Selection of Capacitors for Compensated Self-Excited Induction Generator using Meta-Heuristic Approach

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

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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled " **Selection of Capacitors for Compensated Self-Excited Induction Generators using Meta-Heuristic Technique**" in partial fulfillment of the requirements of the award of the degree of master of engineering in power systems and electric drives submitted in Electrical and Instrumentation Engineering Department of Thapar University, Patiala is an authentic record of my own work carried out under the supervision of Mr. Yogesh K. Chauhan.

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

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

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ABSTRACT

Renewable and sustainable energy is increasingly gaining interest in current research circles. Self excited induction generators (SEIG) are being deployed for the exploitation of power from renewable sources for a long time and they are becoming more and more popular for supplying electrical energy to remote and rural areas for its various advantages over synchronous generators. The SEIG has poor voltage regulation under changing loads and this is one of the major drawbacks due to which the wide applicability of the generator is restricted. Hence the steady state analysis of the machine becomes of paramount importance. Many conventional methods have been used to predict the generator performance under various loading conditions. Followed by the steady state analysis, many conventional methods have been developed for the system consisting of series and shunt capacitors to achieve better voltage regulation at various loading conditions. The values of the capacitors are selected so as to minimize the number of switched capacitors needed to satisfy the voltage regulation criteria.

The selection strategy of the series and shunt capacitors for desired voltage regulation is made through a conventional MATLAB routine ‘fsolve’ where in the generator characteristics are evaluated for resistive and resistive-inductive loads.

In the present thesis work, the results achieved by the conventional method are compared with a meta- heuristic search technique called particle swarm optimization (PSO) to get the optimum set of series and shunt capacitors under different loading conditions. The performances using both the techniques are compared and the effectiveness of PSO is seen as the voltage regulation is slightly improved.

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LIST OF SYMBOLS

R_s	p.u. stator resistance
R_r	p.u. rotor resistance
X_s	p.u. stator reactance
X_r	p.u. rotor reactance
C_{se}	series capacitance
C_{sh}	shunt capacitance
v	p.u. speed
X_m	p.u. magnetizing reactance
f	p.u. operating frequency
V_g	p.u. air gap voltage
V_t	p.u. terminal voltage
V_l	p.u. load voltage
I_s	p.u. stator current
P_l	p.u. load power
$Ø_1$, $Ø_2$	random values
X_{id}	position of particles
P_{id}	local best
P_{gd}	global best
V_{id}	velocities of the particles
j	imaginary operator

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The induction generators have been incepted in the mid of 20^{th} century and now are gradually gaining popularity because of quick depletion of fossil fuels. And in the later runs, i.e. in the 1980s', wider distribution and improved transportation enabled people to scatter from urban concentration.

Increasing rate of the depletion of conventional energy sources such as coal and petroleum etc has given rise to an increased emphasis on renewable energy sources such as wind, mini/micro-hydro, etc. [1–10]. Generation of electrical energy mainly so far has been from thermal, nuclear, and hydro plants. An increasing rate of the depletion of conventional energy sources and the degradation of environmental conditions has given rise to an increased emphasis on renewable energy sources, particularly after the enhancements in fuel prices during the 1970s. Use of an induction machine as a generator is becoming more and more popular for the renewable sources [1]. Reactive power consumption and poor voltage regulation under varying speed is the major drawbacks of the induction generators, but the development of static power converters has facilitated the control of the output voltage of induction generators. There are several other advantages of the induction generators such as low maintenance cost, ruggedness, brush less construction, self protection against faults, good dynamic power, and capability of generating power at varying speed and ease of operation.

1.2 INDUCTION GENERATOR

The construction of induction generator is same as the induction motor. Now when the motor is coupled to a prime mover whose speed can be controlled and now if the speed is increased to synchronous speed, the slip attained is zero. The prime mover running above synchronous speed, the slip is negative and as a consequence, rotor e.m.f. and rotor current torque and power, all attain negative values. Under such conditions the motor acts as a generator delivering power to the supply mains. As the speed during the generating operation is not synchronous, it is also termed as an asynchronous generator. In this case the magnetizing current must be delivered to the generator from the supply mains or some other means so that the rotating flux is established hence the induction generator is not a self excited machine and therefore must continue to get reactive power from external means.

1.3 CLASSIFICATION OF INDUCTION GENERATORS

There are many ways we can classify the induction generators i.e. based on construction, connections and performance. These are subcategorized as following:

- On the basis on excitation given
  - Grid connected induction generator.
  - Self excited induction generator (SEIG).
- Classification based on construction-
  - Wound rotor induction generators.
  - Squirrel cage induction generators.
- Classification based on connections-
  - Simple shunt SEIG.
  - Short shunt SEIG.
  - Long shunt SEIG.
- Depending upon the prime movers used (constant speed or variable speed) and their locations (near to the power network or at isolated places)[21-24]
  - Constant speed constant frequency.
  - Variable speed constant frequency.
  - Variable speed variable frequency.

1.3.1 SIMPLE SHUNT SEIG

Figure 1.1 shows the simple shunt SEIG. The objective of using capacitor bank in SEIG is to provide adequate reactive power for the excitation of the generator when it is operating in standalone mode. As the load varies randomly the capacitor has to be varied to obtain desired voltage. But the main issue with this scheme is that the voltage regulation is not possible as the switched capacitors are absent in this. Poor voltage regulation has been a major bottleneck with this kind of configuration; it can be seen that in this configuration, as there is no starting resistance to limit the starting current, the generated voltage of SEIG can not undertake such sudden changed dynamic load. Hence, the generated voltage collapses and gradually decreases to zero.

