

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

Generation of Green free power has become the more popular in the field of electrical power generation. The depletion of fossil fuels, such as coal and oil, also aid to the importance of replacing to renewable and non-polluting energy sources such as solar, tidal, hydro and wind energy etc., among which wind energy is the most efficient and wide spread source of energy [1]. Wind is a free, clean, and inexhaustible energy source. The high capital costs and the uncertainty of the wind placed wind power at an economic disadvantageous position. In the past four decades' methods of harnessing hydro and wind energy for electric power generation and the technology for such alternate systems are developed. From the recent scenario it is also evident that wind energy is drawing a great deal of interest in the power generation sector. If the wind energy could be effectively captured it could solve the problems such as environmental pollution and unavailability of fossil fuel in future. The above fact gives the motivation for development of a wind power generation system which would have better performance and efficiency [2]. Continuous research is going on taking into account different critical issues in this sector.

Induction generators are increasingly being used these days because of their relative advantageous features over conventional synchronous generators. These features are brushless rugged construction, low cost, less maintenance, simple operation, self-protection against faults, good dynamic response and capability to generate power at varying speed. The small-scale power generating system for areas like remotely located single community, a military post or remote industry where extension of grid is not feasible may be termed as stand-alone generating system. Portable gen-sets, stand-by/emergency generators and captive power plants required for critical applications like hospitals, computer centres, and continuous industrial process come under the category of stand-alone generating systems. Self-excited induction generator is best suitable for generating electricity from wind, especially in remote areas, because they do not need an external power supply to produce the excitation magnetic field.

1.1.1 Classification of Induction Generators

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

(A). Classification on the basis of their rotor construction:

- Squirrel cage induction generator
- Wound rotor induction generator

(1). Squirrel Cage Induction Generator: - For the squirrel cage type induction generator, the rotor winding consists of uninsulated conductors, in the form of copper and aluminium bars embedded in the semi closed slots. These solid bars are short circuited at both ends by end rings of the same material. Without the rotor core, the rotor bars and end rings look like the cage of a squirrel. The rotor bars form a uniformly distributed winding in the rotor slots.

(2). Wound Rotor Induction Generator:-In the wound rotor type induction generator, the rotor slots accommodate an insulated distributed winding similar to that used on the stator. The wound rotor type of induction generator costs more and requires increased maintenance [1].

(B) Classification on the basis of their excitement process:

- Grid connected induction generator
- Self-excited induction generator

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

(2). Self-excited induction Generator: - when induction generator is connected with delta connected capacitor across stator terminal is called Self-excited induction generator which supply reactive power to stator and load, there is some residual

magnetism in the rotor core when rotor is rotated as enough speed then a voltage is induced across the stator terminal which provide reactive power for magnetism.

1.1.2 Self-excitation phenomenon and voltage build-up in SEIG: -When a standalone induction machine is driven by a mechanical prime mover, the residual magnetism in the rotor of the machine induces an EMF in the stator windings at a frequency proportional to the rotor speed. This EMF is applied to the capacitors connected to the stator terminals and causes reactive current to flow in the stator windings. Hence a magnetizing flux in the machine is established. The final value of the stator voltage is limited by the magnetic saturation within the machine. The induction machine is then capable of operating as a generator in isolated locations without a grid supply.

The process of voltage build-up in an induction generator is very much similar to that of a dc generator. When the rotor of induction generator is run, the residual magnetism present in rotor iron creates a small emf. across stator terminals. This voltage causes a capacitor current to flow. The flux due to current is added with residual flux and generates a stator terminal voltage. This voltage produces current in capacitor bank which then generates voltage. This cumulative process continues till the intersection point between saturated magnetization curve and capacitor load line. The intersection point gives no load generated e.m.f.at the magnetizing current. The voltage build process depends upon the capacitor value. Higher the value of capacitance, greater is the voltage build up. In the absence of a proper value of residual magnetism, the voltage will not build up. So it is desirable to maintain a high level of residual magnetism, as it does ease the process of machine excitation. The operating conditions resulting in demagnetization of the rotor (e.g., total collapse of voltage under resistive loads, rapid collapse of voltage due to short circuit, etc. should be avoided).

1.1.3 Performance Analysis of Self-Excited Induction generator: - The performance analysis of self excited induction generator can be categorized in to the following- (i) Steady state analysis (ii) transient analysis (iii) The parallel operation of SEIG.

(1) Steady-state Analysis: -In an isolated power system, both the terminal voltage and frequency are unknown and have to be computed for a given speed, capacitance, and load impedance. Therefore, both from the design and operational point of view, the steady state analysis of SEIG is of great interest.

(2) Transient state Analysis: -The transient studies of induction generators are related to voltage build-up due to self-excitation and load perturbation. To investigate the SEIG transient performance under balanced condition, the D-Q model can be used. Many articles have been presented on the transient/dynamic analysis of self-excited induction generator

(3) Parallel operation of SEIG: - A stand-alone SEIG is unlikely to supply energy demand of ordinarily growing loads for long time. Thus, multiple generators operating in parallel may be required to harvest the maximum energy available at a site. Parallel operation of induction generator has the advantages of eliminating the need for synchronization and of the associated problem with hunting etc.

Condition for parallel operation of SEIG: - (1) Phase sequence must be same (2) Terminal voltage should be same (3) All machine must be operating on same frequency (4) All machine should be synchronized without any noise (5) All machine may or may not be operate on same speed.

1.1.4 Advantages and Disadvantages of SEIGs: -

Advantages:

SEIG has many advantages such as simple construction, absence of DC power supply for excitation, reduced maintenance cost, good over speed capability, and self-short-circuit protection capability. Simple and robust construction Run Independently Inexpensive as compared to the conventional synchronous generator. Minimal maintenance Inherent overload protection - Stand-alone applications, no fixed frequency, Less material costs because of the use of electromagnets rather than permanent

Disadvantages:

Major drawbacks of SEIG are reactive power consumption, its relatively poor voltage and frequency regulation under varying prime mover speed, excitation capacitor and load characteristics. Requires significant reactive energy, Poor power factor, Poor voltage and frequency regulation.

1.1.5 Application of Induction Generator: - Induction generators, generally, have the application in the wind, solar and micro hydro power plants to generate power for various critical situations as given below.

Electrification of far flung areas:

Extension of national grid is not economical

Remote family

Village community

Small agricultural applications

Lighting and heating loads

For feeding critical locations:

Library

Computer canter

Hospitals

Telephone exchange

Cinema Hall Auditorium

Marketing complex

As a portable source of power supply:

Decorative lighting

Lightings for projects and constructional site

1.2 OBJECTIVE OF THESIS:

The objective of the thesis entitled “steady state analysis of three phase Parallel operated self-excited induction generator by three methods loop impedance method and nodal admittance method and optimization techniques. under saturation magnetic reactance conditions” is to analyse the steady state performance of parallel operated

SEIG for balanced loaded conditions under various loading conditions. A PSO model is formulated by different set of data obtained from simulation of machine using suitable MATLAB programme. The comparison of calculated data with machine validated data conforms the results validity and accuracy of the PSO model.

1.2 ORGANIZATION OF THESIS:

For better understanding of induction generator behaviour during balanced conditions, the work in the thesis entitled “steady state analysis of three phase parallel operated self excited induction generator for balanced load conditions” is carried out. The complete thesis work is divided into six chapters.

Chapter 1: This chapter, entitled as “Introduction”, includes the concept of the induction generator, updated classification of induction generator, phenomenon of self-excitation and voltage build and performance analysis of self-excited induction generator, advantage & disadvantage and its application. The updated literature survey on various aspects is also included in this chapter.

Chapter 2: This chapter, entitled as “Literature survey”, includes the concept of nodal Admittance/Loop impedance method and Optimization Techniques. PSO Model is formulated after prediction of data obtained from simulation by MATLAB programme. PSO Algorithm is used for Steady-state Analysis of parallel operated SEIGs under balanced conditions.

Chapter 3: This chapter, entitled as “Steady state analysis of parallel-operated SEIGs for balanced condition”, includes the steady state analysis of the SEIGs for Nodal Admittance model and Loop impedance method under balanced condition using MATLAB iterative method. The simulated results are validated with experimental results.

Chapter 4: This chapter, entitled as “Steady state analysis of parallel operated SEIG for balanced condition”, includes the steady state analysis of the SEIGs for Optimization techniques. under balanced condition PSO Model is formulated after data obtained from simulation by using MATLAB programme iterative method. The results obtained are validated with the experimental results.

Chapter 5: This chapter, entitled as “Results and Discussion on various characteristics of Steady state analysis of Parallel operated Self-Excited Induction generators under balanced loaded conditions.

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

CHAPTER 2

LITERATURE SURVEY

Steady-state analysis of three phase parallel-operated SEIG is of interest, both from the design and operational points of view. In a capacitor-excited generator used as an isolated power source, both the terminal voltage and frequency are unknown and have to be computed for a given speed, capacitance and load impedance. A large number of articles have appeared on the steady-state analysis of the parallel-operated SEIG [1, 6, 22, 34-51].

A.H. Al-Bahraini & N.H. Malik, IEEE [1993]. Steady state analysis of parallel-operated self excited induction generators, a mathematical model is predicted steady-state performance characteristics of three phase self-excited induction generators operating in parallel and supplying balanced load. non-linear required in steady-state analysis of an N machine operating with different speed and different parameters and their performance characteristics can be accurately predicted. Performance characteristics of such machine are influenced by their excitation capacitance, load impedance and load power factor as well as speed parameters and magnetizing characteristics.

Ching-Huei Lee & Li Wang, MIEEE [1998]. A Novel Analysis of parallel-operated Self-excited induction generators, have approach based on eigenvalue and eigenvalue sensitivity analysis to predict both minimum and maximum values of capacitance required for self-excitation of parallel operated three phase induction generators.

F.A. Farrat, B. Palle and M.G. Simoes [2005]. Full expandable model of parallel self-excited induction generators, have proposed SEIGs model is applied to a two turbine case, which can be extended to simulate a wind generating system, an innovative and automatic numerical solution for steady-state and Transient analysis of any number of SEIGs operating in parallel.

A.H. Al-Bahraini & N.H. Malik [1993]. Voltage control of parallel operated self-excited induction generators, have describes two methods of analysis to control the common bus voltage of any number of parallel self-excited induction generators, SEIGs under the steady state balanced condition, Proposed method is simple and applied for single and group of SEIGs operating with equal and unequal prime mover speed.

Ajit K. Chattopadhyay & Ch. Chakraborty [1999]. Analysis of parallel-operated self-excited induction generators, have worked on steady-state performance of self-excited induction generator operating in parallel, analysis is based on voltage and current balance equation derived from inverse model for steady state equivalent circuit of induction machines.

Dr. Ammasaigouden & M. Subbiah et al. [1989]. Wind-driven self-excited pole changing induction generators, proposed two solution technique for the steady state analysis of SEIG. The first technique is based on the loop impedance method and the second technique is based on the nodal admittance method. The iterative technique by assuming some initial value for f and then solving for a new value considering a small increment until the result converges. This technique, however, lacks in making a judicious choice of an initial value and number of iterations required.

Dr. N. kumareshan et al. [2012]. Major methods of steady-state analysis of three phase SEIGs- A summary, have adopted the loop impedance expression, and obtained the following quadratic equation with the magnetizing reactance, X_m of the generator as the variable, by equating the real and reactive parts of the equation separately to zero. Jordon et al. [2000]. Presented a technique for Steady-state analysis of SEIG feeding balanced unity power factor load using artificial Neural Network. and also proposed a multi-objective genetic Algorithm based approach for determining the Steady-state performance characteristics of three phase Self-excited induction generators operating in parallel.

