SELF EXCITED INDUCTION GENERATOR FOR PICO HYDRO STATION IN REMOTE AREAS

A

DISSERTATION

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I, **Kailash Rana**, Roll No. **2K16/C&I/10**, student of **M. Tech (Control & Instrumentation)**, here with declare that the dissertation entitled **"Self Excited Induction Generator for Pico Hydro Station in Remote Areas",** under the supervision of **Sh. D C Meena**, Electrical Engineering Department, Delhi Technological University, in partial fulfilment of the need for the award of the degree of Master of Technology, has not been submitted elsewhere for the award of any degree.

I here with solemnly and sincerely affirm that all the particulars declared above by me are true and correct to the best of my knowledge and belief.

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CERTIFICATE

This is to certify that the dissertation entitled **"Self Excited Induction Generator for Pico Hydro Station in Remote Areas"**submitted by **Kailash Rana** in completion of major project dissertation for the master of Technology degree in **Control & Instrumentation** at Delhi Technological University is an authentic work carried out by him underneath my superintendence and guidance.

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ABSTRACT

The increasing use of renewable energy sources such as wind energy, solar energy, bio gas energy and small hydro energy have gained success in rural electrification which has potential and competence of operating in the remote and hilly areas with very low cost generating system. With wind turbine and micro/mini hydro generators as an alternative source of energy it can deliver electricity to millions of people and improve life standard and create jobs where the extension of grid require a huge investment in infrastructure because of its very cost effective and decentralize system. The induction motor is the widely used electric machine which can work reversible and operate as induction generator for autonomous operation.

The self excited induction generator (SEIG) are found to be most suitable for electrification rural isolated areas using locally available renewable energy because of its advantages well known.

This report focuses on the dynamic study of SEIG-self excited induction generator which is driven by a constant stable torque from hydro turbine is done with the help of MATLAB/SIMULINK software to predict and analyze the performance characteristic of SEIG under different conditions, this thesis aims to study the work done by researchers in evaluating and analyzing the characteristic performance of SEIG-self excited induction generator and its operation under different conditions which includes process of self-excitation, different kind of loading, Reactive Compensation with series capacitor technique and SEIG with electronic load controller(ELC) technique.

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Q	Discharge (m^3)
H	Head (m)
P	Power (kW)
η	Efficiency
N_{sp}	Specific speed
f_r	Rotor frequency (Hz)
J	Moment of Inertia of the rotor (Kgm^2)
P	Number of poles pairs
T_m	Mechanical Torque from the generator shaft (N.m)
T_e	Electomagnetic Torque (N.m
ω_m	Rotor Mechanical Speed
i_s	Stator Current (A)
i_r	Rotor Current (A)
V_s V_r	Stator and Rotor voltage (v)
λ_s λ_r	Stator and Rotor Flux linkages (wb)
R_s R_r	Stator and Rotor winding resistances (Ω)
ω	Arbitrary reference rotating speed (rad/sec)
p	Derivative operator
f_s	Stator frequency (Hz)
L_s L_r	Stator and Rotor self Inductance (H)
L_{ls} L_{lr}	Stator and Rotor leakage inductance (H)
L_m	Magnetizing Inductance (H)
v_{ds} v_{dr}	d- axis stator and rotor voltage
v_{qs} v_{qr}	q-axis stator and rotor voltage
λ_{ds} λ_{dr}	q-axis stator and rotor flux linkage
i_{ds} i_{qs}	d-q axes stator current

$i_{Ld}\, i_{Lq}$	d-q load current
$R_l L_l$	Load resistance and load inductance

ABBREVIATIONS

AC	Alternating Current
CDM	Clean Development Mechanism
CSCF	Constant Speed Constant Frequency
d-axis	Direct axis
DC	Direct Current
ELC	Electronic Load Controller
GCIG	Grid Connected Induction Generator
GHG	Green House Gas
IGBT	Insulated Gate Bipolar Transistor
IVFC	Integrated Voltage and Frequency Controller
KW	Kilowatt
MERS	Magnetic Energy Recover Switch
MW	Megawatt
PAT	Pump as Turbine
q-axis	Quadrature axis
ROR	Run Off River
SEIG	Self-Excited Induction Generator
SHP	Small Hydro Power
SVC	Static VAR Compensator
VSCF	Variable Speed Constant Frequency

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The increasing concern for fast depletion of fossil fuels, the uncertainty in oil prices, growing need of energy demand and the need for low generation cost and environmental problems (emission of harmful greenhouse gases resulting into global warming), have motivated world towards the use of other alternatives and sustainable source such as biogas, solar, wind and pico/micro/mini/small hydro energy for harnessing abundance renewable energy which are easily available in the nature to meet ever-increasing energy demand. The generation of electrical energy has been mainly dominated at this time by conventional sources such as Thermal, Nuclear etc.to meet the increasing demand for energy and also to provide electricity to the remote rural areas where the extension of grid is unfeasible and not economical.

Most of population which are living in remote isolated rural or off grid areas do not have electricity, to provide electricity in these areas is a challenging task which require a huge investment cost and infrastructure, it is therefore convenience utilizing the available renewable energy to provide them with decentralized energy system like distributed generation or hybrid system etc. The non-conventional energy sources like biomass, wind, solar and small hydro can be used. Pico/mini/micro/small hydro schemes can be easily developed for generating power in hilly areas having continuing sources of water and can be catered to match the electricity demand of villages. Such schemes requires electro-mechanical energy conversion system in which kinetic energy available in water for hydro system is converted to rotational mechanical energy with the help of prime mover and the prime mover is coupled with the generator which drives the generator and produce electricity.

Earlier synchronous generator has control over the generation of electricity but with the advantages associated with induction generator like rugged can resist rough condition, low maintenance cost, low cost of operation, brushless low cost, self-protection against short-circuit, and it has ability of generating power at different range of speed, it emerge and become more applicable and suitable in the field of renewable energy. Induction generator requires external source for excitation to generate a rotating magnetic field, the necessary needed reactive power for excitation can be supplied by a capacitor connected to the stator terminal in this mode it is known as self excited induction generator and reactive power can be supplied from the grid in this mode it is known as grid connected induction generator .

1.2 SMALL HYDRO POWER (SHP)

Hydropower is the main source of renewable energy in the world which contributes about 88% of the world renewable electric power and 19% of the world electricity generation, it is cost effective, reliable source and has longer lifespan up to 50 years.

Hydropower generation is carried out by small scale and large scale, but there are many social and environmental problems related to large scale hydropower like high capital cost, , submergence of land which affect the community nearby the project and causes losses of their properties, heritage, archeological and spiritual sites, which will eventually causes displacement and resettlement of people, rehabilitation and geographical disturbance is associated.

Small hydropower is an appropriate solution to all drawbacks related to large hydropower projects, and it overcomes the major environmental and social problems. It can be easily installed with negligible effect on the environment, also it comes under clean development mechanism (CDM) because they do not consume any fuel so it reduces emission of greenhouse gasses, and it also reduces electricity cost. In comparison with other renewable sources it has the best payback and higher energy conversion efficiency. Small hydropower is also supported and provided incentive by the Governments and international bodies to motivate and attract the investment for the development of SHP-small hydropower.

Small hydropower is significant for remote, rural, off-grid isolated areas because most of the untapped small hydro potentials are in the remote areas and extension of grid in these areas is not feasible. Small hydropower development helps in rural electrification of remote and inaccessible villages and improves economic as well as living conditions of the people in the areas. Small hydropower development has many administrative and technical barriers and challenges like clearances and approvals.

1.2.1 Definition of Small Hydropower

Different Countries have different norms for defining the small hydropower capacity worldwide, small hydropower lies between 1.5 MW -50 MW the following table shows the rating capacity of SHP for different countries. Table 1 shows the capacity of SHP around the world.

Table 1: Definition of Small hydropower (SHP) by Country (MW)

Country	**Capacity (MW)**
Sweden	≤ 1.5
Norway	≤ 10
European Union	≤ 20
India	≤ 25
Brazil	≤ 30
Canada	≤ 50
China	≤ 50
USA	5-100

1.2.2 Classification of Small Hydropower (SHP) Schemes

India has a century old history of Hydro power and the first plant was the small hydro which has the capacity of 130 kW commissioned in 1897, Small hydro power in India is categorized according to Ministry of New and Renewable Energy (MNRE) which is responsible and incharge for all developing projects up to 25 MW as given table 2.

Hydro power can be classified or categorized on different characteristics and basis, some of the basis areas follows:

(i) Based on Head.

(ii) Based on Capacity.

(iii) Based on Hydraulic Characteristics.

(iv) Based on its Turbine Characteristics.

(v) Based on Load Characteristics.

(vi) Based on its Interconnection

Table 2: Classification of Small Hydropower (SHP) based on its capacity

Type	**Station Capacity**
Pico	Up to 5 kW
Micro	Up to 100 kW
Mini	101 kW- 2000 kW
Small	2001 kW- 25000kW

1.2.3 Advantages of Small Hydropower

Small hydro plants have a number of benefits over other sources of power generation few of them are listed below.

(i) Small hydropower does not consume or use any fuel for the generation of electricity so it is renewable.

(ii) Small hydropower has low GHG emission and low carbon foot print, so reducing the amount of carbon in the atmosphere, and less effect on the environment in comparison with conventional sources.

(iii) Small hydropower improves life standards by providing electricity to rural population, creating jobs and development of small scale industries also alleviate property.

(iv) Small hydropower did not require any high investment which can easily be affordable by private/local entrepreneurs because of quicker returns benifit, short development period and cheapest operating costs due to low overheads.

1.2.4 Potential Estimation

Hydropower works on the principle of energy conversion in which it converts kinetic energy available in flowing water from higher elevation to lower elevation, to mechanical energy through hydro turbine, this hydro turbine is connected to generator in which this mechanical energy drives the generator in power house and generates electricity. The difference in higher and lower level is called head which is naturally present in rivers and waterfalls or it can be formed artificially by building canals and dams.

The hydropower potential is based upon the head availability (H) and flowing discharge (Q), the hydro potential at turbine shaft and can be calculated from the following equation given as .

$$P = \eta \rho g Q H \quad (1.1)$$

Where, P = mechanical power produced (kW)

η = turbine hydraulic efficiency.

ρ = density of water (kg/m^3).

g = gravity acceleration (m/s^2).

Q = quantity of flowing water through the hydraulic turbine (m^3/s).

H = Available head in meters (m)

While, input torque can be calculated by the following equation

$$T = \frac{P}{\omega} \tag{1. 2}$$

Where,

ω = angular velocity of turbine runner (rad/s)

1.3 TYPES OF HYDROPOWER SCHEMES

The most common small hydro schemes are listed below

a. Run off river scheme.
b. Canal falls scheme.
c. Dam based scheme.
d. Pumped storage scheme.

These schemes are differ in their water availability, some scheme require storage of water or some uses the stream as it comes. The storage of water can be done by diverting a small portion of river or a reservoir is created by building a dam across the river.

1.4 HYDRAULIC TURBINES

The hydraulic turbine is consider to be the heart of hydropower plant, and it may be defined as hydraulic machines which converts the potential energy of flowing water available due to head difference to mechanical energy then utilize this mechanical energy to drive generator power station coupled via gearbox or coupled directly to the shaft.

Following classification of Hydro Turbines are given below :

1. According to the water flow over turbine blade/ bucket/ van

(i) Impulse Turbines (Pelton, Turgo Impulse)

(ii) Reaction Turbines (Francis, Axial flow turbines)

2. According to head and discharge

(i) High head & low discharge (Pelton, Turgo Impulse)

(ii) Medium head & medium discharge (Francis Turbine)

(iii) Low Head & high discharge (Axial flow turbines)

3. According to direction of flow over the runner

(i) Tangential flow turbine (Pelton Turbine)

(ii) Radial flow turbine (Old Francis, Turgo Impulse)

(iii) Axial Flow turbine (Kaplan, Semi -Kaplan, Propeller)

(iv) Mixed flow turbine (Modern Francis)

4. According to the direction of the shaft

(i) Horizontal shaft

(ii) Vertical shaft

(iii) Inclined shaft

5. According to the specific speed

(i) Up to 35 (PeltonTurbine)

(ii) from 30 –80 (Tugo Impulse Turbine)

(iii) from 80 –400 (Francis Turbine)

(iv) from 340 –1000 (Axial flow turbines)

1.4.1 Impulse Turbine

In impulse turbine all the hydraulic energy available in water is transformed into kinetic energy by a nozzle and the jet produced by this nozzle is made to strikes the runner blades. Impulse turbine is an open turbine and operates under the atmospheric pressure, in this type of turbine energy is available initially in form of potential energy and this potential energy is transformed into kinetic energy using one or more nozzles which are in the form of water jet and before the water enters into the runner and strikes the buckets of the turbine causing rotation of turbine runner using impulse force. Turgo-Impulse and Pelton comes under this category.

1.4.2 Reaction Turbine

In reaction turbine only certain quantity of the available hydraulic energy is transformed into kinetic energy before the fluid enters the runner. Reaction turbines are fully submerged in water and it is differ from impulse because in this type the energy in the water is not converted completely into kinetic energy but certain part of it is transformed to kinetic energy and the remaining other part is converted into pressure energy**.** Francis, Kaplan semi Kaplan and propeller comes under this category.

1.5 INDUCTIONMACHINE

The induction machine was invented by Nikola Tesla in 1888. It is an AC electro-mechanical energy conversion device, like other different rotating machines they can operate as motor or as generator. It is available from small horsepower ratings to megawatt levels .

The 3-phase induction motor comprise of two main part the stationary part (fixed) and rotating part. Stationary part is called as stator and the rotating part is called as rotor, each of these are consisting of three windings which are 120º angle apart from each other to form a three phase winding.

There are two types of induction rotor:

(i) Squirrel cage rotor.

(ii) Slip ring or wound rotor.

In squirrel cage rotor type the rotor winding mainly comprises of un-insulated conductors in the form of aluminum and copper bars embedded in semi-closed slots.

These bars are fixed at ends electrically and mechanically by the use of rings. About 90% of induction machines (IM) have squirrel cage rotor construction. This construction resembles and looks like a squirrel cage.

The squirrel-cage rotor figure is shown in fig (1.1). The squirrel-cage rotor construction is very simple, robust and maintenance free, due to simple construction rotors are low priced or cheap.

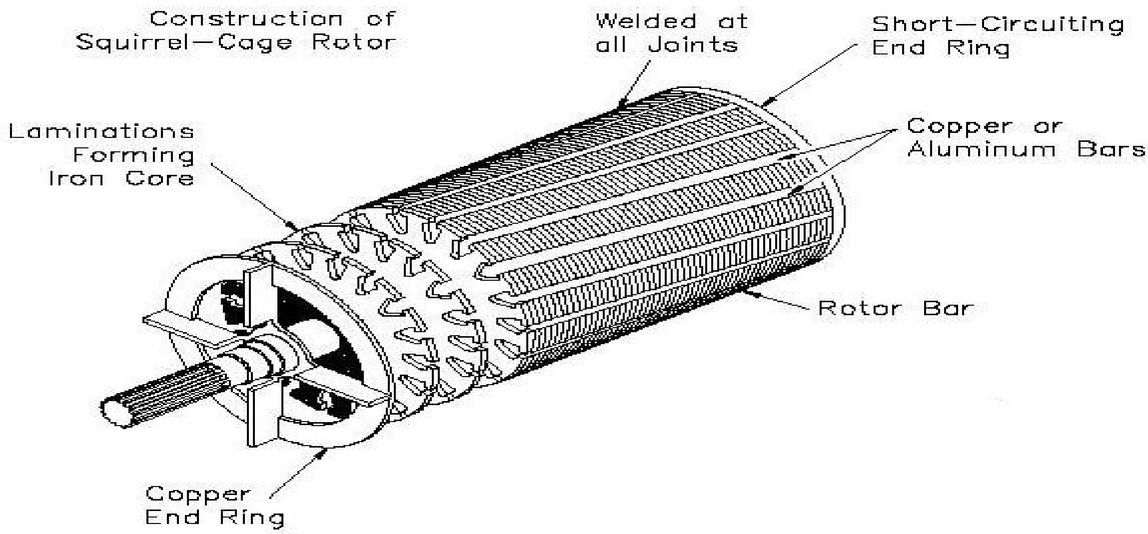

Fig 1.1. Squirrel Cage Rotor

In slip-ring or wound rotor type the rotor slots accommodate an insulated distributed winding which is identical to that used on the stator. The wound rotor is the other form of squirrel cage rotor in which the stator is same as that of squirrel cage.