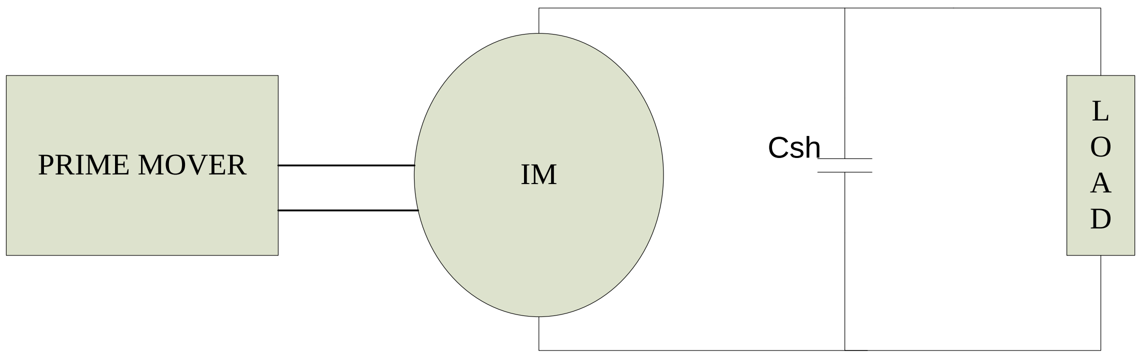

Figure 1.1 simple shunt SEIG

1.3.2 SHORT SHUNT SEIG

For higher loads, the short shunt induction generators are more effective in the voltage regulation. The short shunt scheme is more effective in the optimum voltage regulation for higher loads. This uses series capacitive compensation. When the load current increases, the current passing through the series capacitance also increases. More magnetizing reactive power is furnished to the machine; hence the voltage drop with load will be less severe compared to simple shunt SEIG.

Inclusion of additional series capacitance to provide additional VAR with load is one of the attractive options to improve voltage regulation of SEIG. Basset and Potter in their classical paper have presented some experimental results to highlight the self regulating feature of compounded SEIG [11]. It is also demonstrated experimentally that it is possible to have almost a flat load characteristic with a particular combination of capacitors connected under short shunt configuration (Figure 1.2). This eliminates any additional voltage regulator since the scheme has inherent self regulating feature.

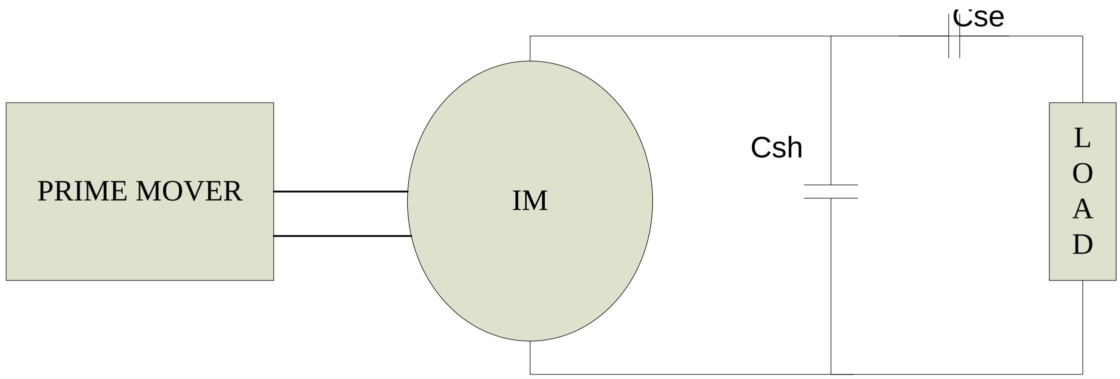

Figure 1.2 short shunt SEIG

The following figure (figure 1.3) shows the schematic diagram of the short shunt SEIG showing the flow of the reactive power from the shunt capacitors. The shunt capacitors deliver reactive power to the load as well as the generator and the series capacitor adds to the reactive power delivery and hence the generator and load gets adequate reactive power for self excitation.

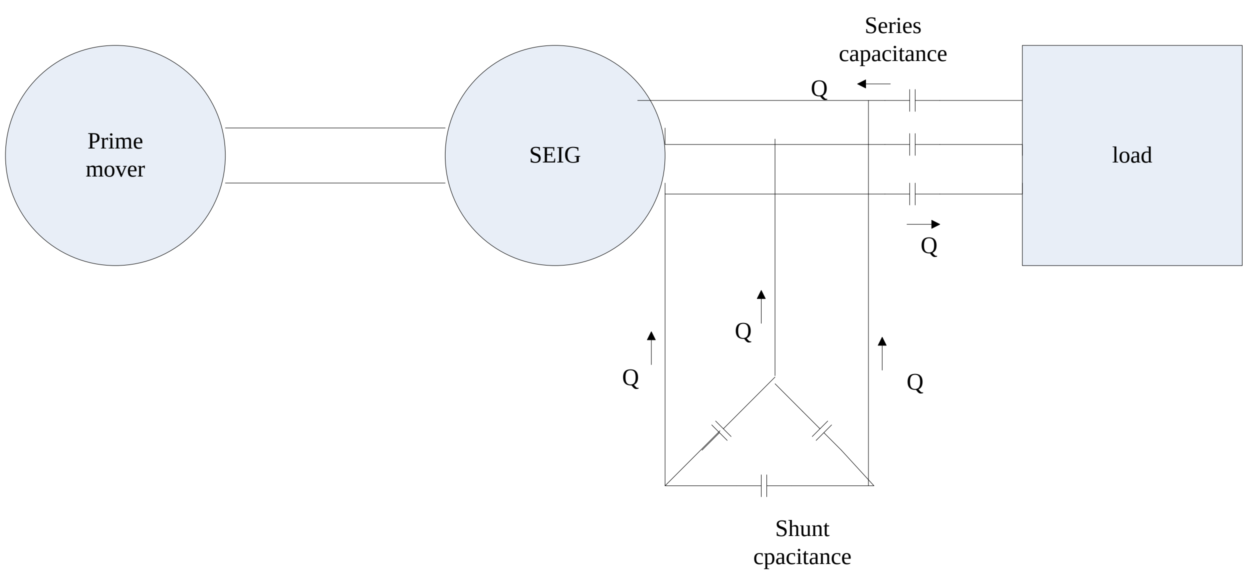

Figure 1.3 delivery of reactive power in the short shunt configuration

1.3.3 LONG SHUNT SEIG

Like the short shunt connections, the long shunt SEIG can also be used to improve the voltage regulation of the induction generator. But in case of the long shunt generator, the series capacitor is deployed in the external circuit as shown in figure 1.4. But for the same series capacitance values as used in the short shunt generator, it can deliver same amount of power but at very low voltages so the values of the series capacitance has to be very high to maintain the desired voltage regulation and this results in higher costs. In case of standalone operation, a booster transformer may be used to enhance the load voltage for higher loads, a low voltage regulation is possible in this configuration but as we see, all this involves additional expenditure and the series capacitors have to be rated for higher line currents as the machine line current also. The graphical method for selection is suggested by Bim *et al* [12].