S. P. Singh et al. [2011] tried an optimization technique by formulating as a multivariate unconstrained nonlinear optimization problem. The impedance of the machine is taken as an objective function. The f and X_m are selected as independent variables, which are allowed to vary within their upper and lower limits so as to achieve practically acceptable values of the variables. The Rosen Brock's method of rotating coordinates has been used for solving the problem.

Murthy et al. [1999] developed a mathematical model to obtain the steady-state performance of SEIG using the equivalent circuit impedance of the machine. Two nonlinear equations, which are real and imaginary parts of the impedance, are solved for two unknowns and using Newton–Raphson method.

Quazene et al. [1989] used a nodal admittance technique to obtain a nodal equation and then separated it into its real and imaginary parts to solve for ' f ' and then for ' X_m '.

A.I. Alolah et al. [2000] present an optimization method to determine the excitation requirements of three-phase SEIG under single phase mode of operation. A single phase load is connected to the generator through two excitation capacitors. The values of these capacitors are chosen to ensure minimum self-excitation of the machine in addition to minimization of the unbalance between the stator voltages.

A.M. Estimably, [1999] presents a new formula to determine the minimum capacitance required for self-excited induction generator, which uses nodal analysis instead of loop analysis.

Induction generator is the most common generator in wind energy systems because of its simplicity, ruggedness, little maintenance, price and etc. The main drawback in induction generator its need of reactive power to build up the terminal voltage and to maintain the voltage. Using terminal capacitor across generator terminals can generate this leading reactive power. The process of voltage build-up in an induction generator is very much similar to that of a dc generator. There must be a suitable value of residual magnetism present in the rotor. So it is desirable to maintain.

CHAPTER 3

3.1 INTRODUCTION

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

3.2 STEADY-STATE MODEL OF THREE PHASE PARALLEL-OP (SEIGs)

For the modelling of the parallel operated self-excited induction generator the main flux path saturation is accounted for while the saturation in the leakage flux path of the core of the machine, the iron and rotational losses are neglected [31]. Most of the steady-state models of SEIGs developed by different researchers are based on per phase equivalent circuit. these models use the following two basics methods: (1) Loop impedance method (11) Nodal admittance method.

3.2.1 NODAL ADMITTANCE METHOD(SEIGs)

For the Steady-state analysis, the following assumptions are made Only the magnetizing reactance is assumed to be affected by magnetic saturation, and all other parameters of the equivalent circuit are assumed to be constant. Self-excitation results in the saturation of the main flux. As the value of the magnetizing reactance X_m reflects the magnitude of the main flux, it is essential to incorporate in the analysis the variation of X_m with the saturation level of the main flux. Leakage reactance of stator and rotor, in per unit, are taken to be equal. This assumption is normally valid in induction-machine analysis.

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

- (2) MMF space harmonics and time harmonics in the induced voltage and current waveforms are ignored. This assumption is valid in well-designed machines.
- (3) Machine parameters (except for magnetizing reactance) remain constant.
- (4) This Model makes assumptions that the load is RL .

The steady-state per phase equivalent circuit of parallel operated SEIGs supplying a balanced resistive load, is shown in Figure2. In this circuit, the impedance line corresponding to the parallel combination of the load impedance and excitation capacitance should intersect the magnetization characteristics well in to the saturation region. For the self-excitation of the machine on no load, the excitation capacitance must be larger than required minimum value, this minimum value decreases with decreasing speed. For the circuit shown in the figure 3.by using Kirchhoff's current law, the algebraic sum of currents at node (1) should be equal to zero, therefore

(1) Proposed Model

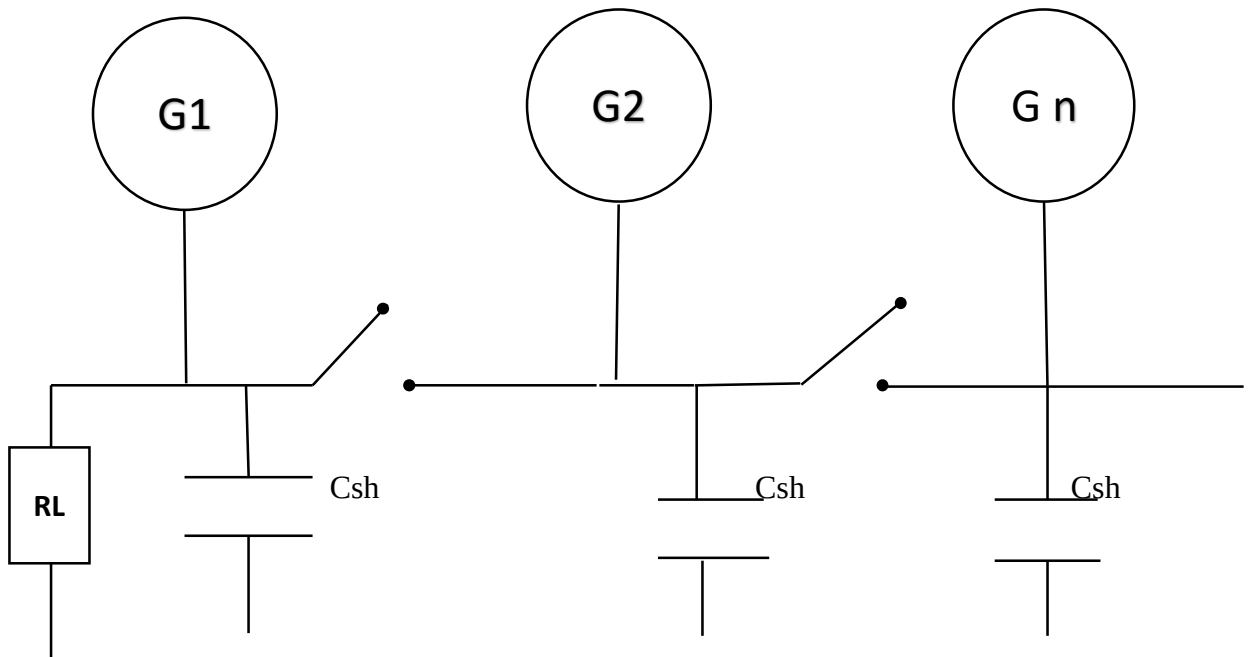


Figure1.1: - Proposed model of parallel operated SEIGs

Figure 1 Shows N induction machine connected to the same bus across an excitation capacitor Csh and a load impedance RL. Assume that these N machine are being driven at per unit speeds of $v_1, v_2, v_3, \dots, v_n$ respectively. In parallel operation, all machine will operate at a common per-unit frequency f.

(2) Existence model

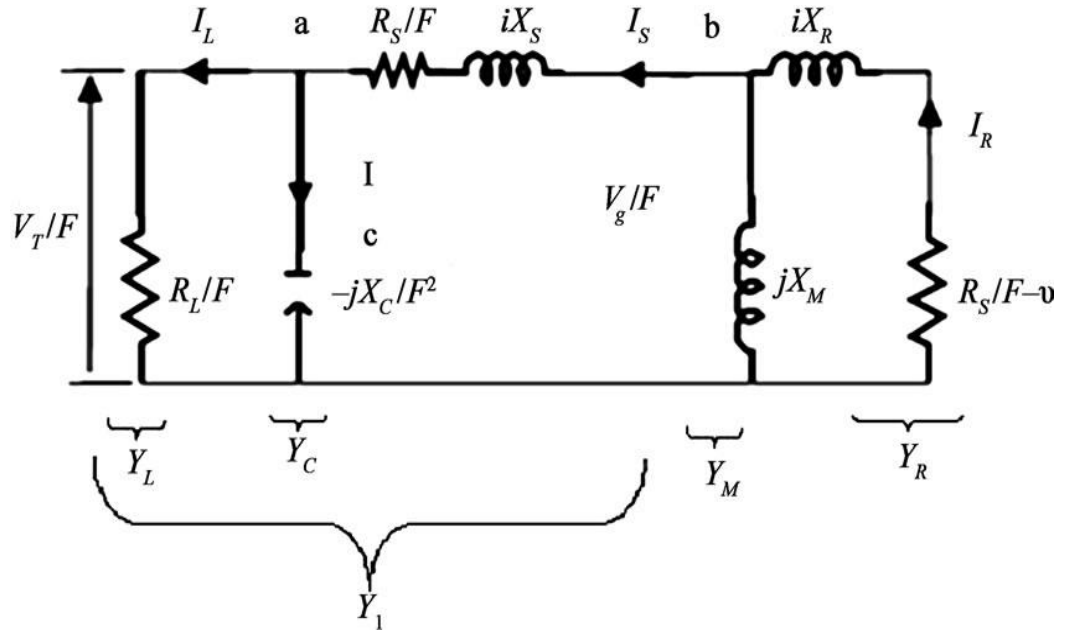


Fig:1.2 Per phase Equivalent circuit of three phase SEIGs

From the equivalent circuit of three phase SEIGs

$$V_i Y_i = 0 \quad (1)$$

Where Y is the net admittance given by

$$V_i = Y_L + Y_C + Y_2 \quad (2)$$

The terminal voltage cannot be equal to zero therefore

$$Y_i = 0 \quad (3)$$

By equating the real and imaginary terms in equation (3) respectively to zero

we have

$$\text{Real } (Y_L + Y_C + Y_2) = 0 \quad (4)$$

$$\text{Image } (Y_L + Y_C + Y_2) = 0 \quad (5)$$

3.2.2 MATHEMATICAL FORMULATION

For self-Excitation process in Induction machine to initiate when the rotor is driven by a prime mover. Capacitor bank of suitable size must be connected across the stator terminals. The Machine core retains some residual flux, inherently depend upon machine configuration. Both the frequency and the magnetizing reactance (which depends upon magnetic saturation) of the SEIGs vary with load even when the rotor speed is maintained constant [34]. Therefore, a main step in the Steady-state analysis of parallel operated SEIGs is, given the machine parameters, speed, excitation capacitance, and load impedance, to determine the value of the per-unit frequency and the magnetizing reactance X_m which result in exact balance of active and reactive power across the air gap.

