reactors to induction motor and after starting

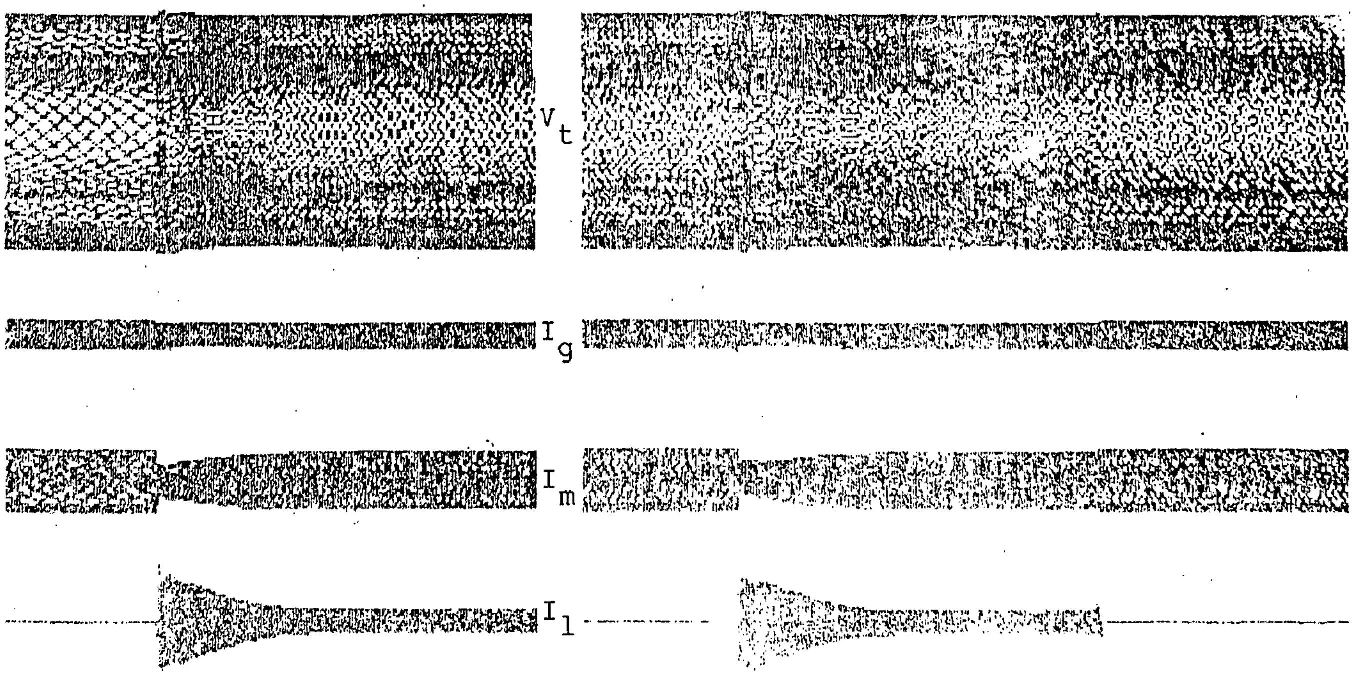


FIG. 5.12 WAVEFORMS OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR SUDDEN APPLICATION AND REMOVAL OF DYNAMIC LOAD (INDUCTION MOTOR LOAD), (i) TERMINAL VOLTAGE (V_t), (ii) GENERATOR CURRENT (I_g). (iii) SATURABLE CORE REACTOR CURRENT (I_m), (iv) LOAD CURRENT (I_1).