The rotor has slip rings and rotor windings. The slip-ring or wound rotor costs more and its construction is complex and frequent regular maintenance is necessary. The wound rotor or slip-ring is shown in fig (1.2)

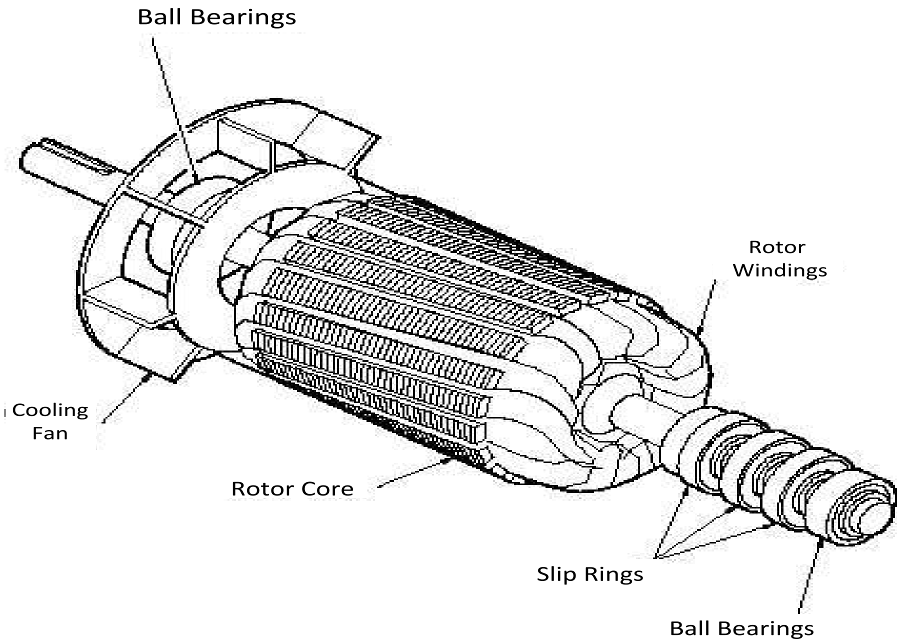

Fig 1.2 . Wound rotor

1.5.1 Working Principle of Induction Motor

When three-phase supply is connected to stator winding of a three-phase induction motor, current flow through the winding and it will cause a rotating magnetic field of constant magnitude to set up. This rotating magnetic field will rotate with synchronous speed which is given in equation no.(1.3)

$$N_s = \frac{120\ f}{p} \tag{1. 3}$$

Where, f = supply frequency (Hz)

p =number of pair poles of stator winding.

It works on the principle of electromagnetic induction, by Faraday's law of electromagnetic induction an electromagnetic force (EMF) is induced in the rotor conductors, since the rotor conductor are short circuited with external resistance in wound rotor or with end ring in cage rotor, the induced EMF causes a current to flow in the rotor conductor, the directional flow of the induced current can be determined by right hand thumb rule.

The current in the rotor conductor generates or produces its own magnetic field, the direction of this force and force produced on the rotor conductor can be determined by left hand thumb rule. The force acting on the rotor conductor is in the same direction as of the rotating magnetic field (RMF), this force will act on tangential direction and develops a torque.

By Lenz's law the direction of induced current in the rotor is so as oppose the cause to produce it, this way the developed torque must opposes the cause, and it will lead to reduce the relative speed between rotating magnetic field (RMF) and the rotor conductors.

The difference between the rotating magnetic field and speed of rotor is known as slip .

$$\text{Slip speed} = N_s - N_r \qquad (1.4)$$

Where : N_s = synchronous speed (rpm)

N_r = actual rotor speed (rpm)

The slip express as fractional slip

$$S = \frac{N_s - N_r}{N_s} \qquad (1.5)$$

And percentage slip

$$\%S = \frac{N_s - N_r}{N_s} * 100 \qquad (1.6)$$

Also we know $f_r = s \ f_s$ (1. 7)

Where, f_r = rotor frequency

f_s = stator frequency

1.5.2 Operation Mode of Induction Machine

The induction machine will operate as motor, generator or brake it will depends on the value of the slip . The induction machine will work as motor when the speed of rotor is below synchronous speed at positive slip ($0<S<1$), and it will works as generator when rotor speed is above synchronous speed at negative slip ($S<0$). And when the slip value is more than one ($S>1$) the induction machine will work as a brake.

1.5.3 Classification of Induction Generator

On the basis of construction of rotor, the induction generators are two types (squirrel cage induction generator and wound rotor induction generator). Based on the prime movers used (variable speed or constant speed). And based on the excitation modes (Self-excited induction generator (SEIG) & Grid-Connected induction generator (GCIG)), Induction generator can be broadly classified into:

(i) "Constant Speed constant frequency (CSCF)".

(ii) "Variable Speed constant frequency (VSCF) .

(iii) Variable Speed variable frequency (VSVF) .

1.6 CLASSIFICATION BASED ON EXCITATION

Induction generator based on excitation can be classified as follow:

(i) Grid-Connected Induction Generator (GCIG)

(ii) Self Excited Induction Generator (SEIG)

1.6.1 Grid Connected Induction Generator (GCIG)

In grid-connected induction generator the induction generator is connected to grid having constant voltage and frequency (infinite bus bar), when prime mover rotates with speed more than the synchronous speed than supply the grid with active power known as grid-connected induction generator (GCIG).

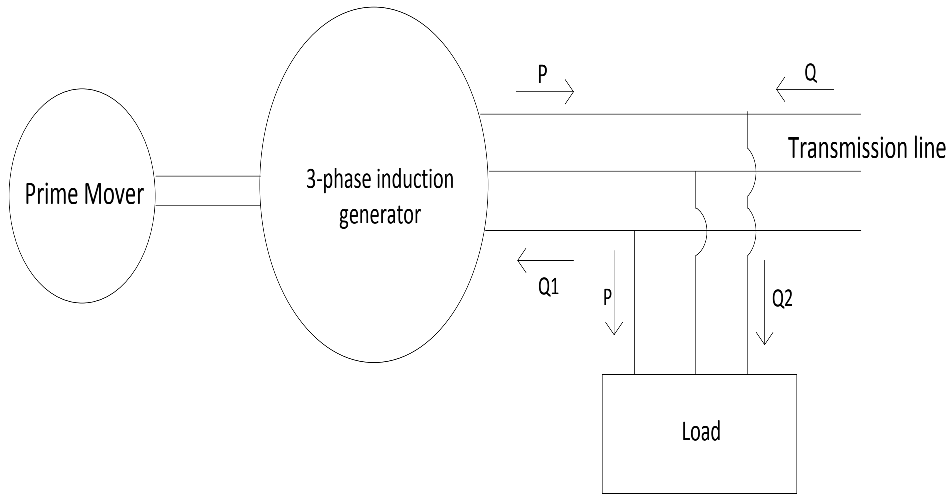

Figure-1.3 Grid-connected Induction generator

The induction-generator draw reactive power from the grid which is equal to supplying leading reactive power to the grid, and the grid modulate the frequency and the voltage of the induction generator.

1.6.2 "Self-Excited Induction Generator (SEIG)"

"In Self-excited induction generator the needed reactive power for excitation is supplied by a capacitor bank which is connected across the stator terminals, it did not requires external grid to draw magnetizing reactive power, the schematic connection diagram of self excited induction generator is displayed in fig.1.4.

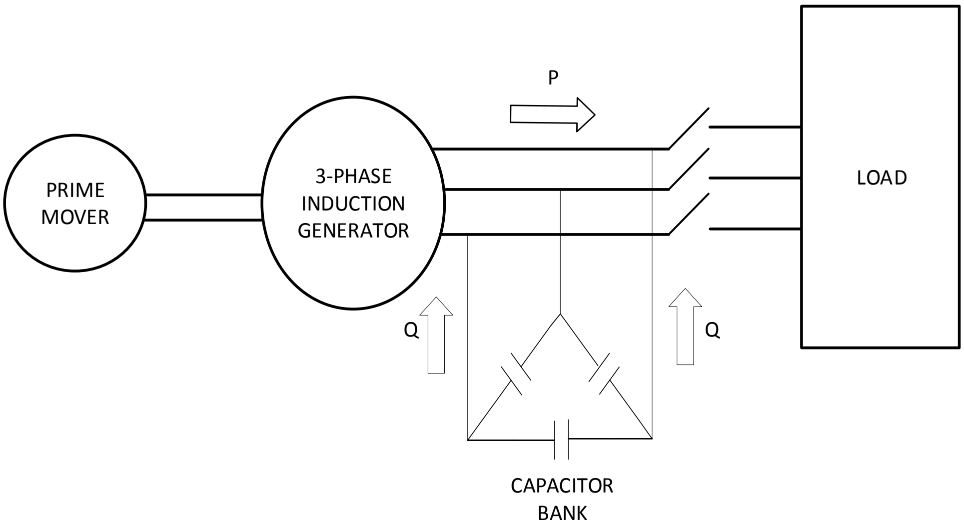

Fig 1.4. Connection diagram of self excited induction generator

There should be sufficient speed needed and excitation capacitance required to excite the machine and to operate machine under no load or loading condition.

Reactive power required for excitation and maintaining the terminal voltage is shown below

Q = Q_1 (Reactive power needed by three-phase induction generator) +

Q_2 (Reactive power needed by the load).

1.7 MERITS AND DEMERITS

Self Excited Induction generator offer several advantages because of following merits associated.

(i) Simple & rugged construction.

(ii) Low cost & reliable.

(iii) Maintenance & operational simplicity.

(iv) DC supply not required for excitation.

(v) Protected against fault short circuit.

(vi) At varying speed capability to generate power.

Following are demerits of SEIG

(i) Poor voltage regulation.

(ii) Poor frequency regulation.

(iii) Without reactive power source it cannot operate independently.

1.8 CONTROL TECHNIQUES

In case of Self-Excited induction generator, the main disadvantage/drawback is its bad voltage regulation as being a standalone/isolated generating system it is very difficult to maintain balance in reactive power transfer, so with variation of load there is change in voltage and frequency, since the frequency depends on capacitance needed for self excitation, speed of prime-mover and load. There are many control techniques for improving voltage regulation as Electronic load controller (ELC) with dump load, reactive power compensation with capacitance switching, Voltage source inverter (VSI), using FACTS devices etc. In this dissertation reactive compensation using series capacitance and Electronic load Controller with dump load is analyzed.

1.8.1 Reactive power Compensation using Series Capacitor

Induction generator needs reactive power to initiate voltage build-up and hence proper generation. In case of standalone/Isolated system like wind power generation, Micro/Mini –hydro power generation where grid supply is not available a capacitor bank is employed to supply reactive power to generator and also load and in case of system connected with grid the induction generator draw this needed reactive power from grid. If the required needed reactive power by the induction generator is not fulfill than no voltage will buildup in the induction generator as it requires needed reactive power to maintain rotating magnetic and helps in voltage buildup. So proper selection of capacitance is most important for voltage buildup.

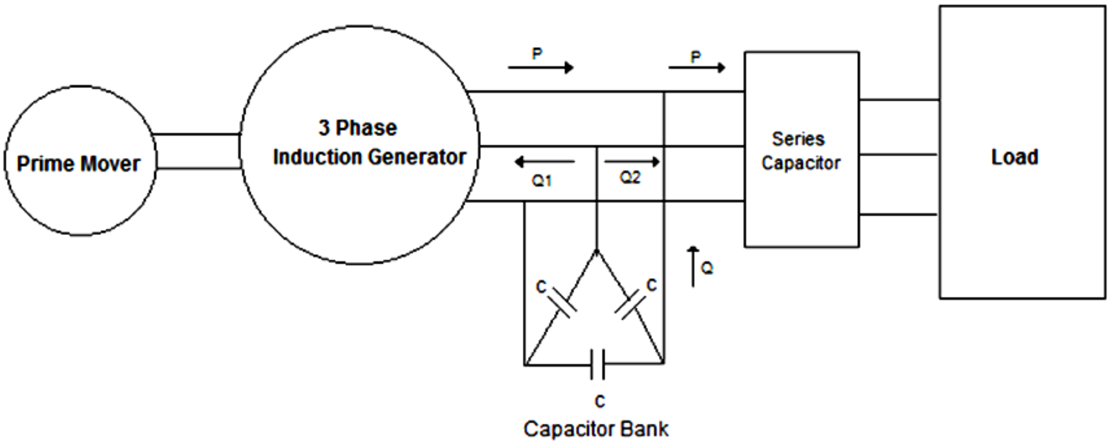

Fig 1.5 Reactive Compensation with Series Capacitor

1.8.2 SEIG with Electronic Load Controller

Self Excited Induction Generator (SEIG) for isolated/standalone mode of operation can be used with Electronic Load Controller (ELC) with proper auxiliary dump load, where ELC-load controller is used to disconnect and connect the dump load through the operation of the system. The Isolated SEIG with ELC is shown below in fig (1.6).

In this SEIG with ELC- Electronic Load Controller system comprises of self excited induction generator which is driven by prime mover and the excitation capacitor are connected across the induction generator stator terminals. The dump-load is also connected through ELC in parallel with consumer load, with proper and appropriate operation of ELC the output power of self excited induction-generator is maintained.

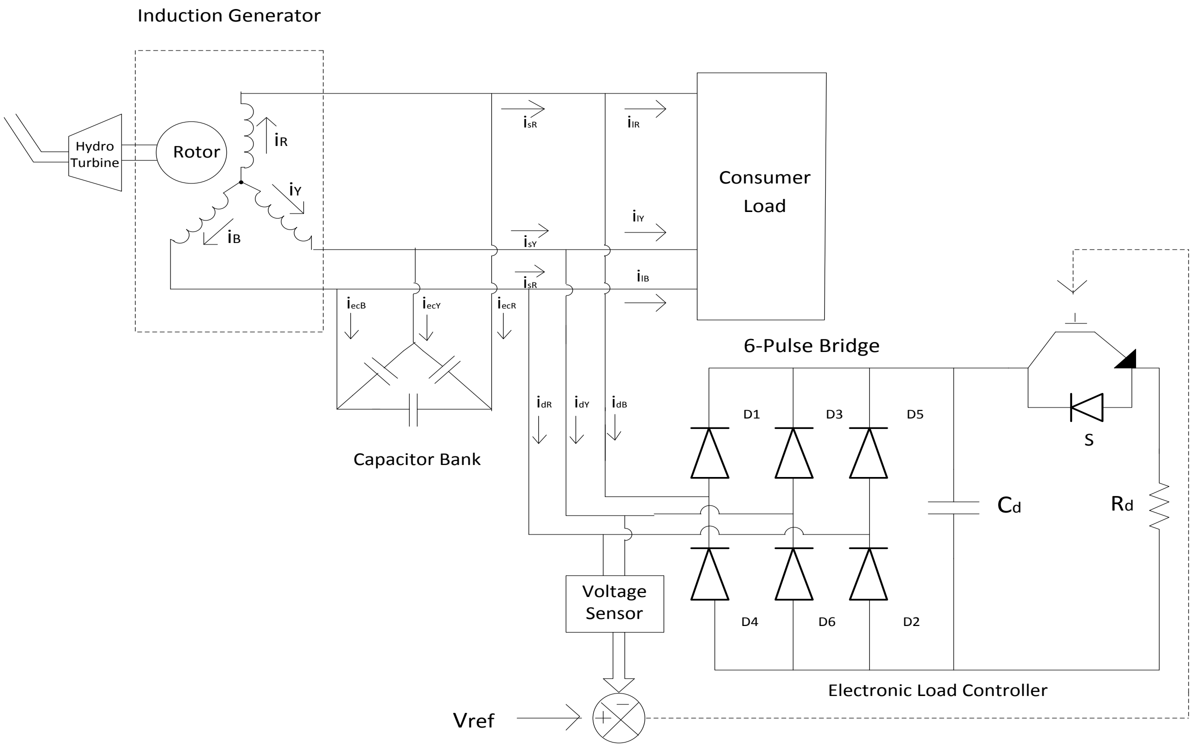

Fig 1.6. Self excited induction-generator with ELC.