From the equivalent circuit of parallel operated SEIGs

R_s : p.u resistance of stator per phase

R_r : p.u resistance of rotor per phase

X_s : p.u reactance of stator per phase

X_r : p.u reactance of rotor per phase

X_m : p.u magnetizing reactance per

f : p.u frequency V : p.u speed

R_L : p.u resistance of the load per phase

X_L : p.u reactance of the load per phase

The nodal admittance model is used for steady state analysis of parallel operated SEIGs [35]. The per phase equivalent circuit of SEIGs shown in the figures2 is used for mathematical formulation. The formulation of synchronization of real and reactive power in terms of network quantities is equivalent to writing that the sum of admittances of the branches in the circuit must be zero, as it is seen that this circuit does not contain any e.m.f source.

$$V_{gi}(Y_{bc} + Y_m + Y_r) = 0 \quad (6)$$

Where

$$Y_{bc} = \frac{1}{R_{ti} - jB_{ti}} = G_{ti} + jB_{ti} \quad (7)$$

$$G_{ti} = \frac{R_t}{R_{ti}^2 + X_{ti}^2} \quad \& \quad B_{ti} = \frac{X_t}{R_{ti}^2 + X_{ti}^2} \quad (8)$$

$$R_{ti} = \left(R_{ab} + \frac{R_{si}}{f}\right) \quad \& \quad X_{ti} = (X_{ab} - X_{si}) \quad (9)$$

$$R_{ab} = \frac{R_L X_C^2}{f[f^2 R_L^2 + (X_L f^2 - X_C^2)2]} \quad (10)$$

$$X_{ab} = \frac{X_L X_C^2 - f^2 X_L^2 X_C - R_L X_C^2}{f^2 R_L^2 + ((X_L f^2 - X_C^2)^2)} \quad (11)$$

$$Y_{mi} = \frac{1}{jX_{mi}} \quad (12)$$

$$Y_{ri} = \frac{1}{\frac{R_{ri}}{(f-vi)} + jX_{ri}} \quad (13)$$

For voltage build-up, $v_{gi} \neq 0$, hence equation (1) becomes

$$(Y_{bci} + Y_{mi} + Y_{ri}) = 0 \quad (14)$$

Equating the real and imaginary parts in equation (9) to zero, we have

$$G_t + \frac{\frac{R_t}{f-v}}{\left(\frac{R_r}{f-v}\right)^2 + X_r^2} = 0 \quad (15)$$

$$\& \quad B_t - \frac{1}{X_{mi}} - \frac{X_{ri}}{\left(\frac{R_{ri}}{f-vi}\right)^2 + X_{ri}^2} = 0 \quad (16)$$

$$\text{Let } \gamma i = f - vi \quad (17)$$

Equation (10) can be rewritten as a quadratic equation in γ as:

$$G_t X_{ri}^2 \gamma i^2 + R_{ri} \gamma i + G_t R_{ri}^2 = 0 \quad (18)$$

Solving equation (13), we get

$$\gamma i = -\frac{R_{ri}}{2G_t X_t^2} \{1 \pm \sqrt{1 - 4G_t^2 X_{ri}^2}\} \quad (19)$$

In practice, γi is small negative number for generator operation; the negative sign in the brackets of equation (14) should be taken.

$$\gamma i = -\frac{R_{ri}}{2G_t X_t^2} \{1 - \sqrt{1 - 4G_t^2 X_{ri}^2}\} \quad (20)$$

For a given rotor speed, load impedance and excitation capacitance, equation 10 May be used to determine f , by using equation (11), we calculate the value of X_{mi} as by given equation (16).

$$X_{mi} = \frac{\left(R_L + \frac{R_{Si}}{f}\right) \left[\left(\frac{R_{ri}}{f - \gamma i}\right)^2 + X_{ri}^2\right]}{\left[\left(\frac{R_{ri}}{f - \gamma i}\right)(X_{Si} - X_L) - X_{ri}\left(R_L + \frac{R_{Si}}{f}\right)\right]} \quad (21)$$

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

$$I_{Si} = \frac{V_{gi}}{f} Y_{bc} \quad (22)$$

$$V_{Si} = \frac{V_{gi}}{f} = I_{Si} Z_{ac} \quad (23)$$

$$I_{Ci} = \frac{V_{abi}}{\frac{-jX_c}{f^2}} \quad (24)$$

$$I_{Li} = I_{Si} - I_{Ci} \quad (25)$$

$$P_{OUT} = V_{abi} I_{Li} \quad (26)$$

3.2.3 COMPUTATIONAL ALGORITHM

The step by step procedure of algorithm for solution of ' X_{mi} ' and ' f ' and subsequent performance of SEIGs using MATLAB are as follows:

Step 1: Read the machine parameters (R_{si} , X_{si} , R , X_{ri}), capacitive reactance X_c , load R_L , prime mover speed, p.f of load, and synchronous speed test data etc.

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

Step 3: Calculate the value of $K_1(i)$, $K_2(i)$, $K_0(i)$ at loaded condition and Evaluate the $G_t(i)$ using equations (6) - (9).

Step 4: Determine γ_i value by using equation (18); hence obtain the updated value of ' f ' using equation (15).

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

Step 6: By getting the value of ' f ' calculate the value of X_{mi} by using equation (19)

Step 7: By using the magnetizations curve (Eg v/s X_m), determine E_{gi} and correspondingly find the value of voltage and current across the load branch by using eq. (20) to eq. (24).

Step 8: Store the relevant data in data file.

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

Step 10: stop

3.2.4 PERFORMANCE CHARACTERISTICS

Performance characteristics of parallel operation of induction generators, two types of machine were used, namely, a squirrel-cage machine (SCM) and a wound-rotor machine (WRM).

The measured per unit variations of the air gap voltages $\frac{E_g}{f}$, based on 220 v with X_m for the two machine are approximated over the practical range of saturation of machine as follows;

SCIM: -Squirrel cage induction machine

*Relation between Airgap voltage (Eg) and magnetizing reactance (Xm).

$$\frac{E_g}{f} = 2.4408 - 0.6080 * X_m \text{ for } X_m \leq 2.3839;$$

$$3.4592 - 1.0352 * X_m \text{ for } 2.3839 \leq X_m \leq 2.8116;$$

$$9.7841 - 3.2848 * X_m \text{ for } X_m > 2.8116.$$

***WRIM:- Wound Rotor induction machine**

*Relation between Airgap voltage (Eg) and magnetizing reactance (Xm).

$$\frac{E_g}{f} = 1.0007 - 0.1741 * X_m \text{ for } X_m \leq 1.3666;$$

$$1.4298 - 0.4881 * X_m \text{ for } 1.3666 \leq X_m \leq 1.7707;$$

$$3.0192 - 1.3857 * X_m \text{ for } X_m > 1.7707.$$

***Machine parameters are given below**

WRM: R1=0.09175, R2=0.06354, X1=0.2112, X2=0.2112, at C=40μF and upf

SCM: R1=0.16543, R2=0.09324, X1=0.1060, X2=0.1060, at C=40μF and upf

***Condition for self-excitation**

When N machine are connected in parallel, any machine will maintain self-excitation, if it operates in saturation region of its own magnetizing characteristics thus, when $X_{mi} \leq X_{max}$, machine i can maintain self-excitation. Self-excitation is only possible when $C_{min} \leq C \leq C_{max}$. It is also important to know that at which minimum value of C all parallel-operated machine will maintain self-excitation under steady-state conditions, therefore range for excitation capacitance is necessary which can provide sufficient reactive power to sustain the charging current to excite the machine. C_{min} and C_{max} for the WRM and SCM types machine is given here in below

M-Type	Speed	No load	No load	RL-load	RL- load
		Cmin (μf)	Cmax (μf)	Cmin (μf)	Cmax (μf)
WRM (1)	1.0	136.2	1239	170.2	1145.0
WRM (2)	0.8	137	1245	170.6	1151.5
SCM (1)	1.0	137.8	1237	171.6	1144.5
SCM (2)	0.8	140	1246	174.8	1152.0

Table 1.1 C min and C max values at no-load and loaded condition

3.2.5 NODAL ADMITTANCE M- CODING

%machine parameter as given below.

```
L=[0.16543 0.09324 0.1060 0.1060;  
0.09175 0.06354 0.2112 0.2112;0.16543 0.09324 0.1060 0.1060;  
0.09175 0.06354 0.2112 0.2112];
```

```
Rs=L(:,1);
```

```
Rr=L(:,2);
```

```
Xs=L(:,3);
```

```
Xr=L(:,4);
```

% load parameter.

```
R=60.0;
```

```
X=0.0;
```

```
C=40*10^-6;
```

```
Xc=79.61;
```

```
f=50;
```

% read the per unit frequency

```
a=1;
```

%find the value of k0, k1, k2 at load condition.

for i=1:1:4;

```
K2(i)=(a)^5*(((Rs(i))*(X)^2*(Xr(i))^2)+(a)^3*(((R)^2*(Rs(i))*(Xr(i))^2)-  
((2)*(Rs(i))*(X)*(Xr(i))^2*(Xc)))+(a)*(((Rs(i))*(Xr(i))^2*(Xc)^2)+((R)*(Xr(i))^2*(  
Xc)^2)));
```

```
K1(i)=(a)^6*(((2)*(Rs(i))*(X)^2*(Xr(i))^2)-((Rr(i))*(X)^2*(Xs(i))^2)))+(a)^4*(((2)  
*(R)^2*(Rs(i))*(Xr(i))^2)+((4)*(Rs(i))*(X)*(Xr(i))^2*(Xc))-  
((R)^2*(Rr(i))*(Xs(i))^2)+((2)*(Rr(i))*(X)*(Xs(i))^2*(Xc))-  
((Rs(i))^2*(Rr(i))*(X)^2)+((2)*(Rr(i))*(X)^2*(Xs(i))*(Xc)))+(a)^2*(((2)  
*(Rs(i))*(Xr(i))^2*(Xc)^2)-((2)*(R)*(Xr(i))^2*(Xc)^2)-((Rr(i))*(Xs(i))^2*(Xc)^2)-  
((R)^2*(Rs(i))^2*(Rr(i)))+(2)*(Rs(i))^2*(Rr(i))*(X)*(Xc))-  
((Rr(i))*(X)^2*(Xc)^2)+(2)*(R)^2*(Rr(i))*(Xs(i))*(Xc))-  
((2)*(Rr(i))*(X)*(Xs(i))*(Xc)^2)+(-(Rs(i))^2*(Rr(i))*(Xc)^2)-  
((R)^2*(Rr(i))*(Xc)^2)-((2)*(R)*(Rs(i))*(Rr(i))*(Xc)^2)));
```

```
G(i) = -(K1(i)+((2)*(a)*(K2(i))));
```

```
D(i)=(G(i))^2-(4*((Rr(i))^2/(Xr(i))^2)*(K2(i))^2));
```

```

b(i)=-(K1(i)+sqrt(D(i)))/((2)*(K2(i)));
S(i)=-
((((Rr(i))^2)*(K2(i)))/((Xr(i))^2)*(a)*(G(i)))+((((Rr(i))^4)*((K2(i))^3))/((Xr(i))^4)
*(a)*((G(i))^3))));
RL=((R)*(Xc)^2)/((a)*(((a)^2*(R)^2)+(((a)^2*(X))-Xc))^2));
XL=(((-X)*(Xc))+((R)^2)+((a)^2*(X)^2)*(Xc))/(((a)^2*(R)^2)+(((a)^2*(X))-
(Xc))^2));
end
%CALCULATE THE VALUE OF Xm.
for i=1:1:4;
    Xm(i)=((RL)+((Rs(i))/(a)))*(((Xr(i))^2+((Rr(i))/(a-b(i)))^2))/((((Rr(i))/(a-
b(i)))*(Xs(i)-XL))-((Xr(i))*((RL)+((Rs(i))/(a))))));
    E(i)=150.96-1.3857*Xm(i);
    Vp(i)=sqrt(((RL)^2+(XL)^2)/((((Rs(i)/a)+RL)^2+(Xs(i)- XL)^2)))*(a)*(E(i));
    Ip(i)=Vp(i)/sqrt(R^2+(a)^2*(X)^2);
    Z=sqrt(R^2+(a)^2*(X)^2);
    Vt(i)=(sqrt((((RL)^2+(XL+(Xc/a^2))^2))/((((Rs(i))/(a)+RL)^2+((Xs(i))-
(Xc/Xs(i)*a^2)-(Xr(i)))^2))))*(a)*(E(i));
    IL(i)=(Vt(i))/sqrt((Rr(i)/(a-b(i)))^2+Xr(i)^2));
    Vc(i)=E(i)*(sqrt((RL)^2+(XL)^2)/sqrt((RL+Rs(i)/a)^2+(Xs(i)-XL)^2));
    Ic(i)=(((a)^2)*Vc(i))/(-Xc);
    Pout(i)=((3)*(Vt(i))*(IL(i)));
    Pm(i)=(((3)*((IL(i))^2)*(Rr(i)))*((b(i))/(a-b(i))));
end,

```

3.3 LOOP IMPEDANCE METHOD

3.3.1 INTRODUCTION

It is well known that an externally driven induction machine can sustain self-excitation when an appropriate value of a capacitor bank is properly connected across its stator terminals [1]. Brushless construction with squirrel-cage rotor, reduced size, absence of DC power supply for excitation, reduced maintenance cost, and better steady-state performance are the main advantages of induction generators over synchronous generators. In recent years, self-excited induction generator has been employed as suitable isolated power sources in hydroelectric and wind energy application where a number of machine operated synchronized parallel to obtain maximum output power and maximum efficiency. In wind power generating system, physical size of the individual machines, operating at maximum efficiency, normal care maintenance, future growth and reliability are the reasons to be operated in parallel.