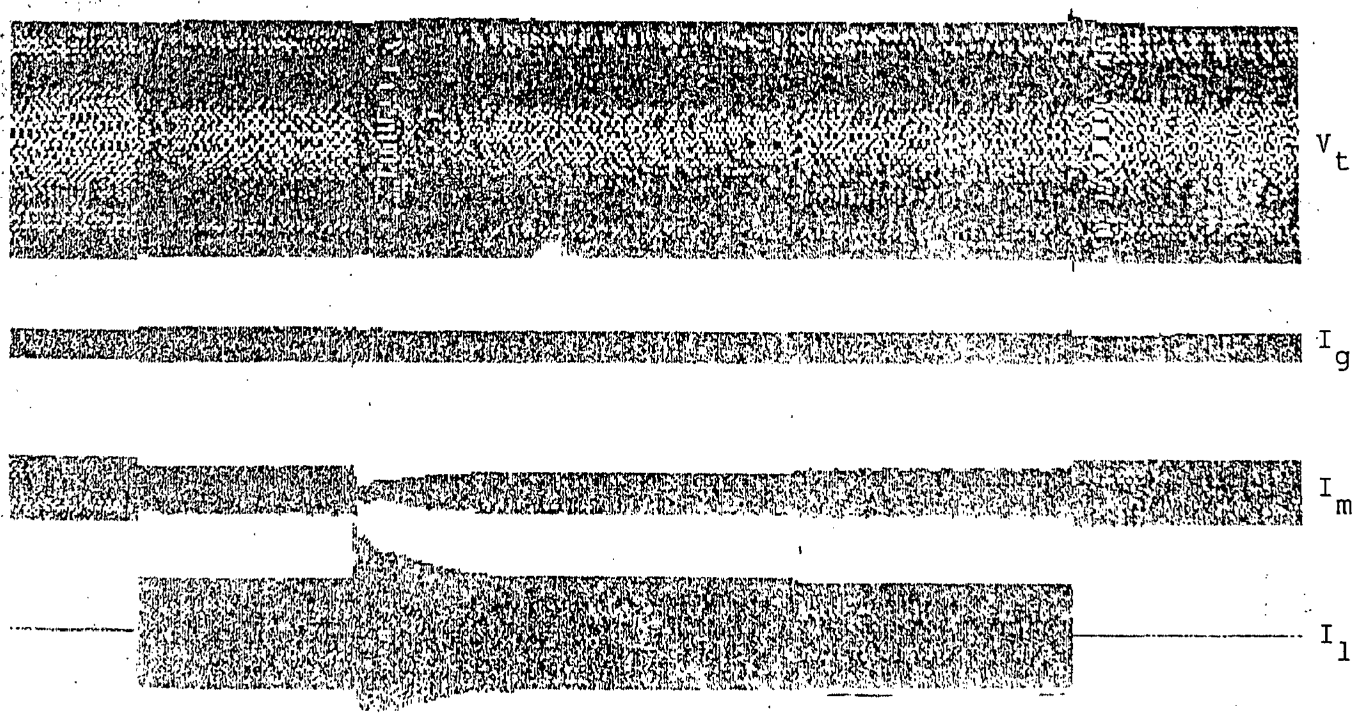


FIG. 5.13 WAVEFORMS OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR SUDDEN APPLICATION AND REMOVAL OF INDUCTION MOTOR WITH RESISTIVE LOAD, (i) TERMINAL VOLTAGE (V_t), (ii) GENERATOR CURRENT (I_g), (iii) SATURABLE CORE REACTOR CURRENT (I_m), (iv) LOAD CURRENT (I_1).