The Electronic load controller (ELC) consist of uncontrolled rectifier, Insulated Gate Bipolar Switch"(IGBT) act as chopper, PI controller, PWM controller and Dump load. The voltage is first sensed through sensor and then compared with reference voltage with the help of PI controller and the output is fed to PWM controller which compares the signal with saw tooth carrier signal and makes pluses to control duty-cycle of chopper. The switching performance of IGBT is controlled by this pulse signal. The IGBT and dump load are connected in series, whenever the IGBT switched on the power is transmitted to dump load by this way electronic load controller control the output power.

Power Generated (P_g) = Power consumed by load (P_L)

+ Power consumed by ELC (P_D)

This ELC dump power (P_D) may be used for space heating, water heater, battery charging, for cooking, baking etc. The ELC keeps a constant electrical load on generator regardless of changing user load.

CHAPTER 2

LITERATURE REVIEW

2.1 OVERVIEW

This chapter presents the brief details about the research papers done by the researchers in the area of self-excited induction generator (SEIG) for renewable energy application so far. The self-excited induction generator (SEIG) is most common because of these reasons its simplicity, price, ruggedness, less maintenance etc, but has two main drawbacks which is its poor voltage regulation and frequency regulation when there is any variation/change in rotor speed and load, to build up a residual magnetic in the rotor winding it requires a reactive power. Following papers were referred and studied to understand the present status of work done on the self excited induction generator.

2.2 SELF EXCITATION AND VOLTAGE BUIDUP

For a long time now it has been known the phenomenon of self-excitation that when the rotor of an induction machine is driven by a prime-mover to speed more than its synchronous speed in negative slip than the induction machine operate as induction generator, and when a suitable value capacitor is attached across its stator terminals then it can operate in standalone (isolated) mode or as self excited induction generator (SEIG).

Following papers will show the voltage-buildup and excitation phenomenon in induction generator.

Bassett & Potter [4] explains experimentally that the induction generator can be made to operate independent or isolated mode with the connection of a shunt-capacitor across the terminal of stator to supply magnetizing current which is necessary for building up the voltage, also found that leading load hold up the voltage while lagging load caused the voltage to fall.

Wagner [5] presented an experiment of self-excitation process in induction motor under different operating conditions, no load, under load, balanced operation and unbalanced operation, also shows the effects of self excitation process on the value of terminal voltage which depends upon capacitor value, the rotor speed and load.

Elders & Woodward [6] shown the phenomenon of self-excitation process and how the self- excitation occurs in induction machines from changing its state to asynchronous from synchronous mode, some important parameter are shown which affect excitation, size of capacitor across stator terminals, residual magnetism, shaft speed, permeability at reduced magnetism. Also presented, due to residual magnetism in rotor winding the voltage is build up at stator terminal from improper value to the rated value of the machine.

Brennen & Abbondanti [7] shows induction motor as the self-excited induction generator (SEIG) or isolated generator using thyristor controlled inductor and capacitor, and observed that the voltage obtained is depends upon magnetizing characteristic of induction motor and for voltage buildup it needs minimum value capacitance , with the help of adjustable reactive power connected across terminals of machine stator they maintain the obtained voltage with variation in speed and load.

2.3 SELF EXCITED INDUCTION GENERATOR MODELING

Thomas & Krause [8] presented computer representation and result are obtained for different mode of operations like balanced conditions, un-balanced stator voltage, un-equal rotor resistor, combination of un-equal rotor resistor and un-balanced stator voltage. The dynamic behavior of machine under these conditions is analyzed from the computer representation of machine referencing rotor and stator to d-q frame of reference.

Ouazene & Mcpherson [9] discussed a method of generating ac from a unregulated speed drive with the help of squirrel-cage induction generator excited with capacitor. Presented steady state analysis of induction-machine with admittance model.

Gritter et al. [10] presented an analytic model based on reference-frame model to analyze the self-excited machine and compared parameters like min. slip for steady state operation, min. rotor speed, min. magnetic inductance, min. slip corresponding to min. inductance and illustrated excitation properties.

Gaonkar & Jayalakshmi [11] presented the transient analysis and modeling of self-excited induction generator which is driven by prime-mover of variable speed like wind turbine, based on d-q synchronous frame and dynamic current, voltage, electromagnetic torque and output power generated for induction generator is analyzed using MATLAB/Simulink.

Tandon et al [12] presented analytical method for analyzing the steady-state performance characteristic of self excited induction generator using Newton Raphson method. For a particular given load, speed and capacitance identifies the magnetizing reactance and frequency of selfexcited induction generator. Using this technique a computer algorithm is generated.

Narayan & Johnny [13] presented a computer method of analyzing stead-state performance of (SEIG) – Self-excited induction generator for given capacitance, speed and load conditions, and procedure/strategy presented to check the operating point of un-controlled wind turbine which is coupled with self excited induction generator is satisfactory for given load, and discussed the minimum & maximum values of frequency, terminal voltage, machine shaft input power etc.

2.4 STEADY STATE ANALYSIS

The Steady-state performance analysis of induction machine is useful for design and operation point, having information about machines different parameters we can predict and estimate the behavior and performance of the machine.

Following papers shows the steady-state analysis of SEIG.

Saad M. Alghuwainen [14] shown the steady-state analysis of 3-phase isolated/standalone self excited induction generator which is driven by unregulated and regulated turbine. The equivalent circuit is solved with method called node admittance and system non linear equation is solved with method called Newton Raphson, and considered linear speed- torque characteristic, and found small variation in speed has significant effect in isolated SEIG performance.

T.F.Chan [15] presented two different techniques for the analysis of self-excited induction generator, the first one technique is loop impedance based in which elimination parameter procedure to get 7^{th} degree of polynomial in the frequency and gets frequency (f) and magnetizing reactance (Xm) by solving polynomial. Nodal admittance method is the second technique in which solved equation of higher order polynomial using symbolic programming, for voltage-control of induction generated series capacitance is demonstrated.

T.F.Chan [16] presented the iterative method for steady-state analysis of SEIG, developed an iteration procedure for determining frequency which helps in solving equivalent circuit, this method has good accuracy and involves dimple calculations, and analyzed SEIG with short shunt long-shunt compensation.

Haque & Malik [17] presented steady-state analysis of isolated SEIG connected to balanced R-L load, considered core losses and air gap flux variations, and predicted value of capacitance required to maintain terminal voltage constant under changing load, power factor, speed. With decreasing speed , power factor and load impedance capacitance need increases.

Li Wang & Ching Huei Lee [18] presented eigen-value and eigen-value sensitivity analysis approach to estimate the min and max capacitance value needed for 3-phase SEIG, performed Forward-Fourier Transform to determine frequency, sudden variation in load impedance and pf-power factor is done and its effect on output voltage and current of the IG is performed,

L.Shridhar, B.Singh & C.S.Jha [19] shown the effect on the performance of SEIG-self excited IG with effect on the parameters experimentally and discussed the concept for improved better regulation and observed the effect of machine parameter on obtained frequency is not as much as on the Var requirement and terminal voltage.

Hashemnia & Lesani [20] discussed a method which is based on conductance minimization to analyze the steady-state performance of SEIG, obtained the magnetization reactance, minimum capacitance required, frequency, shows variation in frequency, magnetizing reactance withload resistance.

Rajakaruna & Bonert [21] to determine steady-state performance of self excited induction generator (IG) which is coupled with regulated & unregulated prime-mover presented analytic method which is based on nodal admittance, in this approach converted the circuit equivalent to a form in which impedance are represented by parallel elements R, L & C .

M.H.Haque [22] presented a method which is based on loop impedance to evaluate steady state performance characteristic of standalone/isolated induction which is coupled through small-hydro turbine prime-mover and used optimization toolbox of MATLAB "fsolve" to solve set of different equations and find frequency, speed and magnetization reactance, the generator steady state characteristic for unregulated and regulated operation also compared.

El-kafrawi & Buamud [23] discussed the steady-state performance analysis of SEIG which is driven by constant or variable-speed turbine, for regulated turbines used simple method to find out frequency but for unregulated turbines used interpolation method of MATLAB to find speed and torque.

T.F.Chan&Loi Lei Lai [24] presented a method to analyze steady-state performance of thee phase SEIG supplying unbalanced load and excited with unbalanced capacitance, solved the equivalent circuit by minimization technique to find out the magnetizing reactance and exciting frequency,

M.H.Haque [25] presented simple method to evaluate the steady-state performance characteristic of 1-phase SEIG which is operated in shunt, long shunt and short shunt configuration, the circuit equivalent of different configuration of generator is represented by very simple circuit which consists of 4 series impedance and equations are solved using MATLAB-optimization toolbox, among all the configuration the short-shunt generator performance is found best.

Selmi & Rehaoulia [26] presented the very simple method to analyze steady state characteristic of self-excited induction-generator, which avoids the complex and tedious/slow method of separating all real and fictitious components, solved the equation using MATLAB-optimization tool, and used nodal admittance method.

2.5 DYNAMIC / TRANSIENT ANALYSIS

Smith & Sriharan [27] developed differential equation which is based on d-q frame of reference to evaluate the transient-behavior of induction machine (IM) by the effect of capacitor and considered the magnetic saturation non-linear effect, shown that without terminal capacitor the transient-behavior of the machine not affect due saturation of main flux.

B.Singh, L.Sridhar & C.S.Jha [28] presented transient-behavior analysis of Shortshunt selfexcited induction generator (IG) under different operating conditions, predicted the performance of induction generator (IG) by using analytical method of saturation effect, presented experimental as well as simulated results, and seen short shunt suffers short circuit, loss ofexcitation.

Salma & Holmes [29] presented the steady state and transient analysis of stand alone SEIG which is based on nodal admittance method and d-q frame respectively by changing different parameters, observed that the value of min and max capacitance changes with change in load resistance.

Wang & Deng [30] presented the transient behavior of isolated induction generator (SEIG) under unbalanced excitation capacitor, to drive dynamic equation of standalone SEIG under unbalanced condition an approach is employed based on 3-phase IM model, simulated and experimental results studied for sudden removal of one excitation capacitor, sudden removal of two excitation capacitor, voltage buildup.

Mahato, Singh & Sharma [31] presented the transient-analysis of 3-phase Induction generator (SEIG) which is feeding 1-phase inductive load with ELC which is used in isolated hydro power generation, based on d-q frame axes reference theory, simulated and its experimental results are compared and observed transient condition for sudden/instant application and removal of load.

Jain, Sharma & Singh [32] presented dynamic analysis of 3-phase delta connected self excited induction generator, based on d-q frame reference theory, performance of SEIG underbalanced and unbalanced fault is observed, investigated line-line shortcircuit, opening of single phase load & 2-phase load, opening of capacitors, experimental & simulated results are compared & observed that self excited induction generator (SEIG) cannot carry 3-phase short circuit.

Olorunfemi [33] presented the modeling of 1- phase SEIG with transient and qualitative behavior performance of SEIG with series & parallel connected load, used the concept of system bifurcation and harmonic balance for qualitative behavior, predicted the self excitation process accurately by the model, observed that for self-excitation to occur min flux linkage is required.

Li Wang & Ching- Huie Lee [34] presented the dynamic characteristic performance of SEIG based on d-q reference frame theory in connection to long shunt and short shunt and subjected to sudden connection of dynamic load (induction motor), experimental and simulated results are compared and observed that short shunt configuration gives better voltage variation while the long shunt connection give rise to unwanted oscillations.

B.Singh & S.S Murthy [35] presented the transient-performance of SEIG with electronic-load controller used in isolated/standalone small-hydro power (SHP) generation with un-regulated turbines, observed the switching of load, experimental and simulated results are compared, developed the mathematical model for ELC, Load, SEIG, prime mover, observed that ELC can handle the switching.

Kishore & Kumar [36] presented the dynamic modeling of 3-phase self excited induction generator (SEIG) to analyze the transient behavior of SEIG using d-q reference theory, this stated model can handle change in prime mover speed and transient conditions, analyzed the effect of change in excitation capacitor.

Pichai Aree [37] presented the dynamic characteristic of SEIG coupled with wind turbine which is feeding induction motor load (IM), developed mathematical model of SEIG, wind turbine, IM are implemented into MATLAB environment, observed that sudden connection of load or decrease in wind speed cause a huge fall in voltage, reveals that sufficient reactive power is necessary for successful operation.

Seyoum, Grantham & Rehman [38] presented the dynamic performance characteristic of self excited induction generator (IG) using d-q reference frame theory, also shown the min and max speed needed for self excitation process of induction generator (IG) for a given capacitance and load, effect of magnetization reactance also presented, observed that decrease frequency can be regulated by increase in prime-mover speed and decrease in voltage can be maintained by increase in capacitor value.

Bhim Singh & Madhusudan Singh [39] presented the transient-performance characteristic of series compensated 3-phase SEIG feeding 3-phase cage-rotor induction motor using d-q reference frame theory, experimental results and simulated results are compared for various operating conditions such as voltage buildup ant no load, switching of induction motor with series capacitor (successful starting)and without series capacitor (failure in starting), by suitable selection of series and shunt excitation capacitor subsynchronous resonance can be avoided.

2.6 CAPACITANCE FOR EXCITATION

Following literature reviews shows the method to find minimum and maximum capacitance value which is required for the excitation process of selfexcited induction generator (SEIG)

T.F.Chan [40] presented a simple method for determining the minimum value capacitance required by 3-phase SEIG to build up voltage which is based on method called nodal admittance, for getting the value of Cmin only six degree polynomial needed to be solved, for maintaining terminal voltage an iterative procedure is developed to estimate required capacitance.

Harrington & Bassiouny [41] presented an approach to compute min value of capacitance required for excitation process in induction generator (IG) based on complex impedance matrix, by solving the algebraic equation yields frequency and min capacitance is computed to maintain terminal voltage.

Malik & Mazi [42] presented an analytical approach to predict min value of capacitance necessary for excitation process of SEIG under no load condition, also observed that no load capacitance necessary is inversely prop to magnetizing reactance and square of speed, also observed that the value of capacitance needed is higher in case of loaded SEIG in comparison to no load.

Jabri & Alolah [43] presented an approach for self-excited induction generator under RL load to determine minimum capacitance requirement, obtained min capacitance needed for selfexcitation process and frequencies under noload, resistive load and inductive load. The Cmin value is chosen slightly more for stable operation, ignored the machine core loss.

Kumar et al. [44] developed a simple approach which involves quadratic equation for getting min and max capacitance value that needed for excitation process of induction generator, also discussed the max load which can be applied to SEIG without losing excitation for given speed and capacitance value.

Ali.M.Eltamaly [45] discussed nodal analysis technique to calculate the minimum-capacitance value needed for self excitation process of induction generator under different load and speed, obtained operating frequency from equating admittance real part to zero and calculated Xc by using imaginary part, by this approach there is no need of iteration whichis time consuming.

Chandran &Vadhera [46] analyzed the steady-state performance of SEIG based on nodal admittance approach and this approach is also used for determining the value of capacitive reactance and value of capacitance required for Self excited IG for excitation under different operating conditions of speed and load, reveals that the capacitance requirement for inductive load is more and with the increase in speed the min capacitance requirement decreases.