3.3.2 EQUIVALENT ELECTRICAL CIRCUIT OF SEIGs

(1) proposed model

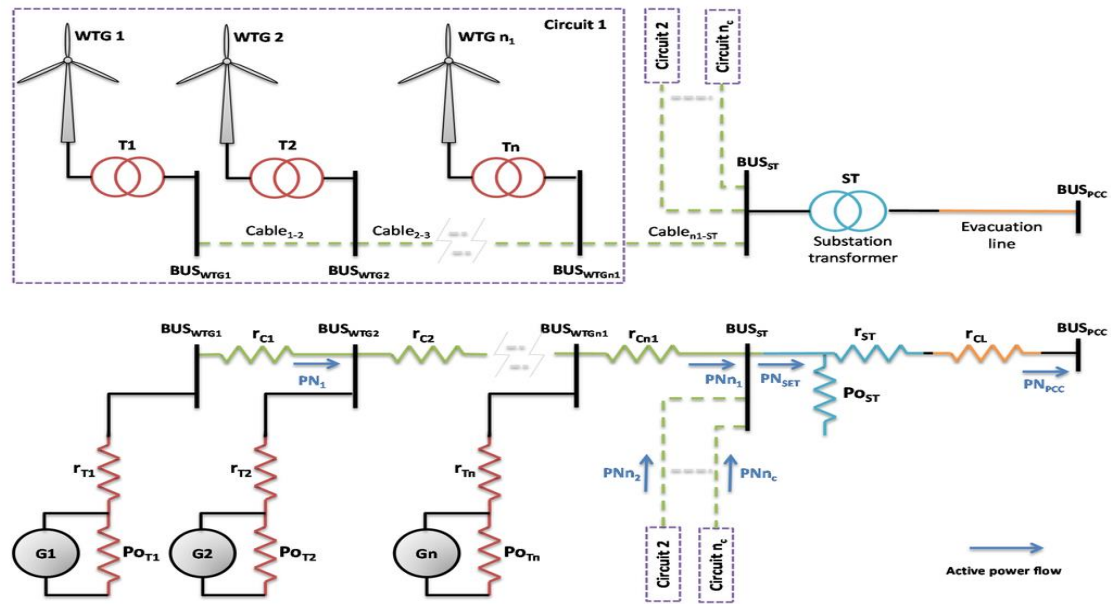


Figure:1.3- proposed model of parallel-operated SEIGs

(2) Existence model

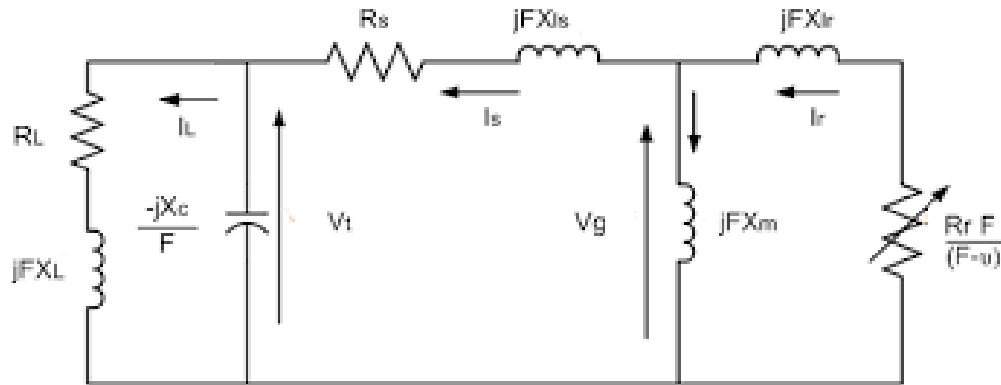


Figure:1.4. Per Phase Equivalent circuit of SEIGs

3.3.3 STEADY STATE SELF-EXCITED SEIGs MODEL

The Analysis of the induction generator can be made under the Steady-state operation using Per Phase Equivalent circuit of the induction machine. However, as The operating frequency of the generator varies with the driving speed and load, the per unit per phase Steady state equivalent circuit of a Self-Excited generator under RL load is shown in Figure 3.6. Where all parameters are referred to the rated frequency.

In the analysis of SEIG the following assumption are made:

- (1) Only the magnetizing reactance X_m is assumed to be affected by magnetic saturation, and all other parameters of the equivalent circuit are assumed to be constant.
- (2) Self-excitation results in the saturation of the main flux and the value of X_m reflect the magnitude of the main flux.
- (3) Leakage flux passes mainly in the air, and thus these fluxes are not affected to any large extent by the saturation of the main flux.
- (4) Stator and rotor leakage reactance, in per-unit are taken to be equal.
- (5) Core loss is neglected.

These assumptions are normally valid in induction machine analysis.

3.3.4 MATHMETICAL FORMULATION

When N number of machines operate in parallel (fig3) the terminal voltage (i.e. the common bus or load voltage) and frequency for all the N machines remain same, whatever may be the individual machines speeds and loading conditions. Fig (1). Shows the ith generators connected to the common load, All the circuit element except the magnetizing reactance, i.e. X_m 's is assumed to remain constant. The magnetizing reactance changes with speed and load, and changes are accounted using the rms saturation characteristics of machines. With reference to fig (4). The following voltage equation expressed in terms of per phase, can be written for ith machine.

For the circuit shown in Figure 4.

$$\frac{V_{ti}}{f} = -Z_{si} I_{si} \text{ for } i=1,2, 3, \dots, N \quad (1)$$

$$Z_{si} = \left[\frac{R_{si}}{f} + jX_{mi} \right] + \left[ja_i X_{mi} \parallel a_i^2 \left(\frac{R_{ri}}{f-v} \right) \right] \quad (2)$$

$$\text{In which } a_i = \frac{X_{mi}}{X_{mi} + X_{lri}} \text{ and } X_{oi} = X_{lsi} + a_i X_{lri} \quad (3)$$

Equating the real and reactive parts of above equation Separately to Zero and Simplifying, above equation in term of per unit frequency can be obtained from load impedance, excitation capacitance and rotor speed in the form of 7th order polynomial, which is rewritten as $P_7 a^7 + P_6 a^6 + P_5 a^5 + P_4 a^4 + P_3 a^3 + P_2 a^2 + P_1 a + a_0 = 0$ Where the coefficients $P_0, P_1, \dots, P_7$ are function of

$[R_1, R_2, X_1, X_2, XC, R, X \text{ and } b]$. The 7th order polynomial has to be solved only by Numerical techniques. Here Explicit relationship between 'a', and 'b' is not evaluated and so a close form solution for slip cannot be obtained in this method. To overcome these problems Eqn.2 is written as a polynomial in Per unit speed b and results in a simple quadratic equation as.

$$K_2(i)b^2 + K_1(i)b + K_0(i) = 0 \quad (4)$$

Where

$$K_2(i) = [D_3(i)D_4(i) + X_1 D_3^2(i) + X_2 D_3^2(i) - a^2 R D_2(i)]$$

$$K_1(i) = [X_2 D_3(i) D_4(i) + X_1 X_2 D_3^2(i) + X_1 D_3(i) D_4(i) + X_1 D_3(i) D_4(i) + X_1^2 D_3^2(i) + X_1 X_2 D_3^2(i) + D_4^2(i) + X_1 D_3(i) D_4(i) + X_2 D_3(i) D_4(i) - a^2 R X_2 D_1(i) + D_1(i) D_2(i)]$$

$$K_0(i) = [X_1 X_2 D_3(i) D_4(i) + X_1 X_2 D_3(i) D_4(i) + X_2 D_1^2(i) + X_2 D_4^2(i) + X_1^2 X_2 D_3^2(i)]$$

Where

$$D_1(i) = R X_C + R_1(i) X_C - a^2 (R_1(i) X + R_X)$$

$$D_2(i) = D_1(i) - a^2 R X_2(i)$$

$$D_3(i) = a(X X_C + R R_1(i))$$

From eqn. (4), b can be Expressed as.

$$b(i) = \frac{-K_1 \pm \sqrt{K_1^2 - 4K_2 K_0}}{2K_2} \quad (5)$$

From operating slip of the machine S, we can calculate Load parameters R_L and X_L .

$$R_L = \frac{R X_C^2}{a[a^2 R^2 + (a^2 X - X_C)^2]} \quad (6)$$

$$X_L = \frac{[-X X_C + R^2 + a^2 X^2] X_C}{[a^2 R^2 + (a^2 X - X_C)^2]} \quad (7)$$

$$X_{mi} = \frac{\left[R_L + \left(\frac{R_{1i}}{a} \right) \right] [X_{2i}^2 + (R_{2i} / (a - bi))^2]}{\left[\frac{R_{2i}}{(a - bi)} \right] [(X_1 - X_L) - X_{2i} i \left[(R_L + \frac{R_{1i}}{a}) \right]}} \quad (8)$$

Calculate the air gap voltage from a knowledge of the magnetization characteristics of the machine. The terminal voltage V_t , Load current I_L and power output P_{out} can be obtained from equivalent circuit shown in figure 4.

$$V_t(i) = \sqrt{\frac{(R_L^2 + X_L^2)}{(\frac{R_1}{a} + R_L)^2 + (X_1 - X_L)^2}} * a E \quad (9)$$

$$I_L(i) = \frac{V_t(i)}{\sqrt{R^2 + X^2} a^2} \quad (10)$$

$$P_{out}(i) = 3V_L \left(\frac{R}{Z} \right) \quad (11)$$

The mechanical input power to the rotor of the generator is known as.

$$P_m(i) = -3I_2^2(i)R_2(i) \left[\frac{b(i)}{a-b(i)} \right] \quad (12)$$

3.3.5 COMPUTATIONAL ALGORITHM:

Step 1 Read the value of machine parameters $R1, R2, X1, X2, Pf, f$ and magnetisation reactance characteristics saturation curve in which E is a function of Xm .

STEP 2 write Load parameter and excitation capacitance value

$$R = 50, X = 0, \text{ and } C = 40 \mu f, X_c = 79.61 \Omega$$

STEP 3 Compute value of $D1(i), D2(i), D3(i), D4(i)$ for evaluating the values of $K1(i), K2(i), K0(i)$ **STEP 4** find the value of $Xm(i)$ with known value of $K1(i), K2(i), K0(i)$ from quadratic Equation.