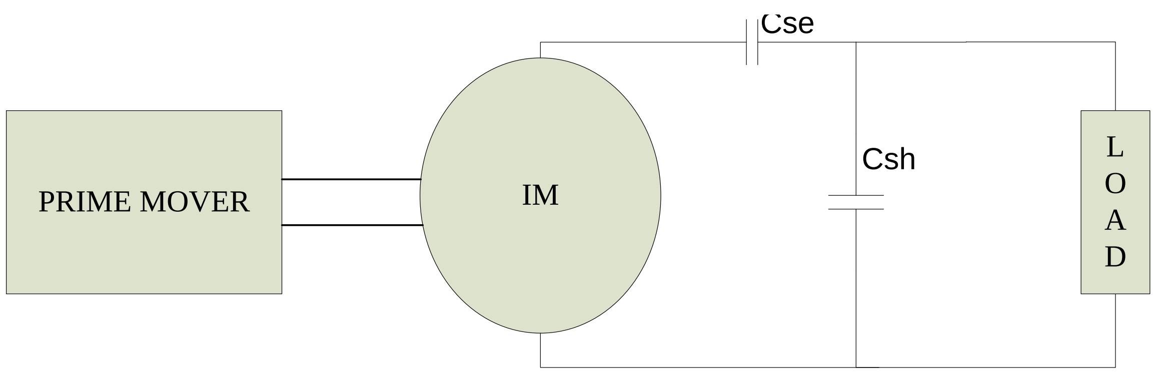

Figure 1.4 long shunt SEIG

1.4 VOLTAGE BUILD UP IN SEIG

The build-up of voltage of the d-c shunt generator is known to depend upon residual magnetism in the field poles of the machine and upon the resistance of the field circuit, the final build-up voltage being determined by the field circuit resistance. It has been discovered that the induction generator with static capacitance connected in shunt across its terminals will build up its voltage in a manner similar to the build-up of the d-c shunt generator. Residual magnetism in the iron of the magnetic circuit sets up a small alternating voltage in the stator; this voltage applied to the capacitance causes a lagging magnetizing current to flow in the stator windings (machine applies leading quadrature current to the capacitance, or draws a lagging quadrature current). If the capacitance is of the proper value, the current that can flow will be large enough to increase the flux existing in the air gap. An increase of the air gap flux will result in a higher voltage, larger exciting current drawn by the capacitance, more air gap flux, and so on until the terminal voltage of the machine reaches its final build-up value. This value is determined by the saturation curve of the machine and by capacitive reactance of the connected capacitance.

Operating as a shunt generator, a short circuit will cause the generator to lose its voltage and the residual magnetism is destroyed preventing the machine from again building up. Any method which gives temporary excitation to the iron will restore the residual magnetism. A few methods given are:

- Running the machine as a motor from an existing a.c. system.
- Discharging the charged condenser through the stator windings while machine is in operation.
- Connecting a 6 V storage battery across two terminals of the machine for a few moments.

1.5 LITERATURE REVIEW

Use of induction generators is becoming very popular for harnessing renewable energy sources to convert into electrical energy [1-10]. Reactive power consumption and poor voltage regulation are the main drawbacks which are mitigated by the use of static power converters to control the output voltage of generators. [11-20]. this chapter presents a survey on the works done on improving the performance of induction generators.

1.5.1 CLASSIFICATION

The induction generators are classified on the basis of construction i.e. squirrel cage induction generator and wound rotor induction generator. They can also be classified on the basis of connections i.e. simple shunt, short shunt and long shunt s.e.i.g [12],[21-23]. Depending upon the prime movers used and their locations, these can be classified as constant voltage constant frequency, variable voltage variable frequency and variable speed constant frequency [24-26].

1.5.2 CAPACITIVE SELF EXCITATION

The capacitive self excitation is a well known phenomenon for the induction generators. If an appropriate capacitor bank is connected across the terminals of an externally driven induction machine, a voltage is developed across its terminals. The residual magnetism in the rotor initiates voltage build up which is augmented by the capacitor current to cause a continuous rise in voltage [27-38]. stebbins [27] in his paper explained how the capacitor delivers reactive power to the machine from where the explication started. Zidani *et al* [28] in their paper gave some basic ideas about the numerical approach used such as the loop impedance method or the nodal admittance method to find the minimum capacitance value required for the self excitation process. Li Wang [31] presents a simple and direct approach based on first-order Eigen value sensitivity method to determine both maximum and minimum values of capacitance required for an isolated self-excited induction generator (SEIG) under different loading conditions. He also deduced the excitation capacitance required for an isolated three-phase induction generator supplying a single-phase load [32]. Eltamaly [35] proposed technique, which uses nodal analysis instead of loop analysis to obtain just one formula for the minimum capacitance required for induction generator operation at different load and speed conditions. In this technique, the operating frequency can be obtained directly from equating the real part of admittance with zero where the real part does not function in X_c, then use the imaginary part to calculate the value of X_c. Harrington *et al* presented a new approach to determine the critical capacitance of the self excited induction generators in which they found out that over this value of capacitance, there will be a voltage collapse possible [36].

1.5.3 STEADY STATE ANALYSIS

Steady-state analysis of SEIG is of interest, both from the design and operational points of view. In an isolated power system, both the terminal voltage and frequency are unknown and have to be computed for a given speed, capacitance, and load impedance. A large number of papers have appeared and a lot of work has been done to improve the performance of SEIG under different conditions whether it be speed, loading, etc[1],[39-

55]. Murthy *et al.* [40] 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 X_m and f using Newton– Raphson method. Jain *et al.* [51] have proposed a method in which the algebraic equation is solved for the initial value of and then the Secant method is used for the exact solution. Rajakaruna *et al.* [44] have used an iterative technique which uses an approximate equivalent circuit and a mathematical model for B–H curve and the solution is reduced to a nonlinear equation in f. Singh *et al.* [47] tried an optimization technique by formulating this as a multivariate unconstrained nonlinear optimization problem. The impedance of the machine is taken as an objective function. The X_m and f are selected as independent variables, which are allowed to vary within their upper and lower limits so as to achieve practically acceptable values of the variables. The Rosenbrock's method of rotating coordinates has been used for solving the problem. Sandhu *et al.* [51] have proposed an approach, which leads to a quadratic equation in slip making the steady-state analysis simple and comprehensive. Wang *et al.* [55] have presented an eigen value-based approach to predict both minimum and maximum values of capacitance required for self-excitation of SEIG The comparison between the steady-state performance of self-excited reluctance and induction generators has been presented in [54]. A reluctance generator is a synchronous machine with a salient or segment rotor, which does not require any dc rotor excitation. Very little work has been reported in regards to reluctance generators, and has relatively minor practical applications.