2.7 VOLTAGE & FREQUENCY REGULATION

Self-excited induction generator (SEIG) suffers from poor voltage regulation & frequency regulation which is the prime drawback, voltage is controlled by changing the terminal capacitor values as load and speed changes, frequency is controlled by involving a inverter and converter schemes.

Various different methods for improving voltage regulation are Electronic load controllers, Switched capacitor strategy, variable VAR controller and other solid state controller.

Singh, Chauhan & Jain [47] presented and discussed various voltage regulating (VR) schemes for self excited induction generator, these regulating schemes are categories for series and shunt compensation as classical scheme based, converter based and switching device based, concludes that for feeding linear load, cost, stability point of view saturable core reactor is best amount the classical schemes, for supplying sensitive loads SVC regulating scheme is best suited among solid state switching devices based, for non-linear unbalanced load converter based STATCOM regulating scheme is best to use.

Singh, Murthy & Gupta [48] analyzed the STATCOM based voltage regulator for SEIG which is feeding non-linear load and dynamic model of STATCOM based SEIG based on d-q frame of reference is developed to predict or foretell its behavior under transient conditions, with use of IGBT based current controller VSI working as STATCOM used for harmonic elimination and provides required reactive VAR power needed for SEIG under changing load to maintain constant static terminal voltage, concluded that STACOM act as a harmonic eliminator, voltage regulator and load balancer.

Fransisco Danang et at. [49] presented a voltage regulator for SEIG which is using SVC MERS (Magnetic Energy Recovery Switch), observed that the voltage is regulated with high performance at changing load and speed, seen advantage of this system as low switching losses, simple and fast control, low harmonic distortion and by connecting fixed AC capacitor parallel to the induction generator (IG) rating reduction of SVC-MERS is attain about 60%.

Chilpi, Singh & Murthy [50] discussed the voltage control and frequency control of SEIG in a isolated micro hydro system using IVFC-integrated voltage and frequency controller, observed that IVFC is capable of feeding linear loads and non linear loads, presented the capabilities of voltage and frequency controller such as load balancing, load leveling ,harmonic elimination and voltage & frequency control.

Ramirez & Torres M [51] presented an electronic load controller with SEIG for standalone operation, discussed ELC schemes which has simple and reliable control strategy in which to control the connection and disconnection of dump load, anti parallel IGBT are used, analyzed different operating conditions and perceive that the voltage is regulated.

Joshi, Sandhu & Soni [52] analyzed the steady-state performance characteristic of SEIG based on genetic algorithm based approach and proposed a new technique to find the different parameters for constant voltage and constant frequency operation, shown a theoretical computed result and experimental result and find closeness in both results. For genetic algorithm taken two control variables excitation capacitance and operating speed to control frequency and voltage.

Singh, Murthy & Gupta [53] presents the performance-analysis and design of ELC-electronic load controller for 3-phase SEIG for pico hydro plant, this proposed ELC system contains chopper with dump load and uncontrolled rectifier, concluded that SEIG with ELC maintains constant voltage and constant frequency with changing load.

Umesh. C. Rathore & Sanjeev Singh [54] presents the performance of 3-phase self-excited induction generator (SEIG) with electronic load controller used in micro/pico hydro power generation system. Shown electronic load controller feeding isolated load under different operating conditions and shown the control strategies for 3-phase self excited induction generator to regulate or maintain the desired voltage and frequency of generated output.

CHAPTER 3

MODELING OF SEIG SYSTEM

3.1 INTRODUCTION

Self-Excited Induction Generator (SEIG) comprises of squirrel-cage induction machine, excitation-capacitor, prime-mover and load. The SEIG system layout diagram is displayed in fig. 3.1 The primary necessary condition for induction-machine to work as generator is the excitation current to produce a rotating magnetic field. For grid-connected system it takes reactive power from grid whereas for isolated/standalone system reactive power for excitation process is provided by capacitor bank.

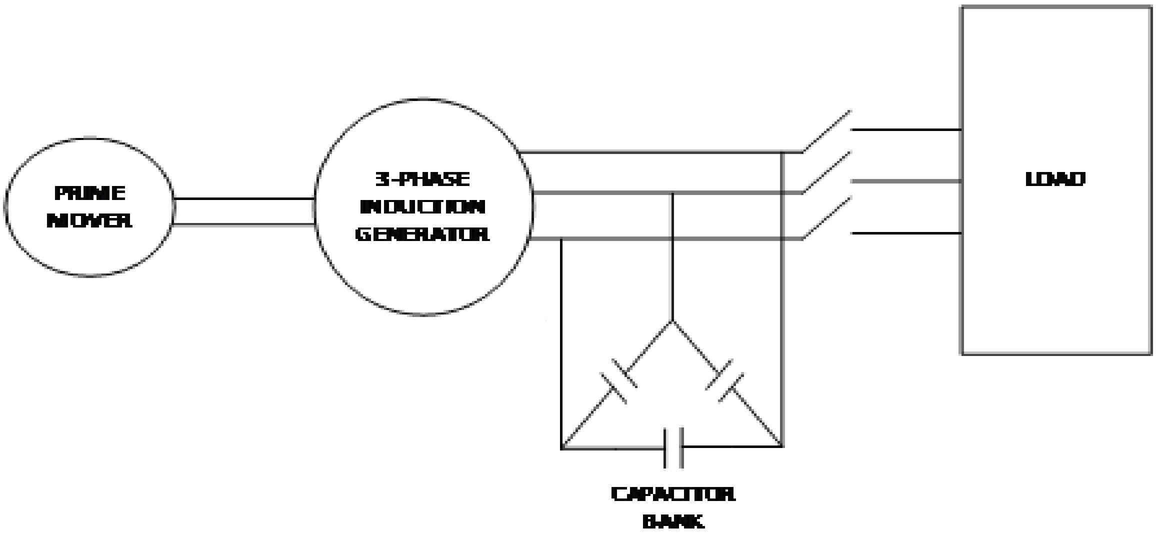

Fig3.1 Self Excited Induction Generator with excitation capacitor driven by prime mover

3.2 INDUCTION MACHINE MODEL

In electrical machine analysis//study a three-axes to two-axes transformation is applied to get easier and simpler expressions which will make complex systems simple to analyze and solutions easy to find. The three axes are representing/depecting the real 3-phase supply system. However, the 2-axes are fictitious-axes representing two fictitious-phases, which displaced by 90 degree, to each other. Here an assumption taken is that the three-axes and the two-axes are in a stationary frame of reference. It can be re-phrased as a transformation between abc and stationary d-q axes. The conventional per-phase equivalent circuit representation of induction machine (IM) is convenient to use for steady-state analysis. However, to model the SEIG under dynamic conditions the d-q representation is used. The d-q representation of a SEIG with capacitors fixed across the stator winding terminals and from the rotor side without any electrical input is displayed in Fig. 3.2. Fig 3.3 representing stationary stator reference frame model in direct-axis and quadrature-axis separately.

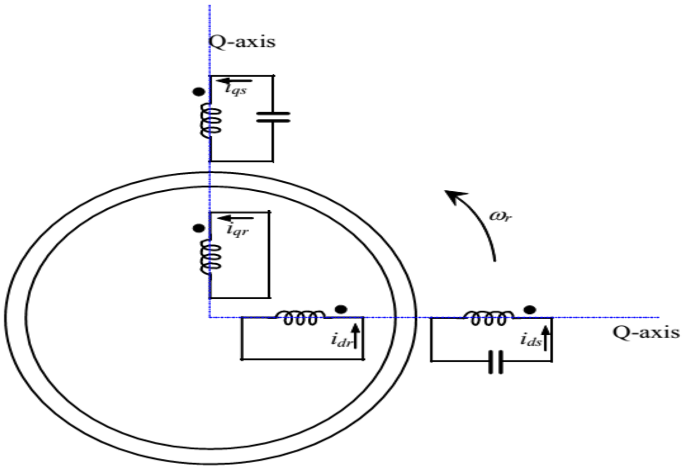

Fig. 3.2 – d-q representation of self excited induction generator

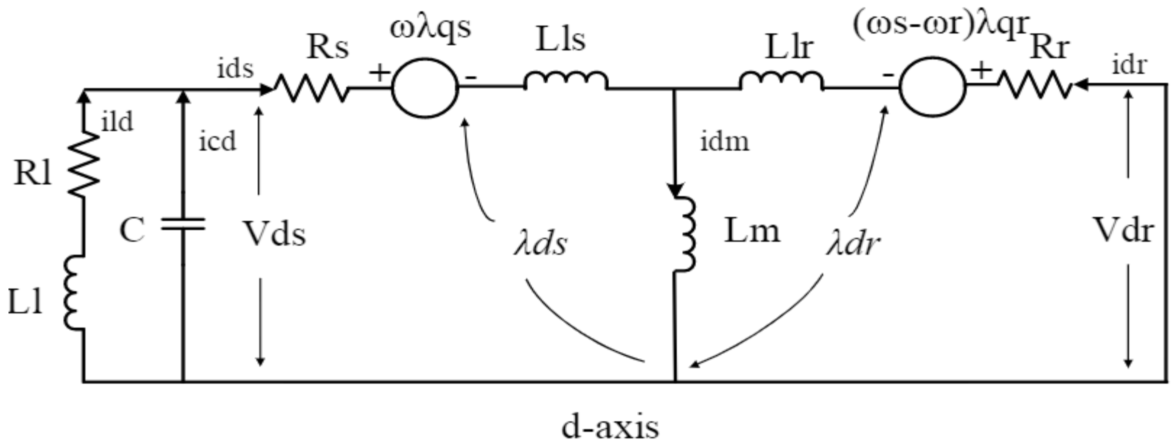

Fig 3.3 d axis equivalent circuit of self excited induction generator

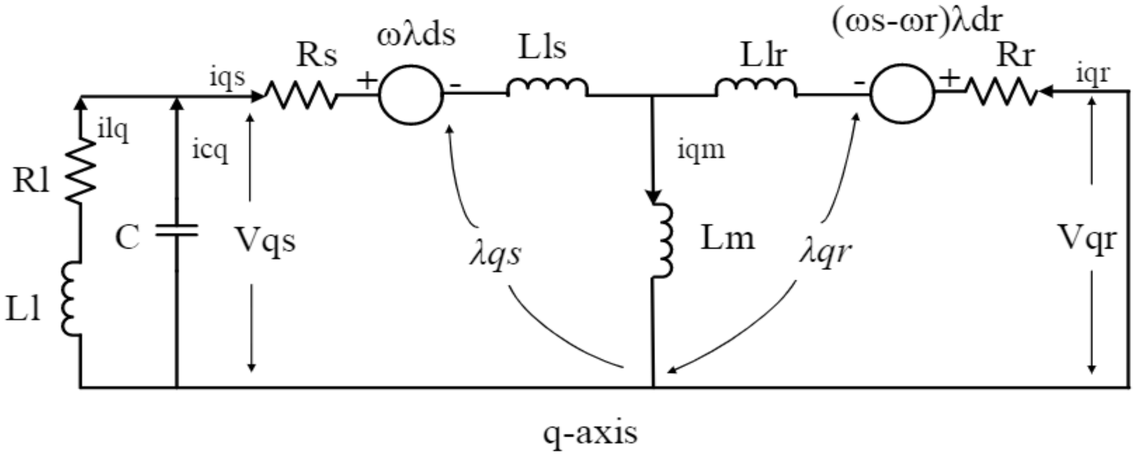

Fig 3.4 q axis equivalent circuit of self excited induction generator

Figure 3.3 and 3.4 shows the d-q circuit equivalent of self-excited induction generator (SEIG), it is suitable to convert the inductances into reactances by appropriate conversion to simplify the equations, therefore it can be done as follows

$$\omega_b = 2\,\pi\, f_s$$

$$X_{ls} = \omega_b\, L_{ls}$$

$$X_{lr} = \omega_b\, L_{lr}$$

$$X_m = \omega_b\, L_m$$

$$X_{lm} = \left(\frac{1}{X_m} + \frac{1}{X_{ls}} + \frac{1}{X_{lr}}\right)^{-1} \qquad (3.1)$$

And flux linkage can be written as

$$F_{ds} = \omega_b \lambda_{ds}$$

$$F_{qs} = \omega_b\, \lambda_{qs}$$

$$F_{dr} = \omega_b \lambda_{dr}$$

$$F_{qr} = \omega_b\, \lambda_{qr} \qquad (3.2)$$

Where,

ω_b = base speed (rad/sec), ω_s = stator angular speed (rad/sec), ω_r = rotor angular speed (rad/sec).

X_{ls} = stator leakage inductance, X_{lr} = rotor leakage inductance, X_m = magnetization inductance.

F_{ds},F_{qs},F_{dr},F_{qr} = stator and rotor dynamic flux linkage

The voltage equations for synchronously reference frame by substituting ω in arbitrary reference frame with ω_s also substituting the flux linkages from equation

$$V_{sd} = R_s i_{ds} + \frac{1}{\omega_b}\frac{dF_{ds}}{dt} - \frac{\omega_s}{\omega_b}F_{qs}$$

$$V_{sq} = R_s i_{qs} + \frac{1}{\omega_b}\frac{dF_{qs}}{dt} - \frac{\omega_s}{\omega_b}F_{ds}$$

$$V_{qs} = R_s i_{qs} + \frac{1}{\omega_b}\frac{dF_{qs}}{dt} - \frac{(\omega_s - \omega_r)}{\omega_b}F_{qr} \tag{3.3}$$

$$V_{qr} = R_s i_{qr} + \frac{1}{\omega_b}\frac{dF_{qs}}{dt} - \frac{(\omega_s - \omega_r)}{\omega_b}F_{dr}$$

For a cage rotor induction machine values of $V_{qr} = V_{dr} = 0$, because all the parameters are in per unit of base impedance.