STEP 5 Compute the value of b from the equation

$$b(i) = a + M2 / M1 \text{ or } b(i) = a + N2 / N1$$

Where $M2, M1$ and $N2, N1$ are set of machine parameters.

STEP 6 calculate the performance of machine parameters V, P_{in}, P_{out}, P_m and η from the given equation above.

3.3.6 PERFORMANCE CHARACTERISTICS

Performance characteristics of parallel operation of induction generators, two types of machine were used, namely, a squirrel-cage machine (SCM) and a wound-rotor machine (WRM).

The measured per unit variations of the air gap voltages $\frac{E_g}{f}$, based on 220 v with X_m for the two machine are approximated over the practical range of saturation of machine as follows;

SCIM: -Squirrel cage induction machine

*Relation between Airgap voltage (Eg) and magnetizing reactance (Xm).

$$\frac{E_g}{f} = 2.4408 - 0.6080 * X_m \text{ for } X_m \leq 2.3839;$$

$$3.4592 - 1.0352 * X_m \text{ for } 2.3839 \leq X_m \leq 2.8116;$$

$$9.7841 - 3.2848 * X_m \text{ for } X_m > 2.8116.$$

***WRIM:- Wound Rotor induction machine**

*Relation between Airgap voltage (Eg) and magnetizing reactance (Xm).

$$\frac{E_g}{f} = 1.0007 - 0.1741 * X_m \text{ for } X_m \leq 1.3666;$$

$$1.4298 - 0.4881 * X_m \text{ for } 1.3666 \leq X_m \leq 1.7707;$$

$$3.0192 - 1.3857 * X_m \text{ for } X_m > 1.7707.$$

***Machine parameters are given below**

WRIM: R1=0.09175, R2=0.06354, X1=0.2112, X2=0.2112, at C=40μF and upf

SCIM: R1=0.16543, R2=0.09324, X1=0.1060, X2=0.1060, at C=40μF and upf

MACHINE 1 (SCIM)

R1=0.16543, R2=0.09324, X1=0.1060, X2=0.1060, at C=40 μ F and upf

a	B	Xm	E	Vt	Ip	Ic	Pout	Pm	η	f	R	Nr
1.0	1.0063	2.444	18.41	3.918	1.83	0.229	4.587	4.615	99.39	50	10	1509.4
1.0	1.0032	1.750	29.65	6.429	1.48	0.371	6.205	6.225	99.67	50	20	1504.8
1.0	1.0021	1.660	35.93	7.970	1.19	0.451	6.380	6.393	99.79	50	30	1503.1
1.0	1.0016	1.629	38.03	8.634	0.95	0.478	5.611	5.620	99.83	50	40	1502.4
1.0	1.0013	1.615	39.01	9.009	0.78	0.490	4.890	4.896	99.87	50	50	1501.9
1.0	1.0011	1.607	39.54	9.237	0.66	0.497	4.286	4.290	99.90	50	60	1501.6

Table 1.2 performance parameters of SCIM-1 machine at R-load and upf

MACHINE-2(WRIM)

R1=0.09175, R2=0.06354, X1=0.2112, X2=0.2112, at C=40 μ F and upf

a	B	Xm	E	Vt	Ip	Ic	Pout	Pm	η	f	R	Nr
1.0	1.0063	2.444	18.41	3.918	1.83	0.229	4.587	4.615	99.39	50	10	1509.4
1.0	1.0032	1.750	29.65	6.429	1.48	0.371	6.205	6.225	99.67	50	20	1504.8
1.0	1.0021	1.660	35.93	7.970	1.19	0.451	6.380	6.393	99.79	50	30	1503.1
1.0	1.0016	1.629	38.03	8.634	0.95	0.478	5.611	5.620	99.83	50	40	1502.4
1.0	1.0013	1.615	39.01	9.009	0.78	0.490	4.890	4.896	99.87	50	50	1501.9
1.0	1.0011	1.607	39.54	9.237	0.66	0.497	4.286	4.290	99.90	50	60	1501.6

Table 1.2 performance parameters of WRIM-2 machine at R-load and upf

MACHINE 3 (SCIM)

R1=0.16543, R2=0.09324, X1=0.1060, X2=0.1060, at C=40 μ F and upf

a	B	Xm	E	Vt	Ip	Ic	Pout	Pm	η	f	R	Nr
1.0	1.0063	2.444	18.41	3.918	1.83	0.229	4.587	4.615	99.39	50	10	1509.4
1.0	1.0032	1.750	29.65	6.429	1.48	0.371	6.205	6.225	99.67	50	20	1504.8
1.0	1.0021	1.660	35.93	7.970	1.19	0.451	6.380	6.393	99.79	50	30	1503.1
1.0	1.0016	1.629	38.03	8.634	0.95	0.478	5.611	5.620	99.83	50	40	1502.4
1.0	1.0013	1.615	39.01	9.009	0.78	0.490	4.890	4.896	99.87	50	50	1501.9
1.0	1.0011	1.607	39.54	9.237	0.66	0.497	4.286	4.290	99.90	50	60	1501.6

Table 1.3 performance parameters of SCIM-3 machine at R-load and upf

MACHINE-4(WRIM)

R1=0.09175, R2=0.06354, X1=0.2112, X2=0.2112, at C=40 μ F and upf

a	B	Xm	E	Vt	Ip	Ic	Pout	Pm	η	f	R	Nr
1.0	1.0063	2.444	18.41	3.918	1.83	0.229	4.587	4.615	99.39	50	10	1509.4
1.0	1.0032	1.750	29.65	6.429	1.48	0.371	6.205	6.225	99.67	50	20	1504.8
1.0	1.0021	1.660	35.93	7.970	1.19	0.451	6.380	6.393	99.79	50	30	1503.1
1.0	1.0016	1.629	38.03	8.634	0.95	0.478	5.611	5.620	99.83	50	40	1502.4
1.0	1.0013	1.615	39.01	9.009	0.78	0.490	4.890	4.896	99.87	50	50	1501.9
1.0	1.0011	1.607	39.54	9.237	0.66	0.497	4.286	4.290	99.90	50	60	1501.6

Table 1.4 performance parameters of WRIM-4 machine at R-load and upf

3.3.7 LOOP IMPEDANCE M-CODING

%machine parameter as given below.

```
L=[0.16543 0.09324 0.1060 0.1060; 0.09175 0.06354 0.2112 0.2112;0.16543 0.09324  
0.1060 0.1060; 0.09175 0.06354 0.2112 0.2112];
```

```
Rs=L(:,1); Rr=L(:,2); Xs=L(:,3); Xr=L(:,4);
```

% load parameter. R=10.0; X=0.0; C=40*10⁻⁶; Xc=79.61; f=50;

% read the per unit frequency a=1;

% calculating the value of D1,D2,D3,D4. for i=1:1:4;

```
D1(i)=(R*Xc)+(Rs(i)*Xc)-(a^2)*((Rs(i)*X)+(R*Xs(i)));
```

```
D2(i)=(D1(i)-((a)^2*(R)*(Xr(i))));
```

```
D3(i)=(a*(((a)^2*(X))+Xc));
```

```
D4(i)=(a*(((Xc)*(X))+((R)*(Rs(i))))); end
```

%calculating the value of K1,K2,K3.

```
for i=1:1:4;
```

```
K1(i)=((D3(i))*(D4(i))+((Xs(i))*((D3(i))^2))+((Xr(i))*(D3(i))^2)-  
(((a)^2*R*D2(i))));
```

```
K2(i)=((Xr(i))*(D3(i))*(D4(i)))+((Xs(i))*(Xr(i))*(D3(i))^2)+((Xs(i))*(D3(i))*(D4(i)
```

```
))+((Xs
```

```
(i))^2*(D3(i))^2)+((Xs(i)*(Xr(i))*(D3(i))^2)+((D4(i))^2)+((Xs(i))*(D3(i))*(D4(i)))+(
```

```
(Xr(i))*(D3(i))*(D4(i)))-((a)^2*(R)*(Xr(i))*(D1(i)))+((D1(i))*(D2(i))));
```

```
K3(i)=((Xs(i))*(Xr(i))*(D3(i))*(D4(i)))+((Xs(i))^2*(Xr(i))*(D3(i))^2)+((Xr(i))*(D4(i)
```

```
))^2)+((Xs(i))*(Xr(i))*(D3(i))*(D4(i)))+((Xr(i))*(D1(i))^2); end
```

%solve the quadratic equation and take positive value of Xm.

```
% as K1(i)*Xm(i)^2+K2(i)*Xm(i)+K3(i)=0. for i=1:1:4;
```

```
D(i)=((K2(i))^2)-(4*(K1(i))*(K3(i)));
```

$$Q(i)=(2*K1(i));$$

$$Xm1(i)=-(K2(i)-(sqrt(D(i))))/Q(i);$$

$$Xm2(i)=-(K2(i)+(sqrt(D(i))))/Q(i); \text{ end}$$

%calculate the value of speed b. for i=1:1:4;

$$M1(i)=((R*Xc)*(Xr(i)+Xm2(1)))/((a^2*((Rs(1)*X)*(Xr(i)+Xm2(i)))+(R*Xs(i))*(Xr(i)+Xm2(i)))+(R*Xr(i)*Xm2(i))))+((Rs(i)*Xc)*(Xr(i)+Xm2(i)));$$

$$M2(i)=((a)^3*((Rr(i)*X*Xs(i))+(Rr(i)*X*Xm2(i))))+(a*((Rr(i)*X*Xc)+(R*Rs(i)*Rr(i)))+(Rr(i)*Xs(i)*Xc)+(Rr(i)*Xc*Xm2(i))));$$

$$b1(i)=a+((M2(i))/(M1(i)));$$

$$N1(i)=a*(((X*Xc)*(Xr(i)+Xm2(i)))+(Xs(i)*Xc)*(Xr(i)+Xm2(i)))+(R*Rs(i))*(Xr(i)+Xm2(i)))/((a^3*((X*Xs(i))*(Xr(i)+Xm2(i)))+(X*Xr(i)*Xm2(i))))+(a*Xr(i)*Xc*Xm2(i));$$

$$N2(i)=((a)^2*((R*Rr(i)*Xs(i))+(Rs(i)*Rr(i)*X)+(R*Rr(i)*Xm2(i)))-(R*Rr(i)*Xc)(Rs(i)*Rr(i)*Xc));$$

$$b2(i)=a+((N2(i))/(N1(i)));$$

$$S(i)=(a-b1(i))/(a); \text{ end}$$

%COMPUTETHEPERFORMANCEQUANTITY.

$$RL=((R*Xc^2)/(a*((a^2*R^2)+((a^2*X)-Xc)^2)));$$

$$XL=((((-X*Xc)+(R^2)+(a^2*R^2))*Xc)/((a^2*R^2)+((a^2*X)-Xc)^2));$$

For i=1:1:4;

$$E(i)=150.96-1.3857*Xm2(i);$$

$$Vp(i)=sqrt(((RL)^2+(XL)^2)/((((Rs(i)/a)+RL)^2+(Xs(i)-XL)^2)))*(a)*(E(i));$$

$$Z=sqrt(R^2+(X*a)^2);$$

$$Ip(i)=Vp(i)/Z;$$

$$Pa(i)=3*Vp(i)*Ip(i)*((R)/(Z));$$

$$Vt(i)=(sqrt((((RL)^2+(XL+(Xc/a^2)^2)/((((Rs(i))/(a))+RL)^2+((Xs(i))-(Xc/Xs(i)*a^2)(Xr(i))^2))))*(a)*(E(i));$$

$$V_c(i) = (V_t(i)) / (a);$$

$$I_c(i) = (((a)^2 * V_c(i)) / (-X_c));$$

$$I_L(i) = (E(i)) / \sqrt{(R_r(i) / (a - b_1(i)))^2 + X_r(i)^2});$$

$$P_m(i) = -3 * (I_L(i)^2 * R_r(i) * (b_1(i) / (a - b_1(i))));$$

CHAPTER 4

OPTIMIZATION METHOD

4.1 INTRODUCTION

Over the past 25 years, many researchers have analysed the steady state performance of the three-phase SEIG on the basis of its approximate equivalent circuit. Two different solution methods have been used to determine the steady-state analysis of the three-phase SEIG driven by constant-speed prime mover.