1.5.4 TRANSIENT AND DYNAMIC ANALYSES

There has been many work performed on the dynamic analysis of the induction generator and most of the transient studies are related to voltage build up due to self excitation and load perturbation. The transient analyses also help in contriving the protection strategies. Various dynamic models have been proposed to study the transient behavior of the generator under various loading conditions [46], [56-67]. In [56], the transient performance of short-shunt SEIG is presented. It is seen that it can sustain severe switching transients, has good overload capacity, and can re-excite over no load after loss of excitation. It is also observed that except for the most unusual circumstances (the short circuit across the machine terminals across the series capacitor), the short-shunt SEIG supplies adequate fault current to enable over current protective device operation. In [46], the voltage buildup of SEIG due to switching of the three-phase capacitor bank at rated speed at no load is presented. It is observed that depending on the machine parameters, the generator voltage builds up from small voltage due to residual magnetism to its rated value in nearly one second. Wang *et al.* [60] have presented the transient performance of stand-alone SEIG under the voltage buildup process, suddenly switching off one excitation capacitor and suddenly switching off two excitation capacitors. It is seen that when one of the three balanced excitation capacitors is switched off from the machine, SEIG can still maintain self-excitation and generates adequate voltage on other two phases. When two of the three balanced excitation capacitors are switched off from the machine, the generated voltage of the SEIG collapses and gradually reduces to zero. Wang *et al.* [63] presented a comparative study of long-shunt and short-shunt configurations on dynamic performance of an isolated SEIG feeding an induction motor load. They showed that the long shunt configurations may lead to unwanted oscillations while the short shunt provides the better voltage regulation. The emphasis

is placed on the situation that leads to voltage collapse and the total demagnetization of the machine and on the variable speed of the induction generator with a fixed capacitor bank.

1.5.5 PARALLEL OPERATION OF SEIG

In mini hydro and wind generating systems, there are usually constraints on the possible size of single machines. In order to utilize the full potential of the energy source, several such generators may have to be operated in parallel. Also a group of capacitor self excited induction generators may have to be operated in parallel for some other reasons **[**68**].** Parallel operation of SEIG requires extensive investigation with regard to different aspects of parallel operation, such as influence of parameter variations on parallel operation, VAR control, etc [68-75]. Bahrani *et al.* [69] analyzed the voltage-control behavior of multi-induction generators operating in parallel with one three phase bank of excitation capacitors connected to a common bus and load. It was examined that voltage regulation under varying load conditions is improved by controlling either the capacitance or speed of one or more generators. Under controlled terminal voltage operation, it is noticed that the capacitive reactive power and speed (active power/frequency) demand increase with the increased load. Under the similar condition of controlled terminal voltage, the system frequency also depends on load power and terminal voltage. Wang *et al.* [74] have presented an Eigen value-based methodology to analyze the dynamic performances of parallel- operated SEIG supplying an IM load to find the minimum starting value of capacitance required for self-excitation. Steady-state and sensitivity analysis of different capacitance values with respect to different system parameters have been investigated. The responses of the output voltage of parallel-operated generators during suddenly switched on and off of an induction motor load have also been reported.

1.5.6 SELECTION OF CAPACITORS

Here the self regulating feature of induction generators using additional capacitors is examined. The analysis of system containing both series and shunt capacitors is made. Adequate work has been done on the selection strategy of capacitance values for the optimum voltage regulation of SEIG [12], [18],[21-28], [76-77]. Haque [76] in his paper presented a simple approach to regulate the voltage of an induction generator using 'fsolve' technique inbuilt in MATLAB where three non linear equations are simultaneously solved for the optimum placement of capacitors for minimum voltage regulation. Bhim *et al* [21] also achieved the selection of capacitance values for both long shunt and short shunt configurations and by comparison, it was shown that the short shunt connections give better results than the long shunt for same values of capacitors. They used newton- raphson method for this approach. S. K. Jain *et al.* [77] proposed the use of damping resistors across series capacitors is proposed to damp out the starting transients and for the stable operation. The simulated annealing approach is used to solve voltage regulation optimization problem.

1.5.7 STATIC CONVERTERS FOR PERFORMANCE IMPROVEMENT

Here the application of power electronic converters for the voltage regulation of SEIG has been discussed. Attempts have been made to maintain a constant terminal voltage by fixed capacitor and thyristor controlled inductor (SVC) [74] and saturable core reactor [75]. However, due to the invention of solid-state self-commutating devices, it is now possible to make a static noiseless voltage regulator, which can provide a continuously variable reactive power to the SEIG with a varying load to keep the terminal voltage constant. This system, called a static compensator (STATCOM), has specific benefits compared to SVC as proposed by Larsen *et al* [76]. Singh and Shilpakar [77] have proposed an analysis of a solid-state voltage regulator for SEIG with a static load. Wekhande and Agrawal [78] have proposed a controller to regulate the three-phase ac output voltage of the SEIG with varying rotor speed, transient load conditions, and reactive loads. Miranda *et al.* [79] have proposed a static volt ampere reactive (VAR) compensator for an electrical pumping system driven by induction generator. Kuo and Wang [80-81] have described a method of voltage control of SEIG under unbalanced/ nonlinear load using a current-controlled voltage source inverter (VSI).

1.6 AIM OF THESIS

The objective of the thesis work is to carry out the selection of series and shunt capacitance values for compensated SEIG which will give optimum voltage regulation in the set voltage band. The optimization technique particle swarm optimization is used to solve the problem formulated. The results have been compared with the results obtained with the conventional MATLAB function which uses ‘fsolve’ routine.

1.7 ORGANIZATION OF THESIS

1) CHAPTER 1 designated as introduction gives the outline of the self excited induction generator with various connection strategies employed and the voltage build up concept. This chapter also includes the updated literature review in which an attempt has been made to throw a light on the works done on self excited induction generator over the years.

2) CHAPTER 2 discusses the selection of capacitors for short shunt self excited induction generator using MATLAB inbuilt function ‘fsolve’ covers the formulation of the selection process as well as the analyses done to maintain the load voltage within upper and lower limits.