The flux linkage equations is written in terms of currents as follow

$$\lambda_{ds} = L_{ls}\, i_{ds} + L_m\,(i_{ds} + i_{dr})$$

$$\lambda_{dr} = L_{lr}\, i_{dr} + L_m\,(i_{ds} + i_{dr})$$

$$\lambda_{dm} = L_m\,(i_{ds} + i_{dr})$$

$$\lambda_{qs} = L_{ls}\, i_{qs} + L_m\,(i_{qs} + i_{qr}) \tag{3.4}$$

$$\lambda_{qr} = L_{lr}\, i_{qr} + L_m\,(i_{qs} + i_{qr})$$

$$\lambda_{qm} = L_m\,(i_{qs} + i_{qr})$$

By multiplying the both sides equation (3.4) by the base angular frequency (ω_b) the flux linkages (F) can be written as

$$F_{ds} = \omega_b\,\lambda_{ds} = X_{ls}\, i_{ds} + X_m\,(i_{ds} + i_{dr})$$

$$F_{dr} = \omega_b\,\lambda_{dr} = X_{lr}\, i_{dr} + X_m\,(i_{ds} + i_{dr})$$

$$F_{dm} = X_m\,(i_{ds} + i_{dr}) \tag{3.5}$$

$$F_{qs} = \omega_b\,\lambda_{qs} = X_{ls}\, i_{ds} + X_m\,(i_{qs} + i_{qr})$$

$$F_{qr} = \omega_b\,\lambda_{qr} = X_{lr}\, i_{dr} + X_m\,(i_{qs} + i_{qr})$$

$$F_{qm} = \omega_b\,\lambda_{qm} = X_m\,(i_{qs} + i_{qr})$$

Substituting values of F_{dm} and F_{qm} in F_{ds} , F_{qs} , F_{dr} and F_{qr} in the above given equations we get

$$F_{ds} = X_{ls}\, i_{ds} + F_{dm}$$

$$F_{dr} = X_{lr}\, i_{dr} + F_{dm}$$

$$F_{qs} = X_{ls}\, i_{ds} + F_{qm} \tag{3.6}$$

$$F_{qr} = X_{lr}\, i_{qr} + F_{qm}$$

From the above given equation the current equation can be written as follow

$$i_{ds} = \frac{F_{ds} - F_{dm}}{X_{ls}}$$

$$i_{dr} = \frac{F_{dr} - F_{dm}}{X_{lr}}$$

$$i_{qs} = \frac{F_{qs} - F_{qm}}{X_{ls}} \tag{3.7}$$

$$i_{qr} = \frac{F_{qr} - F_{qm}}{X_{lr}}$$

Substituting the current equations above (3.7) to obtain F_{dm} and F_{qm}

$$F_{dm} = \frac{X_{lm}}{X_{ls}} F_{ds} + \frac{X_{lm}}{X_{lr}} F_{dr} \tag{3.8}$$

$$F_{qm} = \frac{X_{lm}}{X_{ls}} F_{qs} + \frac{X_{lm}}{X_{lr}} F_{qr}$$

By putting the current equation (3.7) the voltage equations can be written again as follow

$$V_{ds} = \frac{R_s}{X_{ls}} (F_{ds} - F_{dm}) + \frac{1}{\omega_b} \frac{dF_{qs}}{dt} - \frac{\omega_s}{\omega_b} F_{qs}$$

$$V_{qs} = \frac{R_s}{X_{ls}} (F_{qs} - F_{qm}) + \frac{1}{\omega_b} \frac{dF_{qs}}{dt} - \frac{\omega_s}{\omega_b} F_{ds}$$

$$V_{dr} = 0 = \frac{R_r}{X_{lr}} (F_{dr} - F_{dm}) + \frac{1}{\omega_b} \frac{dF_{qr}}{dt} - \frac{(\omega_s - \omega_r)}{\omega_b} F_{qr} \tag{3.9}$$

$$V_{qr} = 0 = \frac{R_r}{X_{lr}} (F_{qr} - F_{qm}) + \frac{1}{\omega_b} \frac{dF_{qr}}{dt} + \frac{(\omega_s - \omega_r)}{\omega_b} F_{dr}$$

The motion equation of SEIG can be expressed as follows

$$T_{em} = \frac{J}{P} \frac{d\omega}{dt} + \frac{B}{P}\, \omega + T_{mech} \tag{3.10}$$

Where,

ω = electrical angular frequency

J = rotor inertia

T_{mech} = Mechanical power applied to the shaft

P = No. of pole pairs

T_{em} = electromagnetic torque

B = viscous frictional torque

Electromagnetic torque can express in term of reactances flux linkages and current as follow

$$T_{em} = \frac{3}{2}\frac{X_m}{2(X_{lr}+X_m)}\frac{P}{\omega_b}(i_{qs}F_{dr} - i_{ds}F_{qs}) \quad (3.11)$$

And the electrical angular frequency by ignoring frictional torque

$$\frac{d\omega}{dt} = \frac{P}{J}(T_{em} - T_{mech}) \quad (3.12)$$

The load impedance model of SEIG can be defined as follow

$$\frac{di_{Ld}}{dt} = \frac{1}{L_l}(V_{ds}\text{-}R_l i_{Ld}) + \omega_s i_{Ld} \quad (3.13)$$

$$\frac{di_{Lq}}{dt} = \frac{1}{L_l}(V_{qs}\text{-}R_l i_{Lq}) + \omega_s i_{Lq}$$

Finally excitation capacitor model can be expressed as

$$\frac{dV_{ds}}{dt} = -\frac{1}{C}i_{ds} + \frac{1}{C}i_{Ld} \quad (3.14)$$

$$\frac{dV_{qs}}{dt} = -\frac{1}{C}i_{qs} + \frac{1}{C}i_{Lq}$$

Where,

i_{ds} , i_{qs} = d-q axes stator current

i_{Ld} , i_{Lq} = d-q load current

C = Excitation Capacitor

3.3 DESIGN OF EXCITATION CAPACITOR

For the proper operation a suitable rating excitation-capacitor is required. Capacitor can be connected in star or delta form. The rating of the capacitor is chosen as per

Apparent power	$S = \sqrt{3}.\, V_L.\, \mathrm{I}_L$
Active power	$P = \mathrm{S}\cos\theta$
Reactive power absorbed,	$Q = \sqrt{S^2 - P^2}$
Per phase reactive power needed,	$q = \frac{Q}{3}$
Voltage per phase,	$V_P = \frac{V_L}{\sqrt{3}}$
Capacitive current,	$I_C = \frac{Q}{V_P}$
Per phase capacitive reactance,	$X_C = \frac{V_P}{I_C}$
Capacitance per phase, =	$\frac{1}{2\,\pi\, f\, X_C}$

CHAPTER4

SIMULATION RESULTS AND DISCUSSION

4.1 INTRODUCTION

In this chapter study the dynamic simulation of self-excited induction generator (SEIG) with the use of MATLAB/ SIMULINK, the SEIG is driven by constant torque from hydro turbine which its model is made by potential equation given by

$$P = \eta \, \rho \, g \, Q \, H$$

The torque is calculated from the torque formula from equation given by

$$T = \frac{P}{\omega}$$

With the help of "SimPowerSystems" block in Simulink a built in induction motor is used as self-excited induction generator , the specification of induction machine is given in Table 3 below.

Table 3: Specification of Induction Machine

Parameters	Value
Power	4KW
Voltage	400v
Frequency	50Hz
Stator- Resistance	2.976 ohm
Stator- Inductance	0.002882 H
Rotor- Resistance	1.408 ohm
Rotor- Inductance	0.002891 H
Mutual Inductance	0.137 H
J (Moment of Inertia)	0.0131 J

The parameter of the 4 KW induction machine were calculated by using MATLAB "power_AsynchronousMachineParams" which is specified in figure 4.1 ,

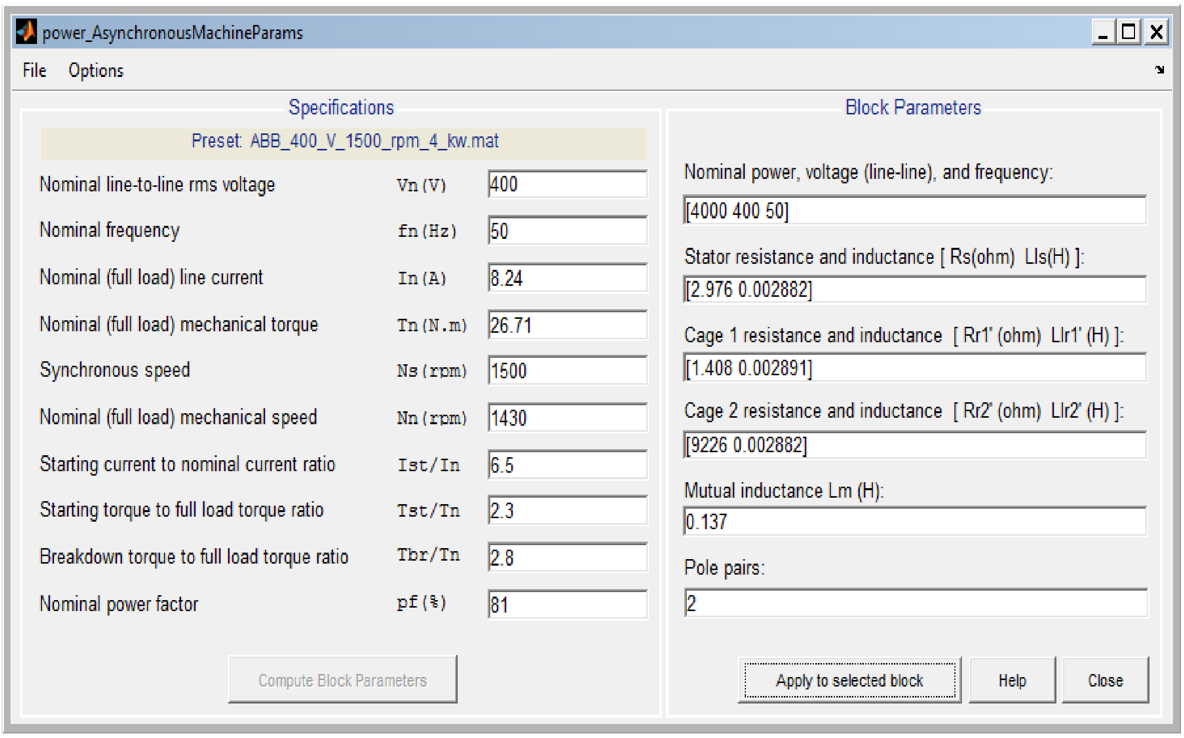

Fig 4.1 - Induction Machine Parameter

For turbine model the head assumed to be 5 m, the discharge to be 0.1 m3, and efficiency to be 0.85, therefore the computed based on the above parameter to be 4.167 KW to match the induction motor power.

The SIMULINK model of SEIG is intended to study the following

(i) Operation of SEIG with R load.

(ii) Operation of SEIG with R-L load.

(iii) Overloading and Loss of Excitation.

(iv) Reactive Power Compensation.

(v) Electronic Load Controller.

4.2 MATLAB SIMULATION OF SEIG

The MATLAB/Simulink model of self-excited induction generator is shown in figure 4.5, it comprises of many different parts, the hydro-turbine model is made based on the potential equation (1.1) and the torque is obtained from equation (1.2) to build the sub system block "TURBINE" is shown in figure 4.5, the turbine subsystem block shown below in figure 4.2.

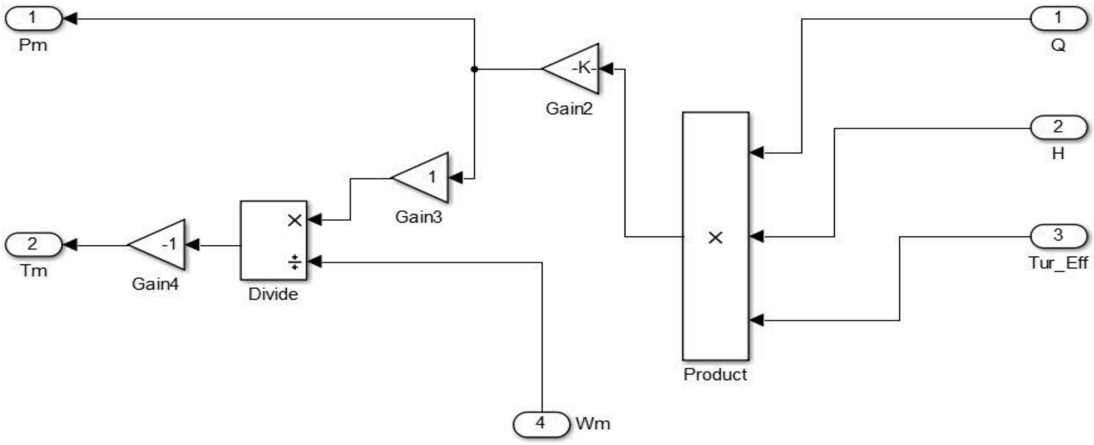

Fig 4.2 Turbine model using power and torque equation

The model of excitation-capacitor connected in star given in figure 4.3, and the model of the excitation0capacitor connected in delta given in figure 4.4

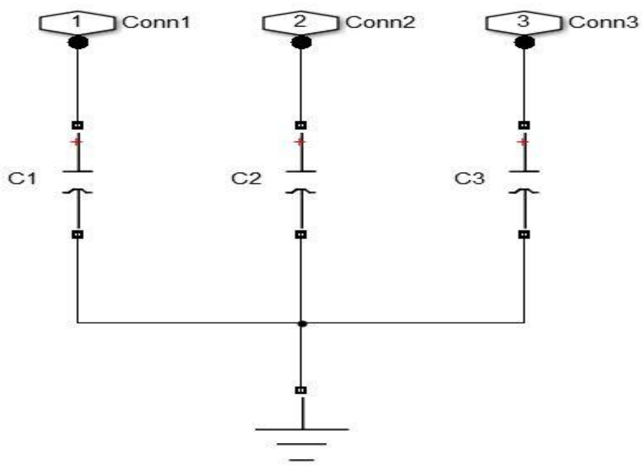

Fig.4.3 Capacitor connection in Star

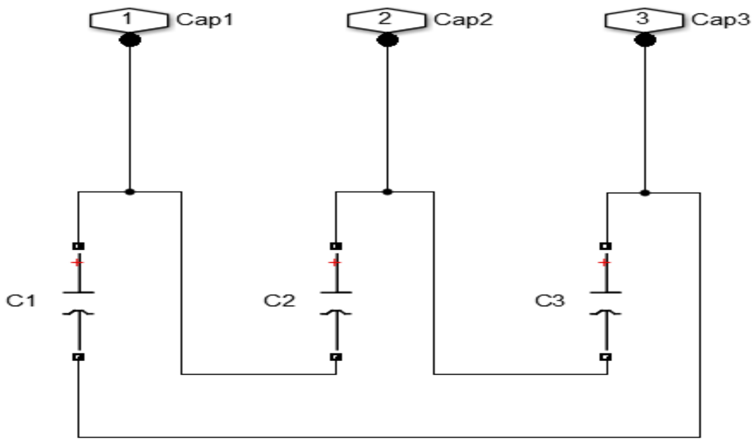

Fig 4.4 Capacitor Connection in Delta

Figure 4.5 shows the whole model of self-excited induction generator to be study with Simulink which consist of "TURBINE" model, capacitor bank model load model, measurement tools and visualization blocks.

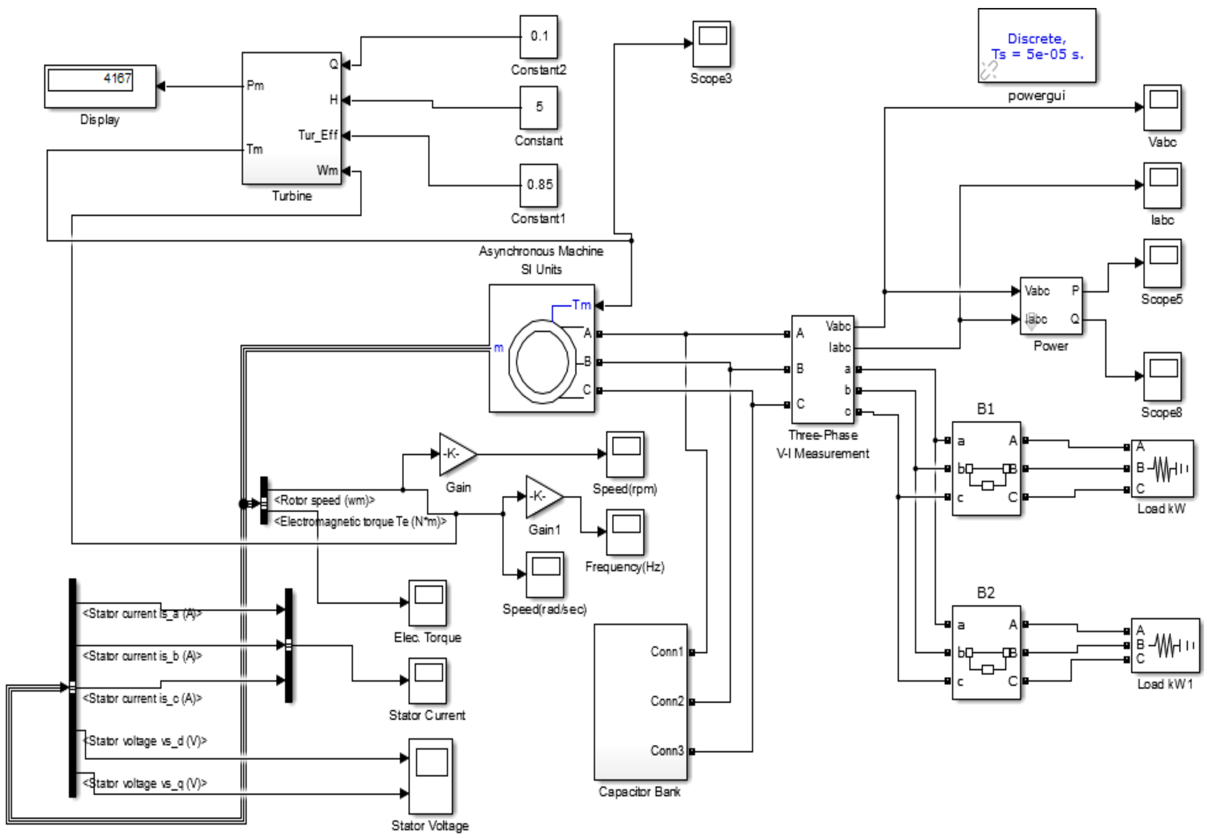

Fig 4.5 Model of Self Excited Induction Generator with turbine in Simulink

4.3 RESULTS AND DISCUSSION

4.3.1 Operation of SEIG with R- Load

With the help of MATLAB/Simulink results are obtained for operation of self excited induction generator with resistive load. The effect on line voltage, line current, Electromagnetic Torque, Rotor speed is shown in fig.(4.6-4.9) From 0-3 sec 2KW resistive load is connected to SEIG and from 3-6 sec 4KW resistive load is connected to SEIG (there is 50% increase in load during this period) so there is dip in voltage is observed and transient in torque and speed can also be seen. In this operation a constant capacitance value of $23\mu F$ is connected to the stator terminal of the SEIG.