The loop impedance approach is the first method. Using loop impedance approach, for a given load and speed, two simultaneous nonlinear equations are derived in terms of frequency (F) and magnetizing reactance (X_m) of the generator by separating the real and imaginary parts of the loop impedance of the equivalent circuit. The equations are then solved for F and X_m . Usually, the Newton-Raphson method is used to solve the simultaneous nonlinear equations, which requires much mathematical effort to derive the elements of the Jacobean matrix.

The second method is the nodal admittance approach, in this method the equivalent admittance of the circuit at the air gap point is separated into real and imaginary parts. The real part of the admittance is independent of X_m and usually expressed by a high order polynomial of F [12]. However, the imaginary part of the admittance is a nonlinear function of both F and X_m .

This method requires the combined admittance of the load, capacitive reactance and stator leakage reactance to be evaluated, which will result in lengthy algebraic manipulations. For complex R-L loads, the degree of the polynomial is seven. Both methods have a common disadvantage that detailed algebraic derivations for the coefficients of the equations are required. In addition, the earlier approaches are not flexible as the coefficients are valid only for a given circuit configuration. Inclusion of core loss resistance or load inductance will increase the order of the equations.

Chan [10] simplified the algebraic derivations in the nodal admittance approach by introducing an iterative technique to find the value of F from real part of admittance.

Chan [14] employed a symbolic programming technique to reduce the manual derivations of the equations. However, these techniques still require some degree of manual manipulation of the mathematical equations before these techniques are applied.

Recently, many researchers have proposed different techniques to tackle these problems based on user-friendly computer software that have been developed for numerical based solution of a set of nonlinear equations [15-19].

4.2 optimization method

Optimization method is very latest approach in the field of induction machine performance analysis as of now a number of work has been done on this unique method. As we know that mathematical numerical method is too lengthy and time consuming. Researchers are continuously doing development in this method, a number of mathematical function solver is present in MATLAB library from which Algorithm is formulated according to requirement to evaluate the problem with accurately,

Different from conventional optimization method, particle swarm optimization (PSO), introduced by Kennedy and Eberhard in 1995 [20-22], uses a simple mechanism that mimics swarm behaviour in birds flocking and fish schooling to guide the particles to search for globally optimal solutions. This paper proposes a novel method for evaluating the SEIG steady state characteristics using PSO algorithm that does not require the detailed derivation of nonlinear equations.

here in below, I formulate PSO Coding for optimization method and problem is evaluated for performance parameters calculation of parallel-operated self-excited induction generator machine.

4.3 PSO ALGORITHM

STEP 1 write the machine parameters (R_s , X_s , R , X_r), capacitive reactance X_c , load RL parameters as Bird in swarm.

STEP 2 Number in quality in bird is assigned as number of number of variables

STEP 3 Food availability=Objective function with one input variable (for more than one variable you may use array)

STEP 3 Assign the values for ranges for a, b, X_m . as minfunfunc and maxfunfunc in array form.

STEP 4 set the options as iterations, step size, accuracy for fast convergence of the optimal value.

STEP 5 write the call handling function one for objective function and other for constraints.

STEP 6 construct the objective function according to formulation to be optimized.

STEP 7 Save the M-file script with name as objecfun.m in MATLAB File.

4.4 PSO CODING

```
%%  
% INPUT VARIABLES  
% Bird_in_swarm=Number of parameters=agents=candidate  
% Number_of_quality_in_Bird=Number of Variable  
%  
% MinMaxRange: jx2 matrix; jth row contains minimum and maximum values of the  
jth variable  
% say you have a variable N1  
% which can have maximum value M1 and minimum value m1  
% then your matrix will be [m1 M1]  
% for more:  
% [m1 M1; m2 M2; mj Mj]  
%  
% Food availability=Objective function with one input variable (for more than one  
variable you may use array)  
% example for two variable  
% function f = funfunc(array)  
%   a=array (1);  
%   b=array (2);  
%   f = a+b;  
% end  
% Food availability is a string, for above example: 'funfunc'  
%  
% availability type is string 'min' or 'max' to check depending upon need to minimize  
or maximize the Food availability  
% velocity_clamping_factor (normally 2)  
% cognitive constant=c1=individual learning rate (normally 2)  
% social constant=c2=social parameter (normally 2)  
% normally C1+C2>=4  
%  
% Inertia weight=At the beginning of the search procedure, diversification is heavily  
weighted, while intensification is heavily weighted at the end of the search procedure.
```

```

% Min_Inertia_weight=min of inertia weight (normally 0.4)
% Max_Inertia_weight=max of inertia weight (normally 0.9)
% laicisation=how many times readjust the position of the flock/swarm of birds its quest
for food
%
%
% OUTPUT VARIABLE
% optimised parameters: Optimal parameters
%%
function [ optimised parameters] = Particle_Swarm_Optimization (Bird_in_swarm,
Number_of_quality_in_Bird, MinMaxRange, Food availability, availability type,
velocity_clamping_factor, cognitive constant, social constant, Min_Inertia_weight,
Max_Inertia_weight, laicisation)
%{
    Checking all functions are present
%}
if (exist ('MinMaxCheck.m')==0)
    clc;
    fprintf
    return;
end
%{
    Checking all parameters are entered
%}
if nargin < 11
    error('Missing input parameter(s)!')
end
%{
    universalize availability type
%}
availability_type=lower(availability_type(1:3));
%{
    Checking for proper boundary Values and entered Matrix
%}

```

```

[row,col]=size(MinMaxRange);
if row~=Number_of_quality_in_Bird || col~=2
    error('Not a proper MinMaxRange Matrix')
end
for i=1:Number_of_quality_in_Bird
    if MinMaxRange(i,1)>=MinMaxRange(i,2)
        error('Minimum value greater than Maximum value!!!')
    end
end

%{
    counter to display % of completion
%}
N=Bird_in_swarm*max_iteration;
q=0;

%{
    distinguishing min and max range
%}
bird_min_range=MinMaxRange(:,1);
bird_max_range=MinMaxRange(:,2);

%{

%}
format long;
for i=1:Number_of_quality_in_Bird
    bird(:,i)=bird_min_range(i)+(bird_max_range(i)-
bird_min_range(i))*rand(Bird_in_swarm,1);
end

Vmax=bird_max_range*velocity_clamping_factor;
Vmin=-Vmax;

```

```

for i=1:Number_of_quality_in_Bird
    Velocity(:,i)=Vmin(i)+(Vmax(i)-Vmin(i))*rand(Bird_in_swarm,1);
end

for itr=1:max_iteration
    fprintf('Completed %d %% ...', uint8(q*100/N ))

    for p=1:Bird_in_swarm
        parameter=bird(p,.,itr);
        availability(p,itr)=feval(Food_availability,parameter);

        switch availability_type
        case 'min'
            format long;
            [pBest_availability,index]=min(availability(p,:));
            pBest=bird(p,.,index);
            if(p==1 && itr==1)
                gBest=pBest;
                gBest_availability=pBest_availability;
            elseif availability(p,itr)<gBest_availability
                gBest_availability=availability(p,itr);
                gBest=bird(p,.,itr);
            end
        case 'max'
            format long;
            [pBest_availability,index]=max(availability(p,:));
            pBest=bird(p,.,index);
            if(p==1 && itr==1)
                gBest=pBest;
                gBest_availability=pBest_availability;
            elseif availability(p,itr)>gBest_availability
                gBest_availability=availability(p,itr);
                gBest=bird(p,.,itr);
            end
        end
    end
end

```

```

otherwise
error('availability_type mismatch')
end
w(itr)=((max_iteration - itr)*(Max_Inertia_weight -
Min_Inertia_weight))/(max_iteration-1) + Min_Inertia_weight;
Velocity(p,:(itr+1))=w(itr)*Velocity(p,,:itr) +
social_constant*rand(1,Number_of_quality_in_Bird).*(gBest-bird(p,,:itr)) +
cognitive_constant*rand(1,Number_of_quality_in_Bird).*(pBest-bird(p,,:itr));
Velocity(p,:(itr+1))=MinMaxCheck(Vmin, Vmax, Velocity(p,:(itr+1)));
bird(p,:(itr+1))= bird(p,,:itr) + Velocity(p,:(itr+1));
bird(p,:(itr+1))=MinMaxCheck(bird_min_range, bird_max_range,
bird(p,:(itr+1)));
q=q+1;
end
clc;
end
optimised_parameters=gBest;

```

***MACHINE-1(SCIM)**

R1=0.16543, R2=0.09324, X1=0.1060, X2=0.1060, at C=40μ-F and 0.8 pf

A	b	Xm	E	Vt	Ip	Ic	Pout	Pm	η	X	R	Nr
1.0	0.966	1.897	21.3	5.76	2.36	0.092	12.11	13.65	88.78	0.5	10	1515.2
1.0	0.965	1.670	33.4	7.89	3.68	0.083	14.17	15.78	88.79	1.2	20	1514.3
1.0	0.963	1.625	35.7	9.76	4.24	0.123	16.77	17.71	94.69	1.5	30	1512.7
1.0	0.961	1.599	38.3	10.09	5.96	0.224	18.81	19.02	96.77	2.0	40	1511.9
1.0	0.958	1.587	39.4	11.79	6.78	0.226	19.93	20.32	98.47	2.5	50	1511.3
1.0	0.956	1.574	40.0	19.11	7.66	0.380	20.32	21.03	98.54	3.0	60	1509.5

Table 2.1 performance parameters of SCIM-1 machine at RL-load and 0.8 pf

MACHINE-2 (WRIM)

R1=0.09175, R2=0.06354, X1=0.2112, X2=0.2112, at C=40μF and 0.8 pf

A	b	Xm	E	Vt	Ip	Ic	Pout	Pm	η	X	R	Nr
1.0	0.976	2.113	32.87	7.76	4.83	0.092	22.61	23.65	95.19	0.5	10	1509.2
1.0	0.973	2.007	33.41	9.89	5.48	0.083	24.10	25.21	96.21	1.2	20	1504.3
1.0	0.971	1.996	35.17	10.75	6.19	0.123	26.76	27.71	97.30	1.5	30	1503.7
1.0	0.968	1.973	37.90	12.91	7.95	0.124	28.55	29.02	98.53	2.0	40	1502.9
1.0	0.965	1.961	38.31	14.76	8.78	0.260	29.91	30.32	98.60	2.5	50	1501.3
1.0	0.961	1.950	39.47	15.18	9.66	0.380	30.93	31.28	98.84	3.0	60	1501.5

Table 3.2 performance parameters of WRIM-2 machine at RL-load and 0.8 pf

MACHINE-3(SCIM)