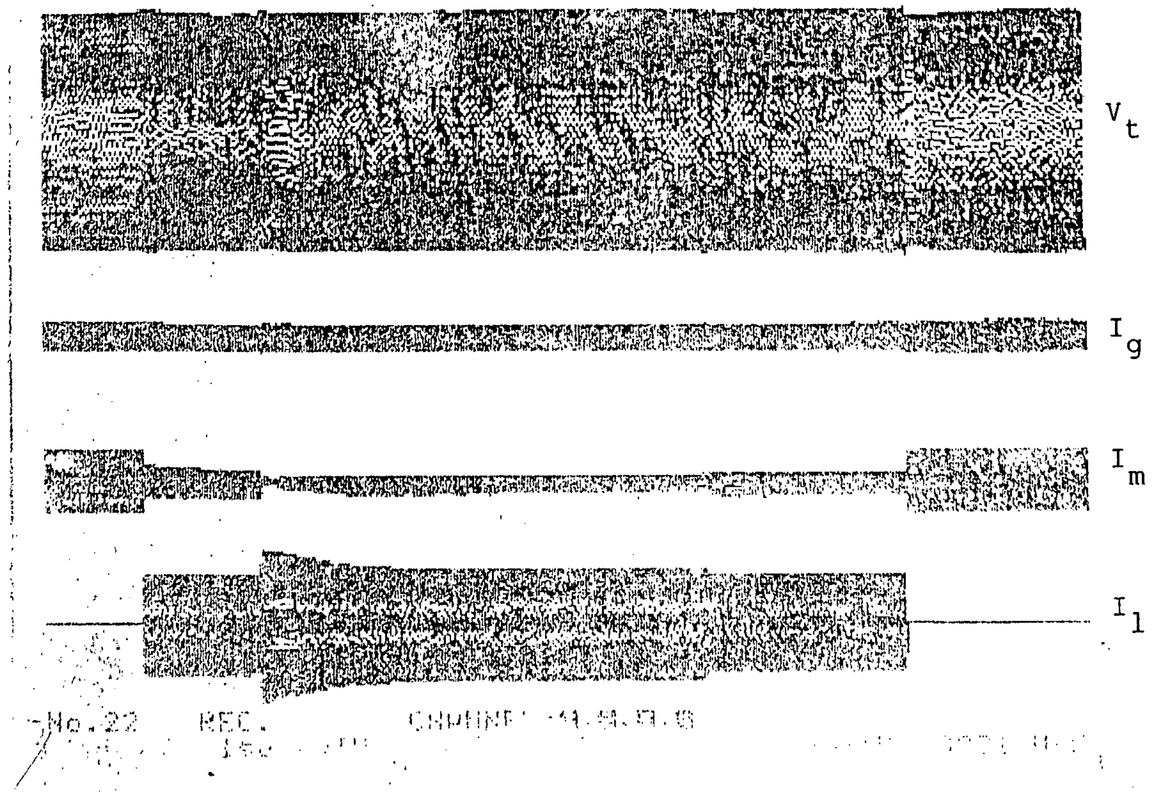


FIG. 5.14 WAVEFORMS OF INDUCTION GENERATOR WITH VOLTAGE REGULATOR FOR SUDDEN APPLICATION AND REMOVAL OF INDUCTION MOTOR WITH REACTIVE LOAD.
(i) TERMINAL VOLTAGE (V_t), (ii) GENERATOR CURRENT, (I_g), (iii) SATURABLE CORE REACTOR CURRENT (I_m), (iv) LOAD CURRENT (I_l).

of induction motor, reactive power gradually shifts back to saturable core reactors. The test results confirms the trouble free starting of induction motor under different loading conditions of induction generator with voltage regulator.

5.4 CONCLUSIONS

Steady state and transient performance of the self-excited induction generator with voltage regulator have been studied for resistive, inductive and motor load. It has been found that the developed voltage regulator is able to maintain constant terminal voltage up to 4.05 KW i.e. more than—rated capacity of generator (3.7 KW). With this system, terminal voltage builds up at rated speed even when load is connected at its terminals. Transient response for sudden application and removal of load shows the good degree of stability and regulation under different loading conditions.

CHAPTER - 6

CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

6.1 MAIN CONCLUSIONS

The main objective of this investigation was to develop a voltage regulator for three-phase self excited induction generator using saturable core reactors. The voltage regulating system has been developed and on the basis of experimental studies over self excited induction generator, the following conclusions are made:

(i) The induction machine starts build up the voltage at no load and rated speed by connecting a capacitor bank of 9.5 μF per phase respectively.

(ii) For a fixed value of capacitance, the terminal voltage of the self excited induction generator drops with its loading. With the four number of capacitor steps, the machine can be loaded upto its rated capacity for unity power factor loads, while maintaining the terminal voltage within ± 5% of rated value.

(iii) It is observed that the machine is capable of developing more than its rated output power for a wide range of voltage at rated stator current and speed with appropriate required capacitors.