3) CHAPTER 3 deals with the theory of particle swarm optimization includes the pedagogic theory of the cited optimization technique and the effectiveness has been proved using a test function and this technique has been used in the formulation of the problem. The advantages and modifications in PSO have also been discussed.

4) CHAPTER 4 deliberates on the selection of capacitors for short shunt self excited induction generator using the PSO technique have been discoursed. This chapter deals with the use of the PSO as an optimization technique in finding out the optimum voltage regulation for the best capacitance value chosen. The results are also compared with ‘fsolve’ routine results.

5) CHAPTER 5 presents the conclusion and future scope covers briefs about the work done in the thesis carried out and the future scope conceives of the work that can be carried out further.

1.8 CONCLUSIONS

This chapter throws light on the works done in the past decades on SEIG and also the working and various categories of induction generator has been discussed in this chapter. A widespread survey on important aspects of SEIG is dealt within the lines of the chapter such as the self excitation process, selection of capacitors etc.

CHAPTER 2

SELECTION OF CAPACITORS IN SHORT SHUNT SEIG USING CONVENTIONAL METHOD

2.1 INTRODUCTION

A self-excited induction generator (SEIG) has poor voltage regulation and that restricts wide applicability of the generator. A simple method of selecting the values of fixed and switched capacitors in a short-shunt SEIG driven by a regulated prime mover to maintain the load voltage within the upper and lower acceptable limits is proposed. The values of the capacitors are selected very carefully to minimize the number of switched capacitors needed to satisfy the above voltage criterion, and that would minimize the cost and complexity of the voltage regulator. This requires evaluating the generator characteristics under constant voltage operation. The equations needed to obtain such characteristics are also derived and solved using a numerical based routine 'fsolve' given in MATLAB. The proposed method of selecting the capacitor values is then tested on a three-phase, 3.7 kW induction generator operating in a short-shunt configuration.

It is an established fact that an ordinary induction motor (IM) can operate as a generator when it is driven by an external prime mover and a proper size of capacitor bank is connected across its stator terminals [14-16]. Such a machine is called a self-excited induction generator (SEIG) and its schematic diagram is shown in Fig. 2.1. The objective of using the capacitor bank is to provide adequate reactive power support for excitation of the generator when it is operating in a stand-alone mode. Alternatively, the stator terminals of the machine can be connected to a grid supply to draw reactive power from the grid. In this case, the machine must be driven above the synchronous speed (for a squirrel-cage machine) to operate it as a generator and such a machine is called grid connected induction generator. The basic operating principles of an induction generator can be found in [11], [30]. Numerous articles on steady-state and dynamic analyses of an induction generator are listed in [27-38]. SEIGs are increasingly being used in small power plants in remote areas because of their many advantageous features over synchronous generators. Recent emphasis on the utilization of clean and renewable energy sources to reduce dependency on fossil fuels makes the use of SEIG even more attractive because vast amounts of renewable energy sources, such as wind and mini-hydro are available in remote areas.

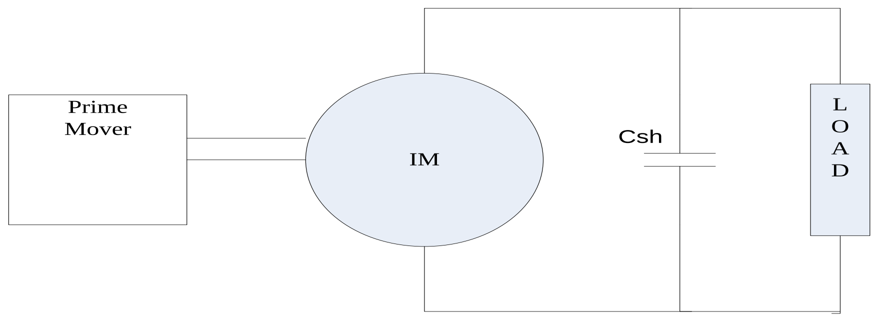

Figure2.1 simple shunt SEIG

Unlike a synchronous generator, an SEIG (squirrel-cage type) is unable to supply reactive power. In fact, it absorbs reactive power from an external source. The reactive power demand of the generator depends on its terminal voltage and other factors. For a constant terminal voltage, the reactive power demand of the generator increases with the increase of its active power delivery. When the excitation capacitor is kept constant, the terminal voltage of the generator usually decreases with the increase in active power delivery. This in turn decreases the amount of reactive power supplied by the capacitor and that causes further reduction of voltage. That is why an SEIG has poor voltage regulation and it is a bottleneck for wide applicability of the generator.

2.2 CONCEPT OF VOLTAGE REGULATION IN SEIG

Effects of various parameters were represented in graphical form and power capability of SEIG was estimated for different sets of parameters using the same value of capacitance. The same curves were used to draw inferences on frequency regulation to suggest design modifications. But in actual practice the value of capacitance required, changes over a wide range for different sets of parameters or different designs. Hence performance compared for different designs need to be made using the corresponding capacitor connected across the terminals. Further good commercial practice and requirements of customers demand a generator to work within a close voltage tolerance band. Due to the use of same capacitance value for different designs there is considerable variation in the terminal voltage level. In most of the cases, peak of the generator output power lies outside the permitted voltage band. And therefore, in general the maximum power capability of the generators (P,) cannot be utilized. The maximum usable power (Pm') of generator is then the power at which the terminal voltage falls to the minimum permissible level, as shown; where **P** ' < P . Since voltage regulation as defined with respect to alternator or dc generator is not applicable to SEIG, it is required to set proper criterion for its voltage regulation. This may seem to be a good contender in the Pi, s respect, but due to the reasons mentioned above and also due to the overlapping curves as shown**,** it can be noted that the set of parameters which give higher P, may not give higher power within a band and hence may result in reduced regulation. Therefore, the criterion that the design giving higher peak power will also have a better regulation does not stand true in all cases. However, with the definition of a voltage tolerance band, which appears logical in practice, the set of parameters which gives maximum usable power also gives a better regulation. It can also be seen that set of parameters for better regulation vary as the permissible voltage band is changed. Since the utility permit a voltage fluctuation of ***+6%,*** a voltage band between V_{max}=1.06p.u. and V_{min}=0.94p.u. has been considered in this thesis. The capacitance Value considered in individual design is the one required to get V at no load. The regulation is estimated in terms of the maximum usable power $P_{m'}$ at V_{mj}.