R1=0.16543, R2=0.09324, X1=0.1060, X2=0.1060, at C=40 μ F and 0.8 pf

A	b	Xm	E	Vt	Ip	Ic	Pout	Pm	η	X	R	Nr
1.0	0.966	1.897	21.30	5.76	2.36	0.092	12.17	23.65	88.78	0.5	10	1515.2
1.0	0.965	1.670	33.40	7.89	3.68	0.083	14.77	25.21	98.79	1.2	20	1514.3
1.0	0.963	1.625	35.74	9.76	4.24	0.123	16.47	27.71	94.69	1.5	30	1512.6
1.0	0.961	1.599	38.37	10.09	5.96	0.124	18.81	29.02	96.71	2.0	40	1511.4
1.0	0.958	1.587	39.41	11.79	6.78	0.260	19.39	30.32	98.47	2.5	50	1510.8
1.0	0.956	1.574	40.03	13.11	7.66	0.380	20.32	31.28	98.54	3.0	60	1509.4

Table 3.3 performance parameters of SCIM-3 machine at RL-load and 0.8 pf

MACHINE-4(WRM)

R1=0.09175, R2=0.06354, X1=0.2112, X2=0.2112, at C=40 μ F and 0.8 pf

A	b	Xm	E	Vt	Ip	Ic	Pout	Pm	η	X	R	Nr
1.0	0.976	2.113	32.87	7.76	4.83	0.092	22.61	4.615	95.19	0.5	10	1509.2
1.0	0.973	2.007	33.41	9.89	5.48	0.083	24.10	6.225	96.21	1.2	20	1504.3
1.0	0.971	1.996	35.17	10.75	6.19	0.123	26.76	6.393	97.30	1.5	30	1503.7
1.0	0.968	1.973	37.90	12.91	7.95	0.124	28.55	5.620	98.53	2.0	40	1502.9
1.0	0.965	1.961	38.31	14.76	8.78	0.260	29.91	4.896	98.60	2.5	50	1501.3
1.0	0.961	1.950	39.47	15.18	9.66	0.380	30.93	4.290	98.84	3.0	60	1501.5

Table 3.4 performance parameters of WRIM-4 machine at RL-load and 0.8 pf

CHAPTER 5

5.1 RESULT AND DISSCUSION

To test the validity of the proposed method of analysis, and to investigate the performance characteristics of parallel operation of induction generators, two types of machine were used, namely, a squirrel-cage machine (SCM). and a wound-rotor machine (WRM). Both machines are three-phase, 380 v (line), 50 Hz, four-pole, 1kw. Base values of frequency, speed and impedance are 50 Hz, 1500 rpm and 75.86 Ω , respectively.

***Machine parameters are given below**

SCIM: $R_1=0.09175$, $R_2=0.06354$, $X_1=0.2112$, $X_2=0.2112$, at $C=40\mu F$ and upf

WRIM: $R_1=0.09175$, $R_2=0.06354$, $X_1=0.2112$, $X_2=0.2112$, at $C=40\mu F$ and upf

***Relation between Airgap voltage (E_g) and magnetizing reactance (X_m).**

***$E_g / f = 2.4408 - 0.6080 * X_m$ for $X_m \leq 2.3839$;
 $3.4592 - 1.0352 * X_m$ for $2.3839 \leq X_m \leq 2.8116$;
 $9.7841 - 3.2848 * X_m$ for $X_m > 2.8116$.***

***Relation between Airgap voltage (E_g) and magnetizing reactance (X_m).**

***$E_g / f = 1.0007 - 0.1741 * X_m$ for $X_m \leq 1.3666$;
 $1.4298 - 0.4881 * X_m$ for $1.3666 \leq X_m \leq 1.7707$;
 $3.0192 - 1.3857 * X_m$ for $X_m > 1.7707$.***

5.2 Experimental set-up

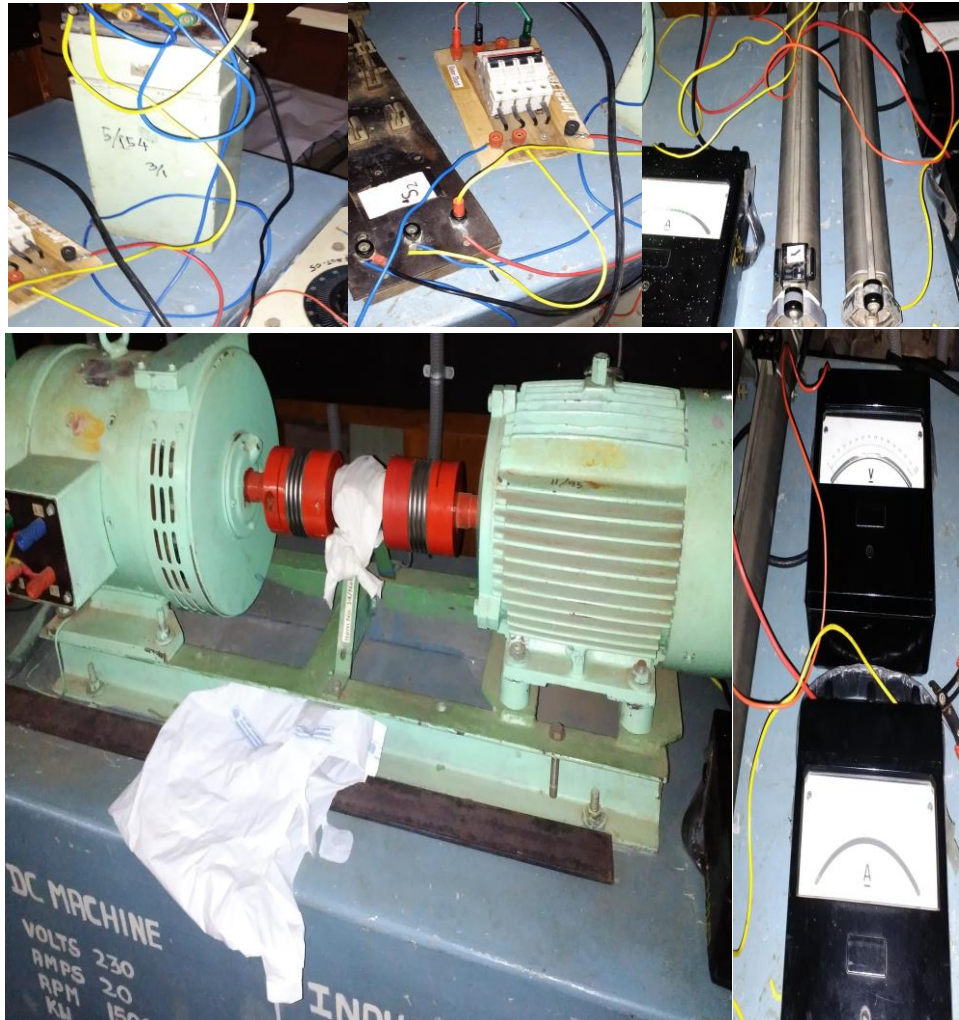


Fig: 5.1 Single line diagram of Experimental Set-up

5.3 PERFORMANCE CHARACTERISTICS

OPTIMIZATION METHOD

Characteristics b/w (Eg) vs per-unit speed (b)



Fig:5.2- Eg air-gap voltage vs per unit speed (b) characteristics

Figure-5.2 represents (Eg) air-gap vs per-unit speed (b) for Resistive load parallel-operated four machine self-excited induction generators, being operated at different speed and same frequency at common terminal load. as two machine is operated at unity power factor and other two machine is at 0.8 pf characteristics presents as the per unit speed (b) increases then air gap voltage (Eg) increases more for those machine which is being operated at 0.8 pf than unity power factor upto a nominal value and after that becomes constant.

Characteristics b/w Pout vs per-unit speed (b)

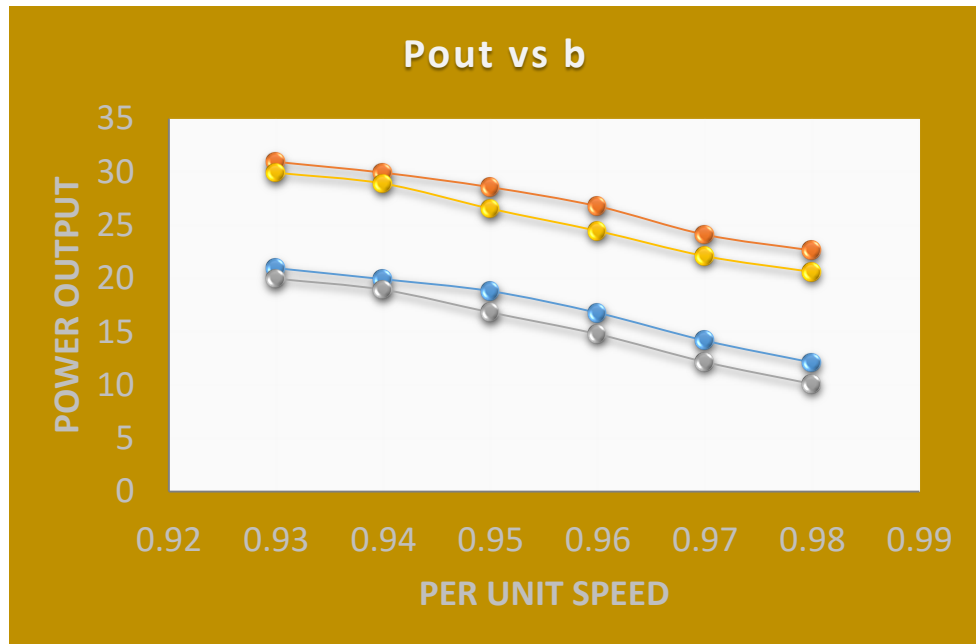


Fig:5.3- Pout vs per unit speed (b) characteristics

As the performance characteristics between output power P_{out} and per unit speed (b) is shown above in the figure:5.3

Two machine is being operated at unity p.f. and other two machine is being operated at 0.8 p.f.

Output power is more for the machine which is operated at 0.8 p.f. is decreasing gradually as compared to the machine operated at unity power factor, for the same value of increase in per unit speed. Therefore, R-L load makes good balance with parallel-operating machine as compare to R-load.

Characteristics b/w η vs per-unit speed (b)

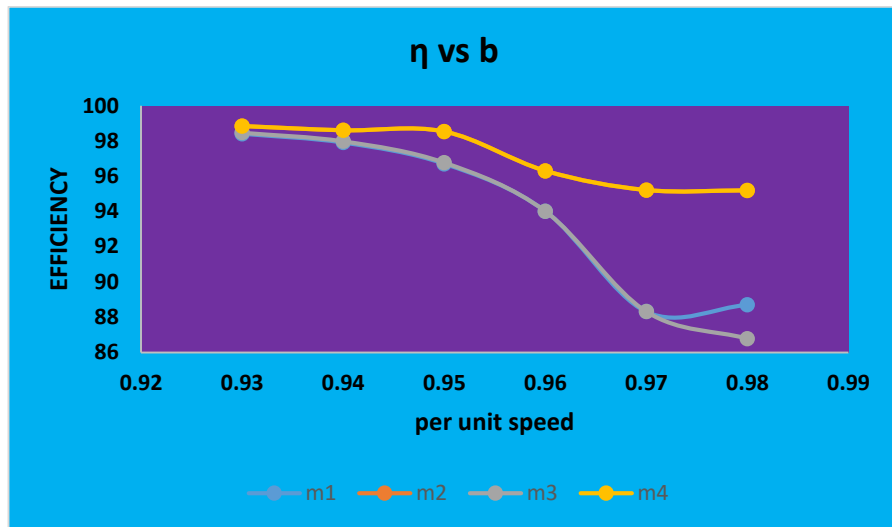


Fig:5.4- η efficiency vs per-unit speed (b)

Here in above in figure: 5.4 graph represents characteristics between η efficiency vs per-unit speed (b).