(iv) It is also observed that the requirement of capacitor reduces with rise in speed of primemover for a given voltage of the generator.

(v) The voltage regulator with proper feedback circuit has been designed and fabricated. All the three developed saturable core reactors under auto-excited mode have shown the satisfactory identical control characteristic required for the proposed regulator.

(vi) The steady state performance of generator with regulating system results in satisfactory voltage regulation for static as well as dynamic loads.

(vii) It was found that the induction generator with its voltage regulating system is capable of starting as well as running a three-phase cage induction motor along with other static loads.

(viii) At the rated speed, assured voltage buildup phenomenon of the induction generator with voltage regulator was observed.

(ix) Dynamic performance of the generator with voltage regulating system in terms of system parameters e.g. voltage and currents were recorded for sudden application and removal of different type of load, and the response of the system was found satisfactory.

Based on the present investigation, it is concluded that the developed voltage regulator worked satisfactorily under steady state and dynamic loading conditions. With this, it is hoped that this type of robust, cheap voltage regulating system for self-excited cage induction generator will find good applications in harnessing the energy from nonconventional energy sources specially in remote and isolated areas.

6.2 SUGGESTIONS FOR FURTHER WORK

The basic objective of the present scheme have been achieved successfully, but certain problems and new ideas have arisen during the course of investigation. The problems and ideas arisen during the present work may be interesting for further investigations. These are listed as follows:

(i) In the present work voltage regulator has been developed for three-phase self excited cage induction generator. A similar voltage regulator using saturable core reactor may be developed for single-phase self excited induction generator which may be more useful for small scale applications.

(ii) The present voltage regulator has been developed for constant speed primemovers. A voltage regulator using saturable core reactors may also be developed for variable speed primemovers.

(iii) A computer algorithm may be developed to design the voltage regulator directly from the induction machine parameters as input data.

(iv) A simple switched capacitor scheme is possible to maintain the terminal voltage within a permissible specified limit by using under voltage and over voltage relays.

(v) Steady state and transient analysis of the whole system under-different loading condition can be done.

(vi) A comparative study of cost, as well as steady state and transient performance of induction generator using different type of voltage regulating system can be attempted.

(vii) The design of cage machine may also be modified for self excited induction generator operation for higher efficiency and improved voltage regulation.

(viii) For the applications having very wide range of speed of primemovers, the pole changing cage generator with simple voltage regulator may also be considered for investigation.

(ix) A voltage regulator for self excited induction generator of higher capacity and suitable for commercial applications may also be developed.

REFERENCES

1. E.D. Bassett and E.M. Potter, "Capacitive Excitation for Induction Generators", AIEE Trans. (Electrical Engineering), Vol. 54, May 1935, PP. 540-545.
2. C.F. Wagner, "Self-Excitation for Induction Motors", AIEE Trans. (Electrical Engineering), Vol. 58, February 1939, PP. 47-51.
3. B.C. Doxey, "Theory and Application of the Capacitor Excited Induction Generator", The Engineer, Vol. 216, November 1963, PP. 893-897.
4. B.T. Ooi and R.A. David, "Induction Generator/Synchronous Condenser System for Wind Turbine Power", Proc. IEE, Vol.126, No. 1, January 1979, PP. 69-74.
5. J.M. Elder, J.T. Boys and J.L. Woodward, "The Process of Self-Excitation in Induction Generators", IEE Proc., Vol.130, Pt. B, No. 2, March 1983, PP. 103-108.
6. J.E. Barkle and R.W. Ferguson, "Induction Generator Theory and Application", AIEE Trans. (Electrical Engineering), Vol. 13, February 1954, PP. 12-19.
7. E. Erdelyi, E.E. Kolatorowicz and W.R. Miller, "The Limitations of Induction Generators in Constant-Frequency Aircraft Systems", AIEE Trans. (Electrical Engineering), Vol. 77, November 1958, PP. 348-351.

8. Peter Vanderwag and I.I. Inculet, "A.C. Power Generation With a Small Self-Excited Poly-Phase Induction Motor", Proceeding ICEM Lausanne (Switzerland), Sept. 1984, PP. 1200-1202.