2.3 SHORT SHUNT CONFIGURATION

The short shunt scheme is more effective in the optimum voltage regulation for higher loads. This uses series capacitive compensation. When the load current increases, the current passing through the series capacitance also increases. More magnetizing reactive power is furnished to the machine, hence the voltage drop with load will be less severe compared to simple shunt SEIG.

Inclusion of additional series capacitance to provide additional VAR with load is one of the attractive options to improve voltage regulation of SEIG. Basset and Potter [11] in their classical paper have presented some experimental results to highlight the self regulating feature of compounded SEIG. It is also demonstrated experimentally that it is possible to have almost a flat load characteristic with a particular combination of capacitors connected under short shunt configuration (Figure). This eliminates any additional voltage regulator since the scheme has inherent self regulating feature. As mentioned earlier, for constant voltage operation, the reactive power demand of an induction generator increases with its active power delivery. Thus, the use of a series capacitor to supply a part of additional reactive power demand would definitely improve the voltage profile. To utilize this feature, short-shunt and long-shunt configurations of induction generators are proposed by some researchers [12],[18]. In both the short- and the long-shunt configurations, two sets of capacitors (series and shunt), as shown in Fig. 2.2, are used. In the short-shunt configuration, the shunt capacitor is directly connected across the machine terminals. The load is then connected to the machine terminals through the series capacitor. In the case of the long-shunt configuration, the stator windings of the machine are connected in series with the series capacitors. The load, in parallel with the shunt capacitor, is then connected across the series combination of stator windings and series capacitors. Comparative studies revealed that the short-shunt configuration can provide better results than its counterpart long-shunt configuration [12]. Even for the short-shunt configuration, the voltage profile in the entire operating range (form no-load to full load) may exceed the upper and lower acceptable limits. However, the voltage profile can be improved by using additional shunt switched capacitors. The number of switched capacitors needed in this case would be much less than that in the conventional shunt generator of Fig. 2.1 (where only the shunt capacitor is used).

This chapter describes a method of determining the values of series and shunt capacitors needed in a short-shunt induction generator to maintain the load voltage within the upper and lower acceptable limits. The effectiveness of the proposed method is then evaluated on a three-phase, 3.7 kW short shunt induction generator.

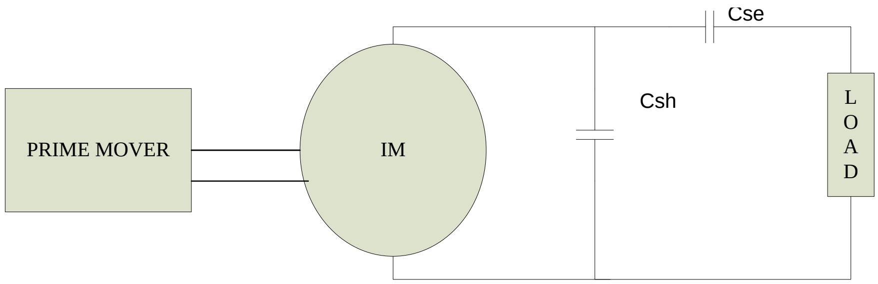

Figure 2.2: schematic diagram of SEIG with short shunt connections

2.4 MATHEMATICAL MODELLING AND PROBLEM FORMULATION

The per-phase equivalent circuit of a three-phase short-shunt induction generator with its excitation capacitors and a resistive load is shown in the figure, where Rs, Xs, R_r, X_r, and X_m represent the stator resistance, stator leakage reactance, rotor resistance, rotor leakage reactance and magnetizing reactance, respectively. f and v represent the per unit (p.u.) frequency and speed, respectively. The reactance of the series and shunt capacitors is represented by X_{se} and X_{sh}, respectively. The load impedance is represented by Z_l. The pu frequency F and the p.u. speed v are defined as

$$f=f/f_b \quad \text{and} \quad v=n/n_s$$

Here, f and N are the actual operating frequency (Hz) and rotor speed (rpm), respectively, of the generator, and f_b and Ns are the base or rated frequency (Hz) and the corresponding synchronous speed (rpm), respectively, of the machine. When the generator operates at a frequency other than the base frequency, all reactance (inductive and capacitive) are to be adjusted accordingly. In a generic way, the inductive reactance are to be multiplied by the pu frequency f and the capacitive reactance are to be divided by f. The circuit shown in Fig. 2.3 represents a generic equivalent circuit of the generator where all parameters (resistance and reactance) and voltages are divided by the p.u. frequency f, whereas the currents remain the same [15].

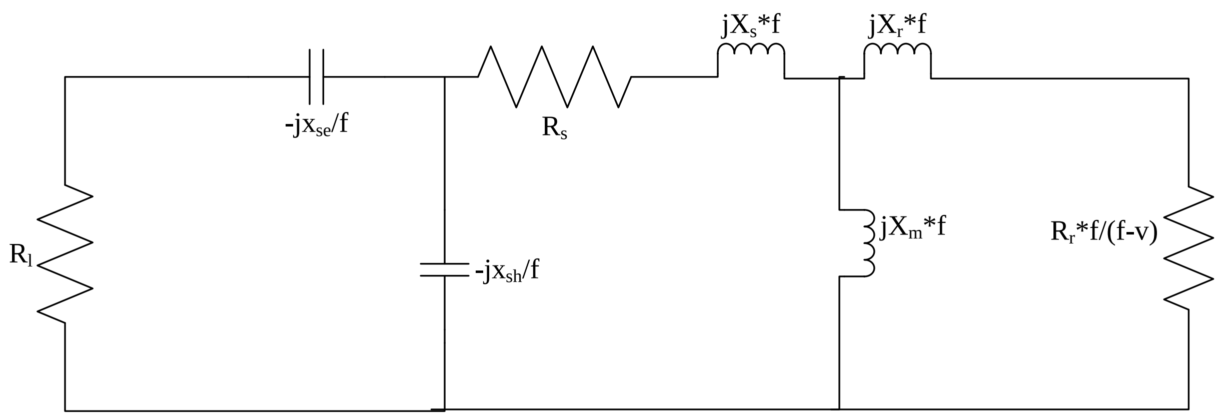

Figure 2.3 equivalent circuit of short shunt SEIG.