Efficiency for two machine being operated with 0.8 power factor is more as compare to the machine which is operated with unity power factor for the same piecewise increase in per unit speed.

Thus machine is being operated parallel then efficiency is maximum when RL load is connected across the common terminal of parallel connected machine.

5.4 Performance characteristics

(B) for loop impedance and nodal admittance method

Output Characteristics curve

Characteristics b/w E_g vs per-unit speed

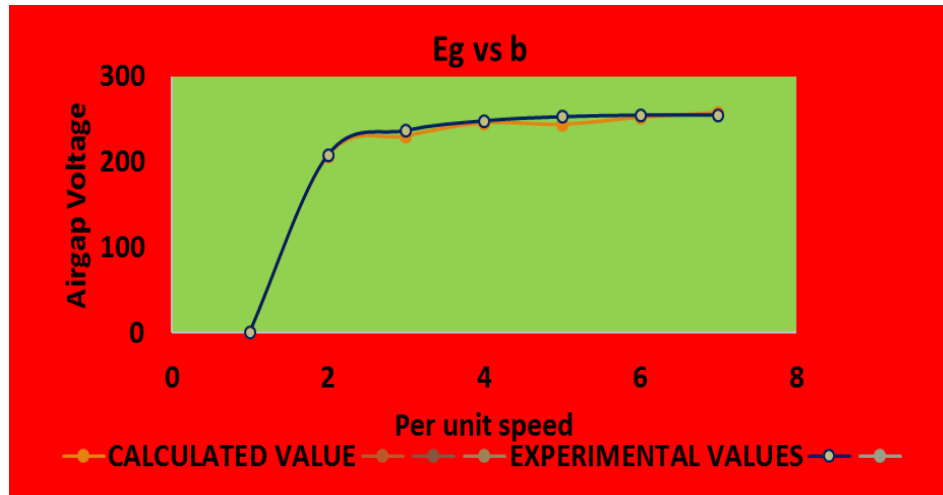


Fig:5.5 air-gap voltage vs per unit speed at upf and 40 μ f

Figure 5.5 represents the characteristics between E_g air gap voltage and per unit speed for calculated and experimental values which determines as per unit speed increase then air-gap voltage also increases, when machine is being operated at same terminal voltage and frequency and different speed at R-load condition and unity power factor.

Characteristics b/w Pout vs per-unit speed (b)

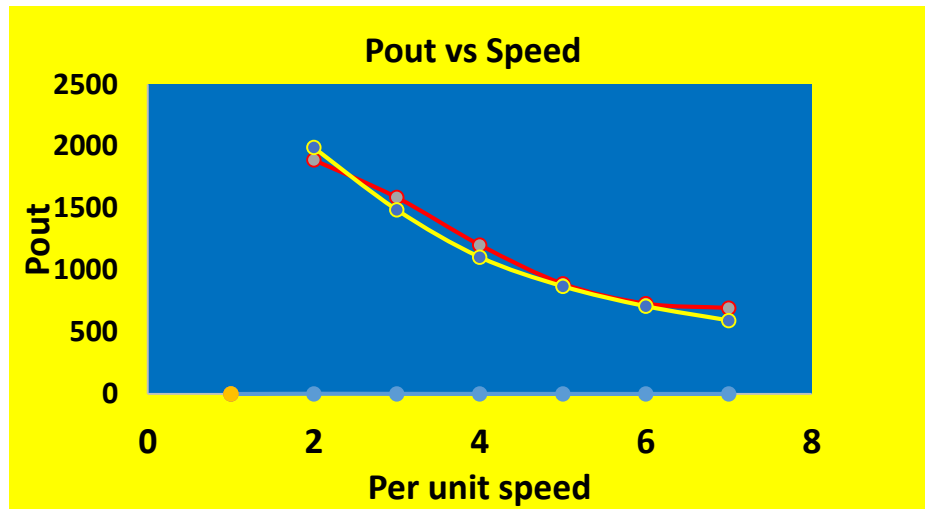


Fig:5.6 Pout vs per unit speed at upf and 40 μ f

As figure 5.6. indicates performance characteristics between output power and per unit speed for calculated and experimental values, which predicts as per unit speed is increases then output power decrease drastically up-to nominal value and after that it becomes constant. Machine are being operated at same frequency and terminal voltage at different speed connected with R-load and unity power factor.

Characteristics b/w η vs per-unit speed (b)

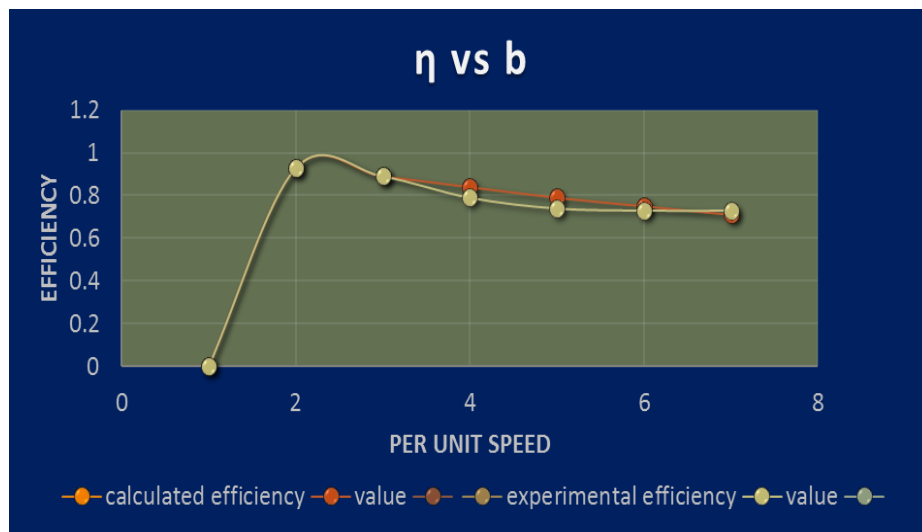


Fig:5.7 Efficiency vs per unit speed at upf and 40 μ f

From the above figure:5.11 characteristics between efficiency vs per unit speed, as machine is being operated at common terminal voltage and frequency but different speed at unity power factor and R-load condition, it depicts comparison between evaluated value with experimental value as machine per unit speed increases then efficiency also increases and very close to each other.

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

It is known that long transmission lines are inevitable for supplying loads away from generating stations. As a result, transmission line losses are also increasing for supplying such remote loads. Nowadays, it is evident that renewable energy is one of the most promising energy resources in the field of distributed power generation.

In this project, performance analysis of parallel operated SEIGs supplying isolated loads has been carried out by various methods. This parallel operated SEIGs can be integrated with wind/wind and wind/hydro electric energy conversion system. Loop impedance, nodal admittance and minimization methods such as GA, PSO Algorithms have been employed for the steady-state analysis of parallel operated SEIGs. It is found that the performance analysis of SEIGs is simpler using minimization techniques. Because the necessity of solving higher order polynomial in case of loop impedance and nodal admittance method is eliminated.

Further, in view of accuracy and rate convergence, improved minimization algorithms can be employed for the analysis of such parallel operated SEIGs.

6.2 FURTHER SCOPE OF WORK

(1) In the thesis work, the steady state performance of parallel operated SEIGs for balanced condition has been carried out with conventional Iterative method and Optimization (PSO) method respectively. The results computed for some cases are validated through experimental results.

(2) Most of the loads in remote and rural areas are single phase loads. The machine operated under this case is unbalanced due to the voltage and current negative sequence components. Unbalanced operation leads to voltage stresses and over heat in the machine and correspondingly leads inefficient operation. To reduce these problems, strategy to be made to minimize the unbalancing by selecting the appropriate size and rating of excitation capacitors.

(3) Transient analysis can also be made to evaluate the performance and designing of machine parts such as winding and coupling shaft and devising of the protection strategy during unbalanced condition.

(4) The steady state performance during unbalanced condition is also verified from other simplified methods such as node admittance method to reduce the computational time and fast convergence.

(5) Power electronics converter such as static compensator (STATCOM) can be simulated and implemented to nullify the effect of unbalance and other related problems

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APPENDIX-A

$$K_2(i)b^2 + K_1(i)b^1 + K_0(i) = 0$$

Where

$$K_2(i) = [D_3(i)D_4(i) + X_1D_3^2(i) + X_2D_3^2(i) - a^2RD_2(i)]$$

$$K_1(i) = [X_2D_3(i)D_4(i) + X_1X_2D_3^2(i) + X_1D_3(i)D_4(i) + X_1D_3(i)D_4(i) + X_1^2D_3^2(i) + X_1X_2D_3^2(i) + D_4^2(i) + X_1D_3(i)D_4(i) + X_2D_3(i)D_4(i) - a^2RX_2D_1(i) + D_1(i)D_2(i)]$$

$$K_0(i) = [X_1(i)X_2(i)D_3(i)D_4(i) + X_1(i)X_2(i)D_3(i)D_4(i) + X_2(i)D_1^2(i) + X_2(i)D_4^2(i) + X_1^2(i)X_2(i)D_3^2(i)]$$

Where

$$D_1(i) = RX_C + R_1(i)X_C - a^2(R_1(i)X + R_X)$$

$$D_2(i) = D_1(i) - a^2RX_2(i)$$

$$D_3(i) = a(XX_C + RR_1(i))$$

APPENDIX-B

the performance characteristics of parallel operation of induction generators, two types of machine were used, namely, a squirrel-cage machine (SCM) and a wound-rotor machine (WRM). Both machines are three-phase, 380 V (line), 60 Hz, four-pole, 1 kW. Base values of frequency, speed and impedance are 60 Hz, 1800 rpm, and 75.86 Q, respectively. The per-unit measured parameters of the two machines are given in Table

***Machine parameters are given below**

SCM: $R_1=0.16543$, $R_2=0.09324$, $X_1=0.1060$, $X_2=0.1060$, at $C=40\mu\text{F}$ and upf

WRM: $R_1=0.09175$, $R_2=0.06354$, $X_1=0.2112$, $X_2=0.2112$, at $C=40\mu\text{F}$ and upf

SCM: -Squirrel cage induction machine *Relation between Airgap voltage (E_g) and magnetizing reactance (X_m).

$$\begin{aligned} E_g / f &= 2.4408 - 0.6080 * X_m \text{ for } X_m \leq 2.3839; \\ &3.4592 - 1.0352 * X_m \text{ for } 2.3839 \leq X_m \leq 2.8116; \\ &9.7841 - 3.2848 * X_m \text{ for } X_m > 2.8116. \end{aligned}$$

WRM: Wound Rotor machine*Relation between Airgap voltage (E_g) and magnetizing reactance (X_m).

$$\begin{aligned} E_g / f &= 1.0007 - 0.1741 * X_m \text{ for } X_m \leq 1.3666; \\ &1.4298 - 0.4881 * X_m \text{ for } 1.3666 \leq X_m \leq 1.7707; \\ &3.0192 - 1.3857 * X_m \text{ for } X_m > 1.7707. \end{aligned}$$