9. M.H. Nagrial and A.M. Shami, "Operation of Induction Generators for Wind Mill Applications", Proceeding ICEM Lausanne (Switzerland), Sept. 1984, PP. 213-215.

10. S.S. Murthy, O.P. Malik and A.K. Tandon, "Analysis of Self-Excited Induction Generators", IEE Proc., Vol. 129, Pt. C, No. 6, November 1982, PP. 260-265.

11. Bhim Singh, "Optimum Utilization of Single-Phase Induction Machine as a Capacitor Self-Excited Induction Generator", Electric Machine and Power Systems, Vol. 13, 1987, PP. 73-85.

12. S.S. Murthy, O.P. Malik and P. Walsh, "Capacitive Requirements of Self-Excited Induction Generator to Achieve Desired Voltage Regulation", IEEE Industrial and Commercial Power Systems Conference, Milwaukee 1983.

13. S. Berchten, "Steady State Analysis of Capacitor Self-Excited Induction Generators", Proc. ICEM Lausanne (Switzerland), 18-21, Part-3, Sept. 1984, PP. 1129-1132.

14. Lahcene Ouazene and George McPherson, "Analysis of the Isolated Induction Generator", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-102, No. 8, August 1983, PP. 2793-2798.

15. A.K. Tandon, S.S. Murthy and G.J. Berg, "Steady State Analysis of Capacitor Self-Excited Induction Generators", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-103, No. 3, March 1984, PP. 612-618.

16. A.K. Tandon, S.S. Murthy and C.S. Jha, "New Method of Computing Steady State Response of Capacitor Self-Excited Induction Generator", IE(I) Journal-EL, Vol. 65, June 1985, PP. 196-201.

17. S.S. Murthy, B.P. Singh, C. Nagamani and K.V.V.Satyanarayana, "Studies on the use of Conventional Induction Motors as Self-Excited Induction Generators", IEEE Trans. on Energy Conversion, Vol. 3, No. 4, December 1988, PP. 842-847.

18. S.S. Yegna Narayanan and V.J. Johnny, "Contributions to the Steady State Analysis of Wind-Turbine Driven Self-Excited Induction Generators", IEEE Trans. on Energy Conversion, Vol. EC-1, No. 1, March 1986, PP. 169-176.

19. N. Ammasaigounden, Prof. M. Subbiah and Prof. M.R. Krishnamurthy, "Wind-Driven Self-Excited Pole-Changing Induction generators", IEE Proc., Vol. 133, Pt. B, No.5, Sept. 1986, PP. 315-321.

20. N.H. Malik and S.E. Haque, "Steady State Analysis and Performance of an Isolated Self-Excited Induction Generator", IEEE Transaction on Energy Conversion, Vol. EC-1, No. 3, Sept. 1986, PP. 134-140.

21. S.S. Murthy, H.S. Nagaraj and Ancnie Kuriyan, "Design Based Computational Procedure for Performance Prediction and Analysis of Self-Excited Induction Generators Using Motor Design Packages", IEE Proc., Vol. 135, Part B, No. 1, January 1988, PP. 8-16.

22. J.M. Elder, J.T. Boys and J.L. Woodward, "Self-Excited Induction Machine as a small Low-Cost Generator", IEE Proc., Vol. 131, Pt. C, No. 2, March 1984, PP. 33-40.

23. C. Grantham, D. Sutanto and B. Mismail, "Steady State and Transient Analysis of Self-Excited Induction Generator", IEE Proc., Vol. 136, Pt. B, No. 2, March 1989, PP. 61-68.

24. J.A.A. Melkebeck, "Magnetising Field Saturation and Dynamic Behaviour of Induction Machines, Part-2: Stability Limit of A Voltage Fed Induction Motor and of A Self-Excited Induction Generator", IEE Proc., Part-B, Vol. 130, No.1, January 1983, PP. 10-17.

25. J.A.A. Melkebeck and D.W. Novotony, "Small Signal Dynamic Analysis of Regeneration and Self Excitation in Induction Machines", Electric Machines and Power System, Vol. 8, No. 4-5, July-Oct. 1983, PP. 259-275.