All parameters of the generator, except the magnetizing reactance, are considered as constant. The variation of magnetizing reactance X_m is the main factor in the process of the voltage build-up and stabilization of the operating point of an SEIG. The value of X_m depends on magnetic saturation or air-gap flux, which in turn depends on the ratio of the air-gap voltage to frequency (Vg/f). The relationship between Vg/f and X_m can be established from the synchronous speed test results [48]. The relation is given as:

$$V_g/f = k_1 - k_2 * X_m \quad \text{......................................(2.1)}$$

The coefficients of the above polynomial can easily be obtained by applying any standard curve fitting technique to the synchronous speed test results.

2.4.1 ANALYSIS

The steady-state performance of an induction generator is usually determined from its equivalent circuit. To simplify the analysis, the circuit of Fig. 2.3 is represented by three series impedances as shown in Fig. 2.4. The impedances are

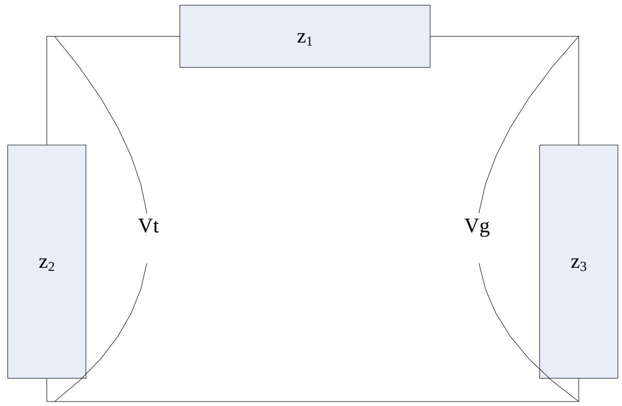

Figure 2.4 simplified representation of the circuit.

Where

Z_1 = Rs+(j*Xs*f)……………………………………………………………………..(2.2a)

Z_2 = (j*f*X_m)*((R_r*f/(f-v))+(j*X_r * f)))/(R_r * f/(f-v)+(j*f*(X_m + X_r))……………........(2.2b)

Z_3 = (-j*X_{sh}/f)*(R_L-(j*X_{se}/f))/(R_L-((j*X_{sh}/f)+(j*X_{se}/f)))……………………………..(2.2c)

The loop equation in the figure 2.4 is

$$I_s(Z_1 + Z_2 + Z_3) = 0 \quad (2.3)$$

Under normal running conditions, the stator current is never zero hence the impedance function has to be zero.

Therefore,

$$(Z_1 + Z_2 + Z_3) = 0 \quad (2.4)$$

Note that the above equation must be satisfied for all operating conditions of the generator. By separating the real and imaginary parts of (2.4), the following two scalar equations can be obtained

$$G1= real\ (Z_1 + Z_2 + Z_3) = 0 \quad (2.5)$$

$$G2= imag\ (Z_1 + Z_2 + Z_3) = 0 \quad (2.6)$$

Note that (2.5) and (2.6) can provide the values of only the two unknowns. However, the circuit of Fig. 2.3 has six unknowns or adjustable parameters: magnetizing reactance X_m, p.u. speed v, p.u. frequency f, series capacitive reactance X_{se}, shunt capacitive reactance X_{sh} and load impedance Z_L (for a given power factor). In general, (2.5) and (2.6) are simultaneously solved to obtain the values of Xm and f for given values of v, X_{se}, X_{sh} and Z_l. The above equations, in a general form, can be written as

$$G(X) = 0 \quad (2.7)$$

Where G= [G1; G2]' and X= [X_m; f]' Once the value of X_m and f are known, V_g can be evaluated through (1). The terminal voltage Vt of the generator (in Fig. 4) can be written as:

$$V_t=V_g*Z_3/(Z_1+Z_3) \quad (2.8)$$

Here, V_g is considered as the reference.

In this study, (2.7) are solved using a numerical based routine 'fsolve' given in the optimization toolbox of MATLAB. It uses a nonlinear least-squares algorithm that employs the Gauss–Newton or the Lavenberg– Marquardt method. A least-squares-based method usually converges to a point where the residual is the minimum. However, if the formulated problem (2.7) does not have a zero (numerically) because of the selection of unrealistic values of some parameters, the routine may still converge to a point where the residual is the minimum but not necessarily zero. Such a solution cannot be considered as acceptable and it can easily be identified by evaluating the residual at the solution point and comparing it with a very small tolerance (say, 10^{-18}).

After evaluating Xm and f, we can now easily calculate the performance parameters of the machine which are power output, load voltage, stator current, rotor current, load current and load voltage and hence the load power which are useful for the analysis purpose of SEIG.

$$I_s=V_g / (Z_1 + Z_l Z_{ch}/ (Z_l + Z_{ch})) \quad (2.9)$$

$$I_r=Vg/ (Rr*f/ (f-v) +jfX_r) \quad (2.10)$$

$$I_l= Is* Z_{ch} / (Z_l + Z_{ch}) \quad (2.11)$$

$$V_l=I_l*R_l \quad (2.12)$$

$$P_{out}=3*I_l^2*R_l \quad (2.13)$$

Where Z_l and Z_{ch} are the load impedance and the impedance of the shunt capacitor respectively and are given by equations (2.14) and (2.15).

$$Z_l = R_l - j*X_{se}/f \quad (2.14)$$

$$Z_{ch} = - j*X_{sh}/f \quad (2.15)$$

2.4.2 SELECTION PHILOSOPHY OF ELEMENTS

When the SEIG is operating under no load condition, there will not be any current through the series capacitor (C_{se}) and only shunt capacitor is effective in the circuit. Therefore, effect of C_{sh} is reflected on the no load performance of the SEIG. But when loaded, both shunt and series capacitors will be effective. Hence, proper value of these elements can be chosen by first studying the variation of no load terminal voltage with C_{sh}. Having chosen a suitable value for C_{sh} from this curve, the influence of C_{se} can be studied by observing the effect of C_{se} on voltage regulation of the SEIG. Appropriate value of C_{se} can be selected from the range of values thus obtained depending upon the desired regulation and other operating constraints.