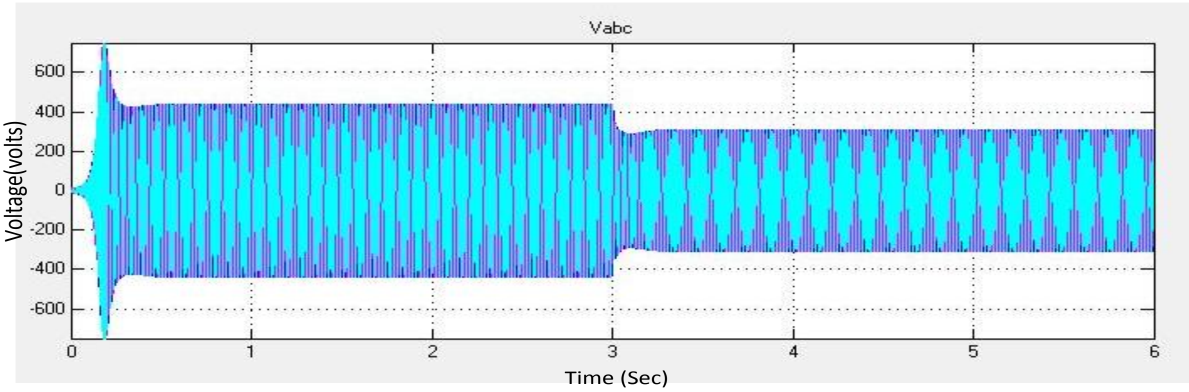

Fig.4.6 Voltage Vs Time

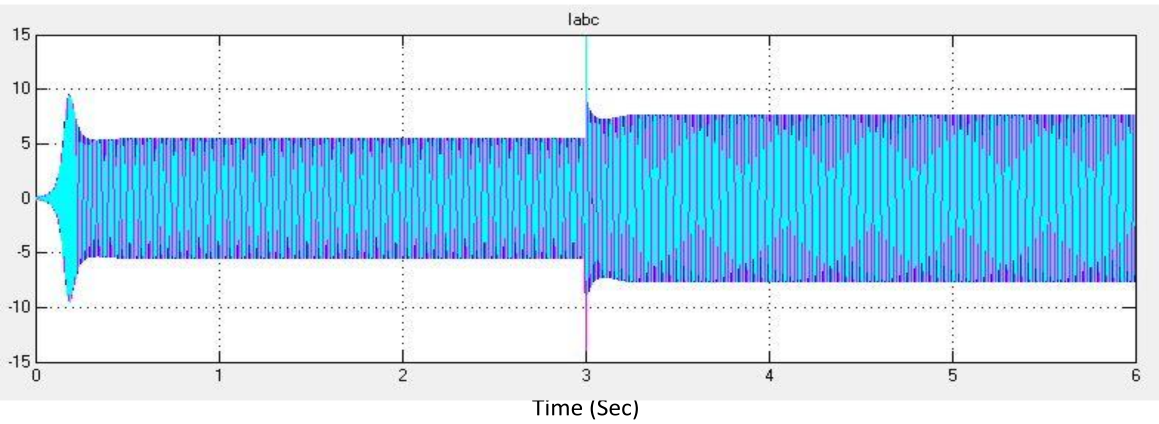

Fig 4.7 Current Vs Time

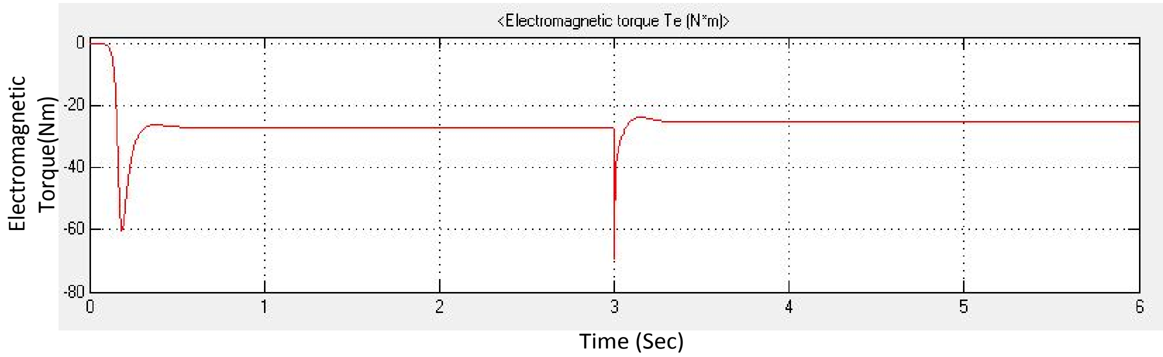

Fig 4.8 Electromagnetic Torque Vs Time

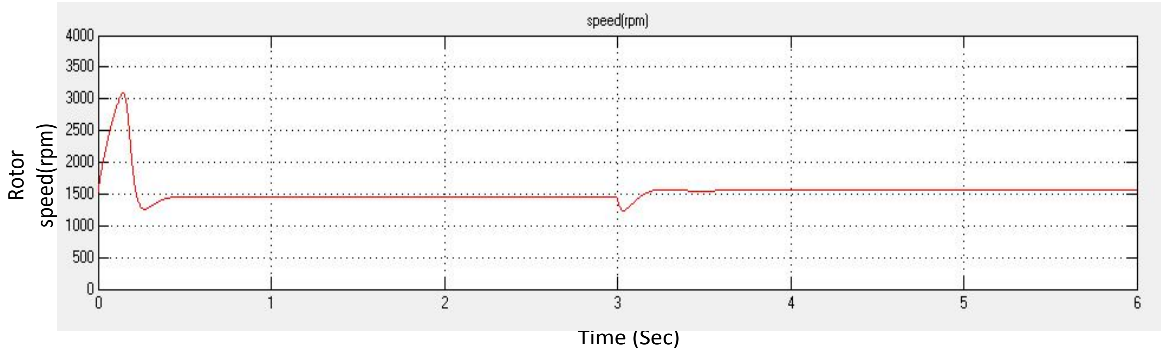

Fig.4.9 Rotor Speed Vs Time

4.3.2 Operation of SEIG with R-L Load

In case of operation of Self-Excited Induction Generator with R-L load in which MATLAB/Simulink results of voltage, current, Electromagnetic Torque, Rotor speed is obtained and shown in fig. From 0-3 sec only 3.5kW resistive load is connected to SEIG and from 3-6 sec 2kW resistive load with 3.464kVAr inductive load is connected to SEIG and with the variation of load the effect on voltage, current, torque & speed are shown in fig(4.10-4.13)

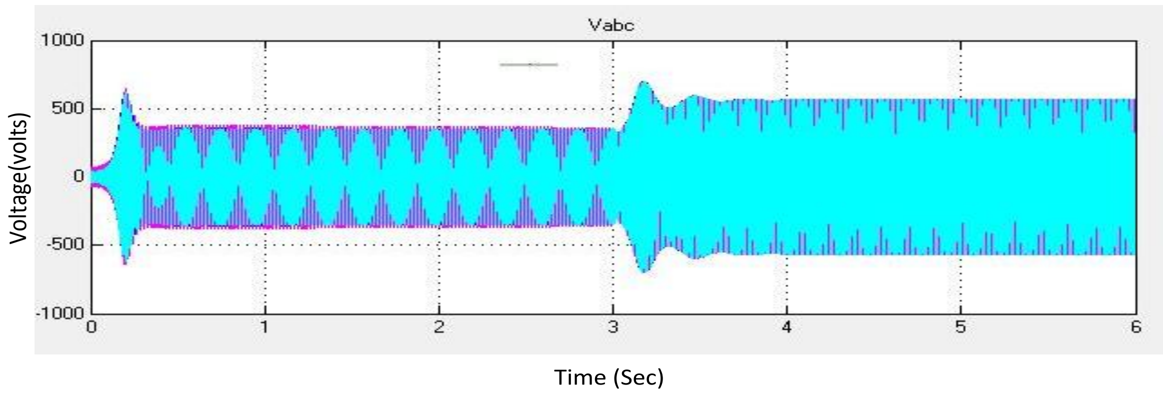

Fig.4.10.Voltage Vs Time

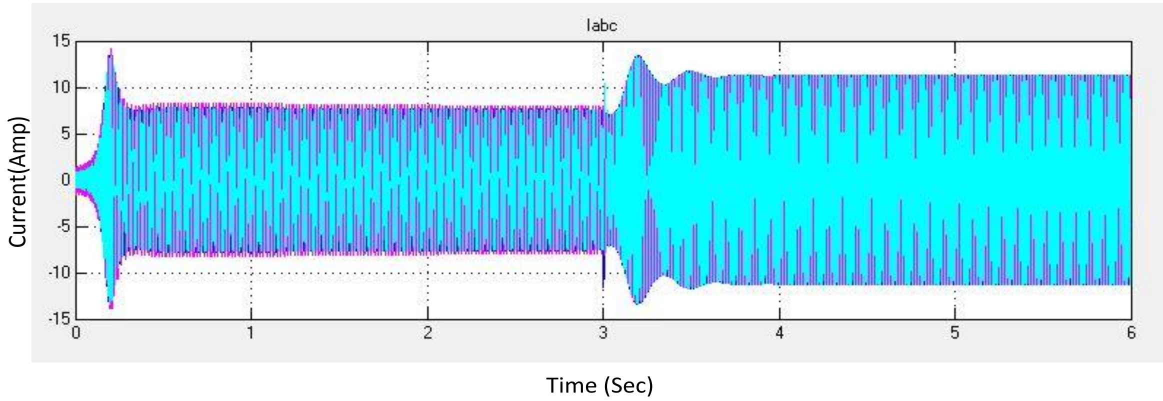

Fig 4.11. Current Vs Time

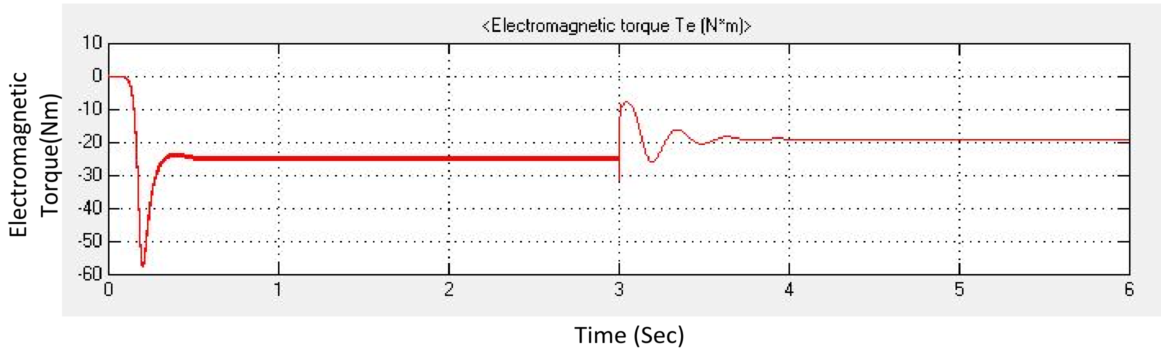

Fig 4.12 Electromagnetic Torque (T_e) Vs Time

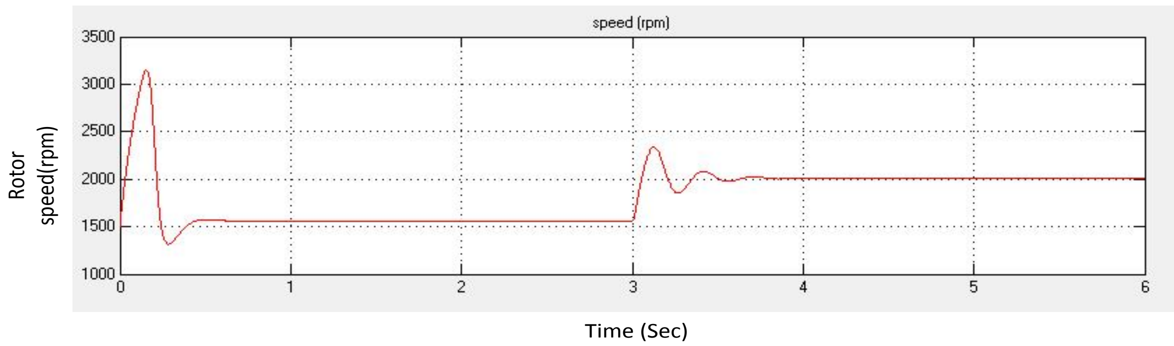

Fig.4.13. Rotor Speed Vs Time

4.3.3 Overloading and Loss of Excitation

In this overloading operation of SEIG it will loaded with higher load and it continue to excite up to a certain limit of load and then it will lose terminal voltage, figure (4.14) shows self excited induction generator loaded with 11.7kW resistive load and continue to excite for fixed value capacitance of 69 μF connected in star, and figure (4.15) shows self excited induction generator connected to 11.9KW load and its terminal voltage drops to zero.