26. D.B. Watson and I.P. Milner, "Autonomous and Parallel Operation of Self-Excited Induction Generators", International Journal of Electrical Engineering Education, Vol. 22, 1985, PP. 365-373.

27. D.W. Novotny, D.J. Gritter and G.H. Studtmann, "Self-Excited in Inverter Driven Induction Machines", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-96, No. 4, July/August 1977, PP. 1117-1125.

28. Bhim Singh, R.B. Saxena, S.S. Murthy and B.P. Singh, "A Single-Phase Self-Excited Induction Generator for Lighting Loads in Remote Areas", IJEEE, Vol. 25, 1988, PP. 269-275.

29. Michael B. Brennen and Alberto Abbondanti, "Static Exciters for Induction Generators", IEEE Trans. on Industry Applications, Vol. IA-13, No. 5, Sept./Oct. 1977, PP. 422-428.

30. George Kontons and Anatony Lytsikar, "Steady State Operation of A Three Phase Voltage Fed Autonomous Inverter", Proc. ICEM Lausanne (Switzerland), 18-21, Part-2, Sept. 1984, PP. 818-821.

31. J. Arrillaga and D.B. Watson, "Static Power Conversion from Self-Excited Induction Generators", Proc. IEE, Vol. 125, No. 8, August 1978, PP. 743-746.

32. D.B. Watson, J. Arrillaga and T. Densem, "Controllable D.C. Power Supply from Wind Driven Self-Excited Induction Machines", Proc. IEE, Vol. 126, No. 12, December 1979, PP. 1245-1248.

33. S.S. Murthy, C.S. Jha, B.P. Singh, C.R. Vidyashankar, C. Nagamani and A.K. Tandon, "Some Studies on Design and Voltage Regulation of Capacitor Self-Excited Induction Generators", Proc. of IEE Conference on Electrical Machines, PP. 180-184.

34. G. Raina and O.P. Malik, "Wind Energy Conversion Using A Self-Excited Induction Generator", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-102, No. 12, December 1983, PP 3933-3936.

35. O.P. Malik, D. Divan, S.S. Murthy, T. Grant, and P. Walsh, "A Solid State Voltage Regulator for Self-Excited Induction Generators", IEEE Industrial and Commercial Power Systems Conference, Milwaukee, May 1983.

36. C.H. Watanabe and A.N. Barreto, "Self-Excited Induction Generator/Force-Commutated Rectifier System Operating as A D.C. Power Supply", IEE Proc., Vol. 134, Pt. B, No. 5, Sept. 1987, PP. 255-260.

37. D.B. Watson and R.M. Watson, "Microprocessor Control of A Self-Excited Induction Generator", International Journal of Electrical Engineering Education, Vol. 22, No. 1, January 1985, PP. 69-82.

38. Ziyad Salameh and Sunway Wang, "Microprocessor Control of Double Output Induction Generator", IEEE Trans. on Energy Conversion, Vol. 4, No. 2, June 1989, PP. 172-176.

39. James D. Bailey, "Factors Influencing the Protection of Small-to-Medium Size Induction Generators", IEEE Trans. on Industry Applications, Vol. 24, No. 5, Sept./Oct. 1988, PP. 955-964.

40. John R. Parsons, "Cogeneration Application of Induction Generators", IEEE Trans. on Industry Applications, Vol. IA-20, No. 3, May/June 1984, PP. 497-503.

41. E.H. Frost-Smith, "The Theory and Design of Magnetic Amplifiers", Science Paperback and Chapman & Hall Ltd., London 1966.

42. M.G. Say, "Magnetic Amplifiers and Saturable Reactors", George Newnes Limited, London, First Edition 1954.

43. Charls S. Siskind, "Electrical Control System in Industry", McGraw-Hill Inc. 1963.

44. William A. Geyger, "Magnetic-amplifier Circuits, Basic Principles, Characteristics and Applications", McGraw-Hill Book Company Inc., Second Edition 1957.