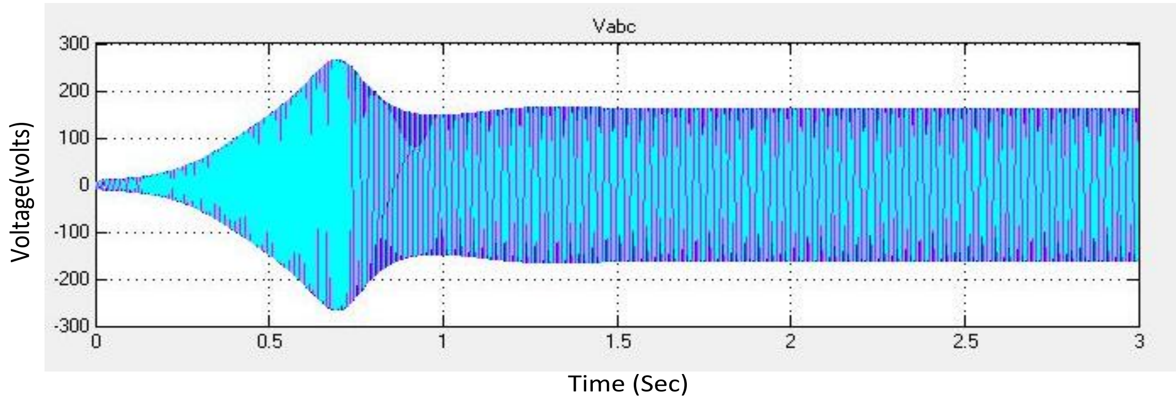

Fig4.14. SEIG voltage when connected to 11.7KW load

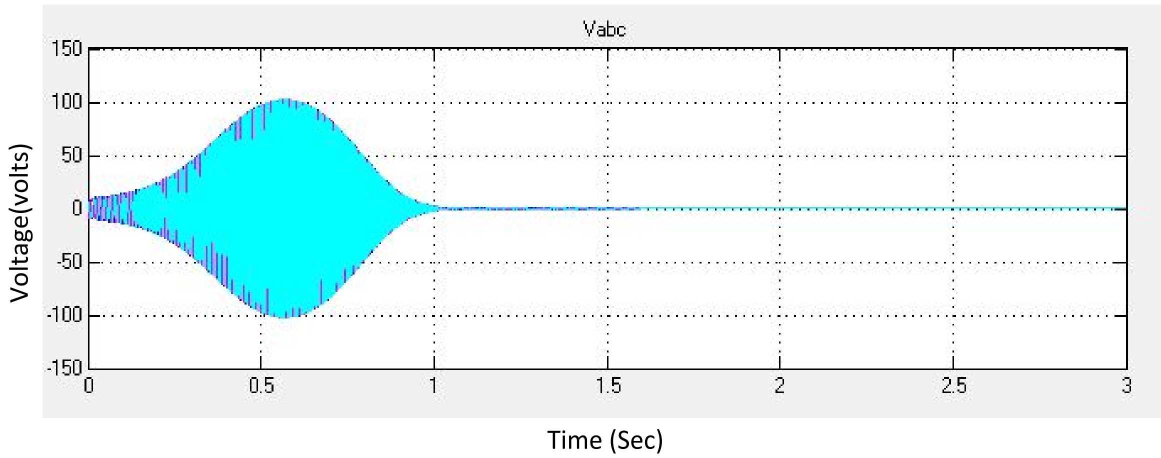

Fig.4.15 SEIG voltage when connected to 11.9KW load

4.3.4 Reactive Power Compensation with Series Capacitor

In reactive power compensation three different resistive load of value 3KW, 3.5KW and 4KW is used. With the use of circuit breaker from t = 0- 3sec 3kW load is connected, from t = 3-6 sec 3.5kW load is connected and from t = 6-9 sec 4kW load is connected. The fig (4.16) shows the terminal voltage of SEIG with series compensation and fig (4.17) shows the terminal voltage without series compensation. The capacitance value of series capacitor 120 μF is chosen and it can be seen from the simulation result that with series capacitance voltage is maintained.

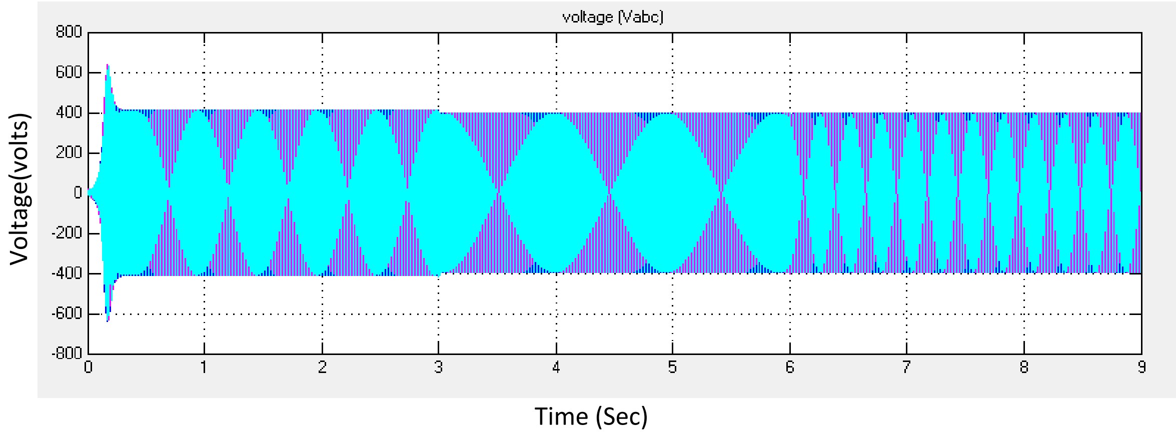

Fig.4.16 Voltage Vs Time graph with Series-Capacitor

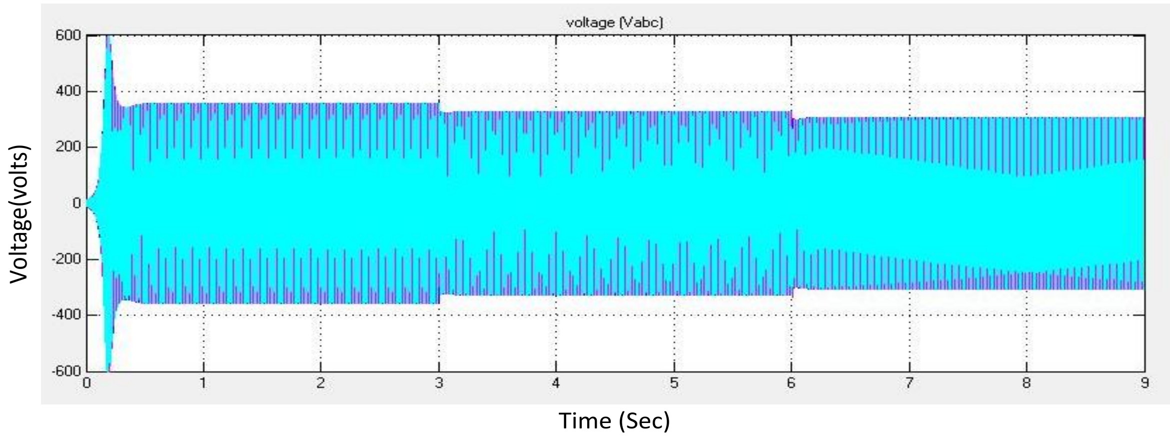

Fig 4.17 Voltage Vs Time graph without Series-Capacitor

4.3.5 SEIG with Electronic Load Controller

The performance of self-excited induction generator with ELC-electronic load controller is performed on MATLAB/Simulink environment to observe the load dynamic behavior. The ELC is to design so as to maintain the desired load level which enables the o/p voltage and o/p frequency within limit. The output waveforms are shown in Fig (4.18- 4.25). It can be observed that the initial load of 3.5kW is changed to 1.05kW (70% decrease in load) at 2 second voltage and frequency vary only slightly as it is within limits.

When the load is decreased by 70% at 2 sec then most of the current flow through ELC-electronic load controller circuit and power consumed by dump load. Due to the presence of rectifier circuit certain harmonics are present in the circuit which results in slight distortion in voltage & current waves.

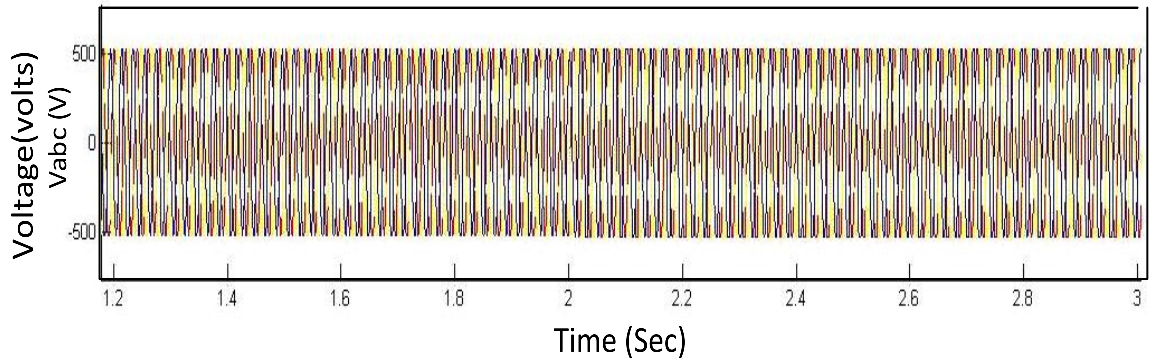

Fig.4.18 Generated Voltage of SEIG

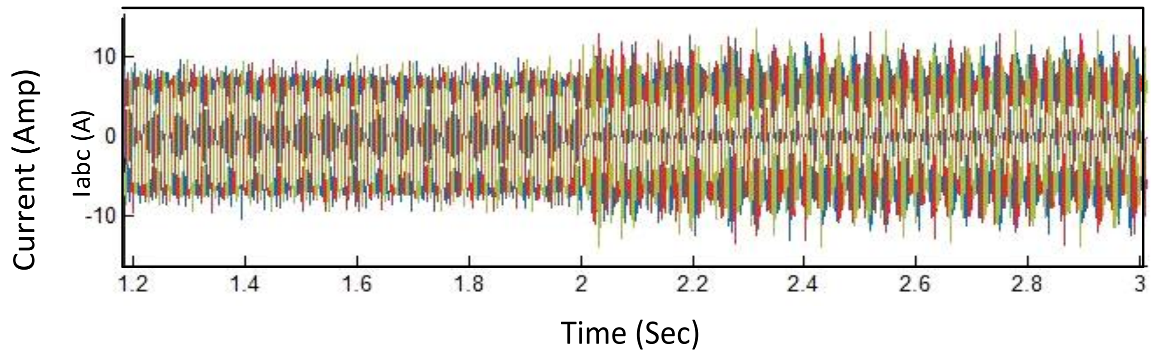

Fig.4.19 Generated current of SEIG

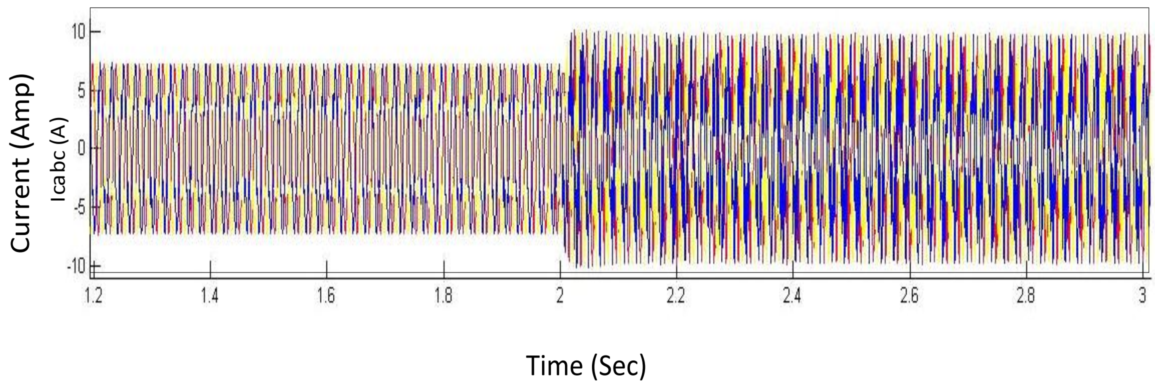

Fig.4.20 Generated Capacitor Current

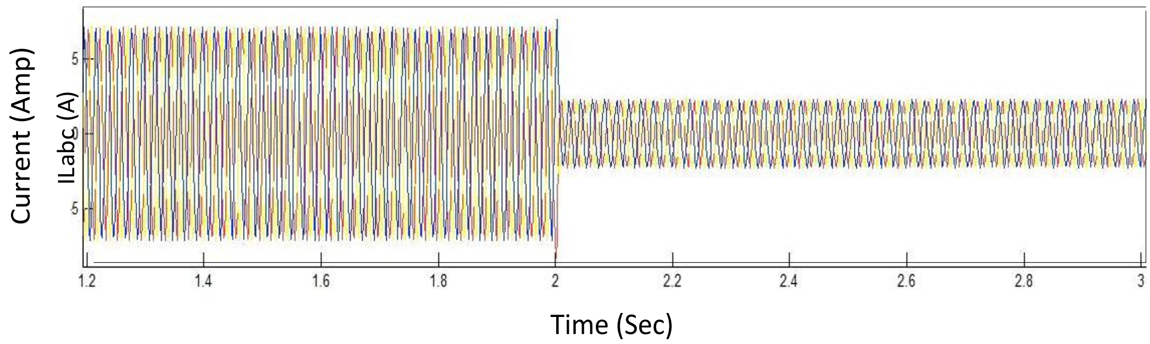

Fig.4.21 Generated Load current

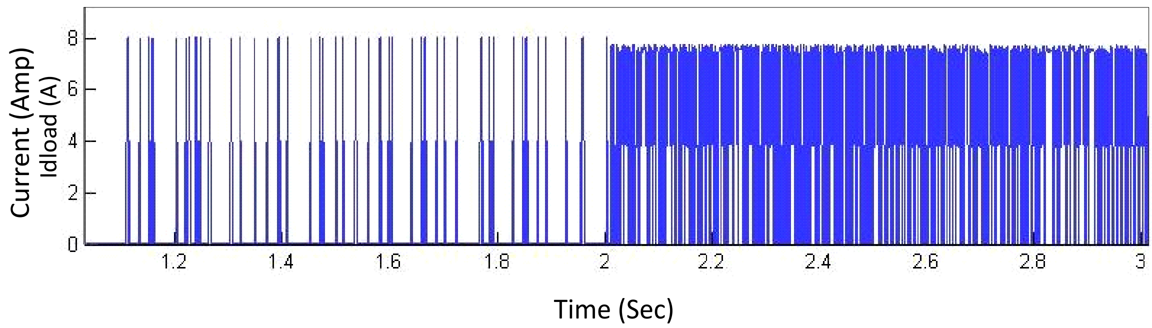

Fig.4.22 Generated Dump Load Current

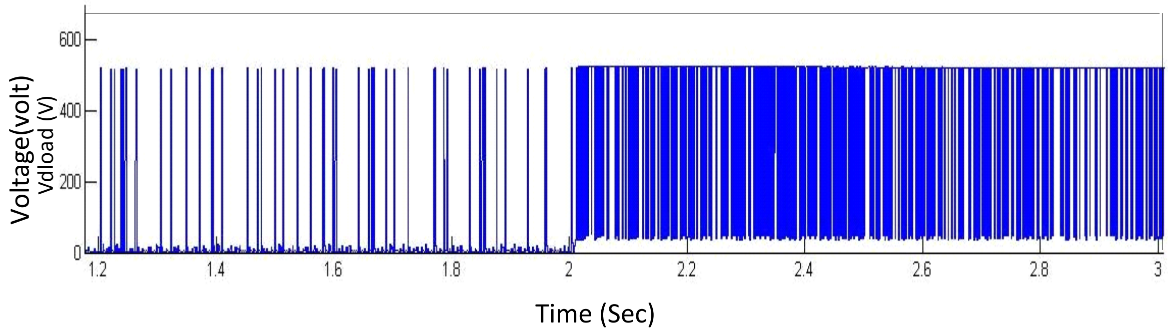

Fig.4.23 Generated Dump Load Voltage (V)

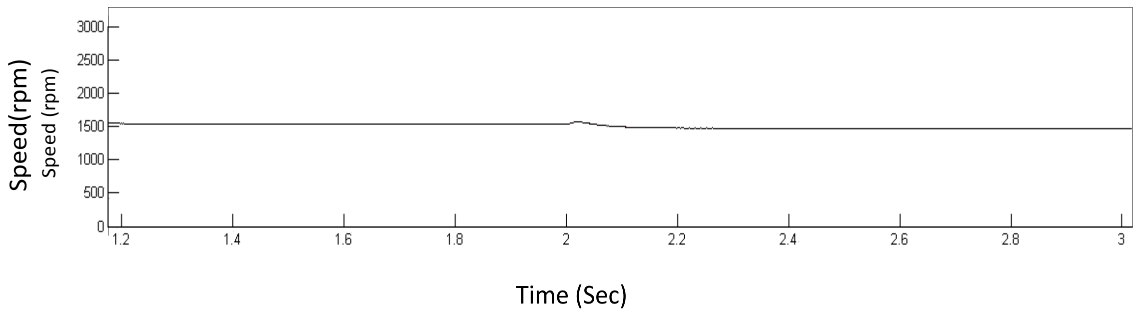

Fig.4.24 Generated Rotor Speed (rpm).

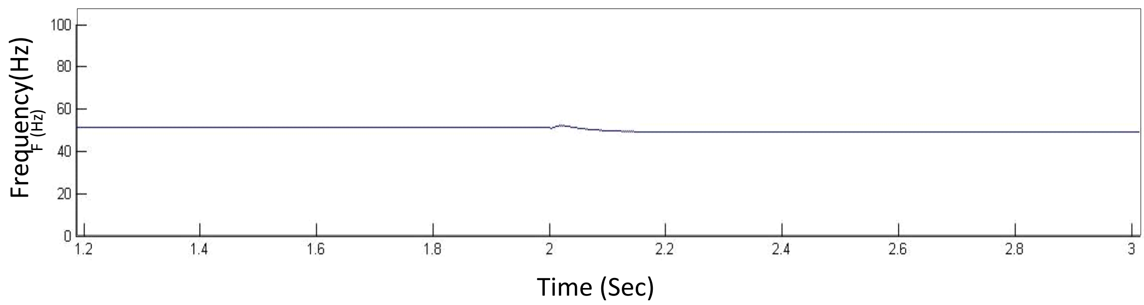

Fig.4.25 Generated Frequency (Hz)

CHAPTER 5

CONCLUSION

5.1 CONCLUSION

The studies shown that the use of induction machine (IM) as a induction generator (IG) for harnessing the electrical power from renewable or non-conventional source like pico/micro/small hydro power or from wind energy sources which is capable to operate in remote rural/hilly areas. Self excited induction generator has several advantages like low price, simplicity, little maintenance, ruggedness, brushless (for squirrel cage), absence of separate DC source, protection against overloading & short-circuit and that there is no need of reactive power from transmission lines as it draws reactive power from capacitor bank connected in shunt.

The SEIG was analyzed under different loading condition in which with variation of load there is variation in voltage, current, speed, torque etc and can undergo overloading up to certain point then terminal voltage drops to zero.

The voltage build up depend on the value excitation capacitor, the load connected across it and the speed of the rotor. This analysis gives broad idea about the performance of generator which can be helpful in field operation

As the main drawback of a standalone generating system, demand of reactive power which in turn causes the poor voltage regulation, can be effectively minimized by voltage control strategy like reactive compensation with series capacitor and Electronic Load Controller with dump load.

The reactive compensation technique is simple technique with low harmonics whereas the Electronic load controller is a complex technique which includes power electronic circuit which introduces harmonics and there is wastage of energy to dump load.

5.1 FUTURE SCOPE OF WORK

1. Better methods of reactive power/voltage control techniques for self excited induction generators.

2. Majority of the micro//pico hydro power plants in isolated mode are located in the areas which has shortage of water during winter season and resulting lesser power generation. To meet power requirement under such conditions distributed generation system comprising of various combination of wind-solar, wind-pico/micro hydro hybrid system of renewable energy conversion system with precise control of output voltage and frequency could be option.

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LIST OF PAPERS COMMNUNICATED

1- “Self Excited Induction Generator for Isolated Pico Hydro Power Plant in Remote Areas” Kailash Rana, Duli Chand Meena submitted in International Conference on Power Electronics, Intelligent Control and Energy system-ICPEICES2018.

2- “A Review on Self Excited Induction Generator for Renewable Energy Application in Remote Areas” Kailash Rana, Duli Chand Meena- submitted in Journal.

APPENDIX

1. The hydropower potential depends upon the head (H) availability and flowing discharge (Q), Thehydropotentialat turbine shaftcan be calculated from the following equation.

$$P = \eta \rho g Q H \quad (1.\ 1)$$

Where P = mechanical power produced (kW)

η = turbine hydraulic efficiency.

ρ = density of water (kg/m^3).

g = acceleration due to gravity (m/s^2).

Q = quantity of water flowing through the hydraulic turbine (m^3/s).

H = Net available head in meters (m)

While input torque can be computed by the following equation

$$T = P / \omega \quad (1.\ 2)$$

Where, ω = angular velocity of turbine runner (rad/s)

So, $\eta = 0.85$ $\rho = 1000$kg/m^3 g = 9.8m/s^2. Q = 0.1m^3/s H = 5m

Therefore, $P = \eta \rho g Q H$ = 4167 W = 4.167kW

And Torque (T) is given as P/ω, which is found to be 26.52 Nm

2. For the proper operation a suitable rating excitation capacitor is is required. Capacitor can be connected in Delta or Star form. The rating of the capacitor is chosen as per

Apparent power	$S = \sqrt{3}. V_L. I_L$ = 4000 VA
Active power	$P = S \cos\theta =$ 3.24 kW
Reactive power absorbed,	$Q = \sqrt{S^2 - P^2}$ = 2.345KVar
Per phase reactive power needed,	$q = \frac{Q}{3}$ = 781.66Var
Voltage per phase,	$V_P = \frac{V_L}{\sqrt{3}}$ = 230.9V
Capacitive current,	$I_C = \frac{Q}{V_P}$ = 3.38A
Per phase capacitive reactance,	$X_C = \frac{V_P}{I_C}$ = 68.3 ohm

Capacitance per phase, $= \frac{1}{2\pi f X_C}$ = 46μF per phase connected in star

So, for delta connection per phase capacitor value is 15.4μF

For the rated terminal voltage with load we used 23μF capacitor value per phase in delta connection and 69μF value capacitor per phase in star connection.

3. Electronic load controller with SEIG MATLAB/SIMULINK model is shown below

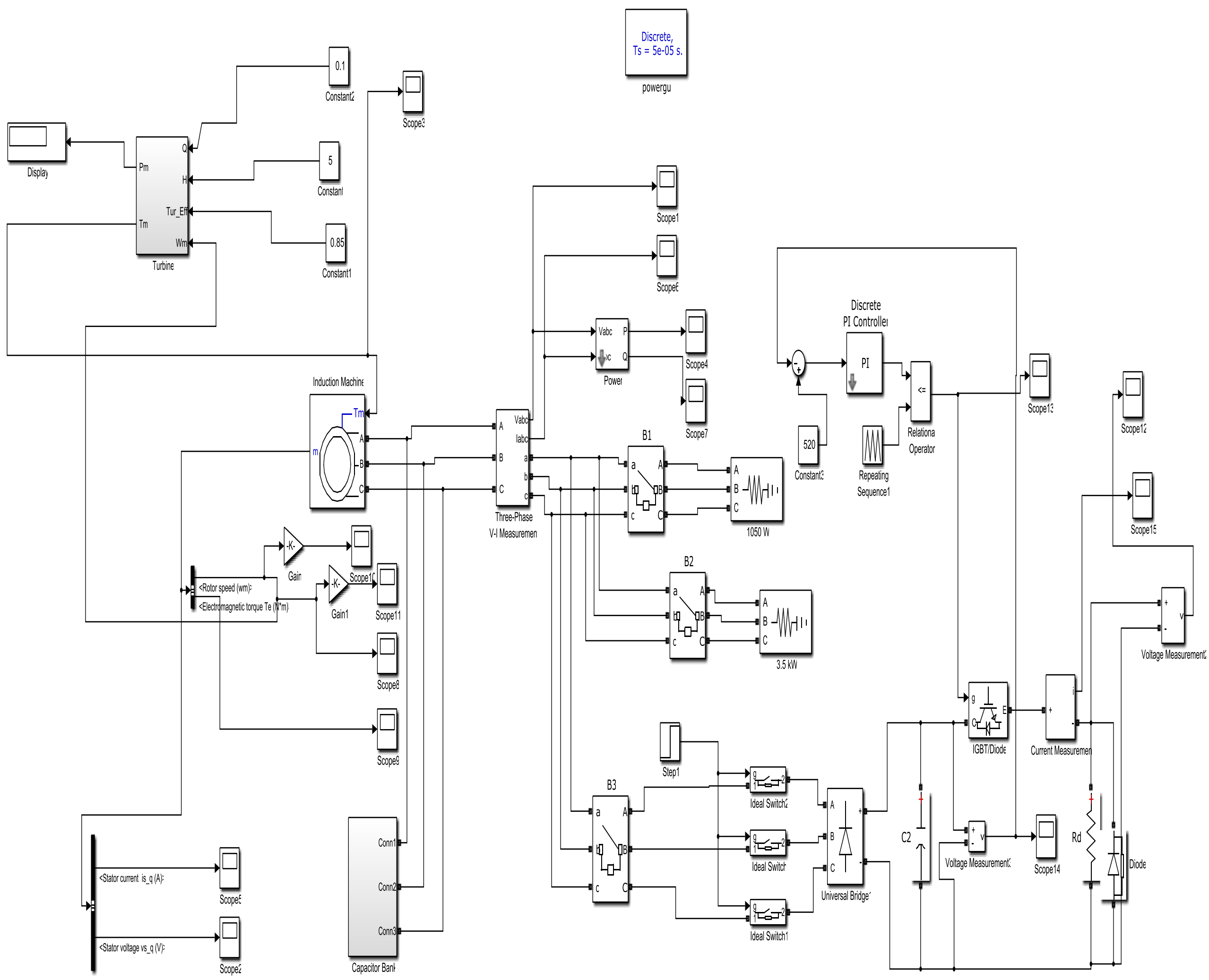


Figure. MATLAB/Simulink model of SEIG with ELC

The rating of the different components of the Electronic Load Controller is given as follows:

$$V_{DC} = {3\sqrt{2}V_{LL}}/{\pi} = (1.35)\, V_{LL} \quad (1)$$

V_{LL} is the Root Mean Square value of the line to line voltage of Generator.

For the 4 KW SEIG, the line voltage is 400V and the value of V_{DC} is given by

$$V_{DC} = (1.35) \times 400 = 540 \text{ V} \quad (2)$$

For transient condition an overvoltage of 10% of the rated voltage is considered;

so the Root Mean Square AC input voltage which will be with a peak value is obtained using

$$V_{peak} = \sqrt{2} \times 440 \text{ V} = 622.25 \text{ V} \quad (3)$$

During the operation of the system this peak voltage will appear across the components of ELC. The current rating of the chopper switch and uncontrolled rectifier is decided by active component of input AC current and calculated as

$$I_{AC} = \frac{P}{\sqrt{3}V_{LL}} \quad (4)$$

where V_{LL} is the RMS value of the SEIG terminal voltage and P is the power rating of SEIG. The current Iac of SEIG is calculated using

$$I_{AC} = \frac{4000}{\sqrt{3}\times 400} = 5.77 \text{ A} \quad (5)$$

The 3-phase uncontrolled rectifier draws approximately quasi-square current with the distortion factor of ($3/\pi$ = 0.955). The input AC current of ELC is calculated using

$$I_{DAC} = \frac{I_{AC}}{0.955} = \frac{5.77}{0.955} = 6.041 \text{ A} \quad (6)$$

The Crest Factor (CF) varies from 21.4 to 2.0 of the AC current drawn by an uncontrolled rectifier with a capacitive filter ; hence, the AC input peak current can be calculated using

$$I_{peak} = 2I_{DAC} = 2\times 6.041 = 12.083 \text{ A} \quad (7)$$

So the maximum voltage and peak current in the uncontrolled rectifier is 622.25 volts and 12.083 amperes, respectively. The rating of an uncontrolled rectifier and chopper switch is 700V and 15A, which is more than the calculated values, respectively.
The rating of auxiliary dump load resistance is calculated by using

$$R_D = \frac{V_{DC}^2}{P_{rated}} \quad (8)$$

From this equation, the value of R_D is computed with

$$R_D = \frac{540^2}{4000} = 72.9 \text{ ohm}$$

On the basis of the ripple factor the value of the DC link capacitance of the ELC is selected. The relation between the Ripple Factor (RF) and the value of DC link capacitance for a three-phase uncontrolled rectifier is given by

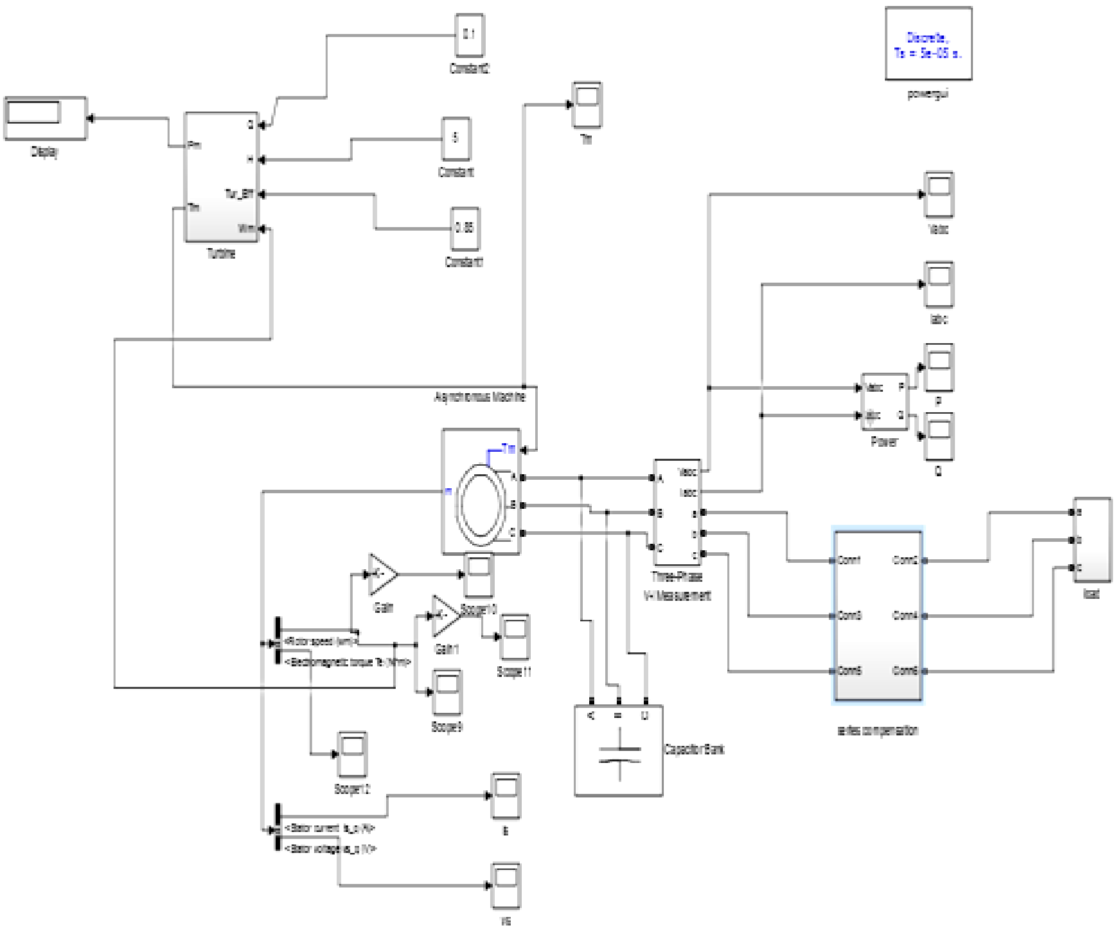
$$C = \left(\frac{1}{12\, fR_D}\right)\left(1 + \frac{1}{\sqrt{2}\, RF}\right) \quad (9)$$

In the average value of DC link voltage normally 5% ripple factor is permitted. The capacitance value is calculated using the previous formula which is given by

$$C = \left(\frac{1}{12 \times 50 \times 72.9}\right)\left(1 + \frac{1}{\sqrt{2} \times 0.05}\right) = 333.1\ \mu\text{F} \qquad (10)$$

The integral part of control mechanism involves the use of ELC which is basically a switching circuit using fast electronic switching devices such as IGBT or MOSFET to connect or disconnect dump load according to consumer load across the generator. As the consumer load increases, the corresponding decrease in DC link voltage forces the control circuit to decrease the on time of IGBT.

.4. Reactive power Compensation with series capacitor MATLAB/Simulink model



The value of series capacitor is obtained from compensation factor value (k) which is defined as the ratio of series capacitive reactance to shunt capacitive reactance.

$$k = \frac{\text{series capacitive reactance}}{\text{shunt capacitive reactance}}$$

The value of K varies between 1 and 0.4 suggested from articles [54] [55] .

The series capacitance value used is 120μF.