2.5 ALGORITHM AND FLOWCHART

The computational procedure for 'fsolve' method for the selection strategy is as follows:

1. Read machine data such as R_s, R_r, X_s, X_r, R_l, etc.
2. Assume initial values of X_m and f.
3. Set the iteration for the power counter.
4. Apply the 'fsolve' technique for solving Xm and f.
5. Calculate the voltage deviation.
6. Select value of shunt capacitance from the graph between no load voltage and capacitance between the 0.94 p.u. and 1.06 p.u.
7. Select value of series capacitance from the graph between regulation and series capacitance values.
8. Run the iterations till the convergence point is reached.
9. Then run the iterations for various capacitance values for series and shunt values.
10. When the voltage deviation is optimum i.e. around 2%, then we can say that the selection is proper.

11. Calculate the other performance parameters which are necessary in the analyses and draw relevant graphs.

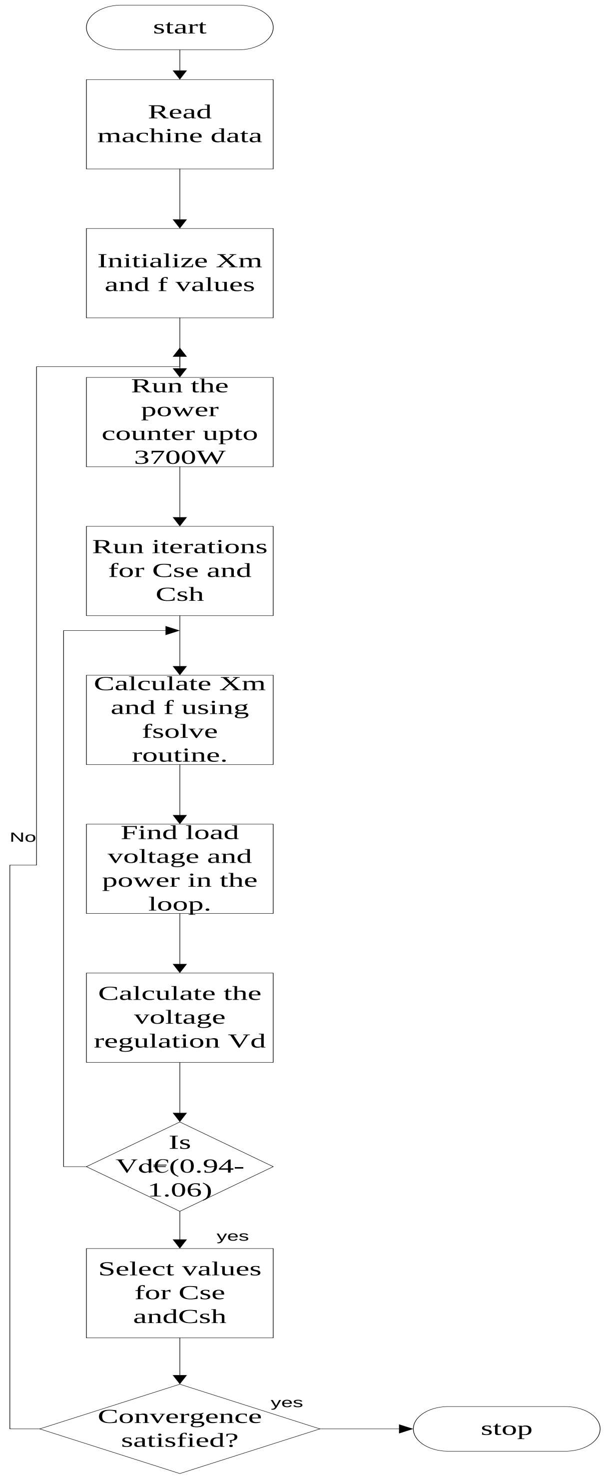

Figure 2.5 flowcharts for 'fsolve' process

2.6 RESULTS AND DISCUSSIONS

Simulation results are shown in this section using the MATLAB routine 'fsolve'. Various graphs have been plotted for different machine parameters for different capacitance values and speeds for resistive and reactive loadings.

2.6.1 FOR RESISTIVE LOAD (UNITY P.F.)

- Variation between V_l and power output for C_{sh}=16.7µF and C_{se}=165µF.
- Variation between Vt and power output for C_{sh}=16.7µF and C_{se}=165µF.
- Variation between Is and power output for C_{sh}=16.7µF and C_{se}=165µF.

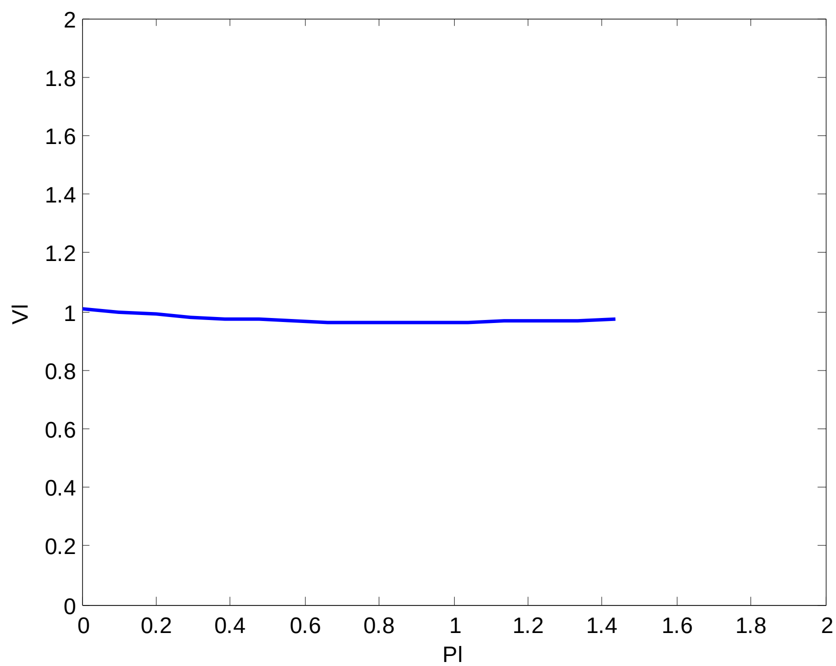

Figure 2.6 variation between load voltage and load power

This figure (figure 2.6) shows the variation between the load voltage and the load power for the selected capacitance values and it has been shown that for this selection, the load voltage doesn't vary much and hence can be termed as a constant voltage operation. The voltage regulation with the selected capacitance comes out to be 4.3%.

Figure 2.7 shows the variation between machine terminal voltage and the load power for this particular selection and we see that there is a very slight rise in the voltage as the power increases but given the rise is high that is seen for lower values of Cse, that can result in a poor voltage regulation.

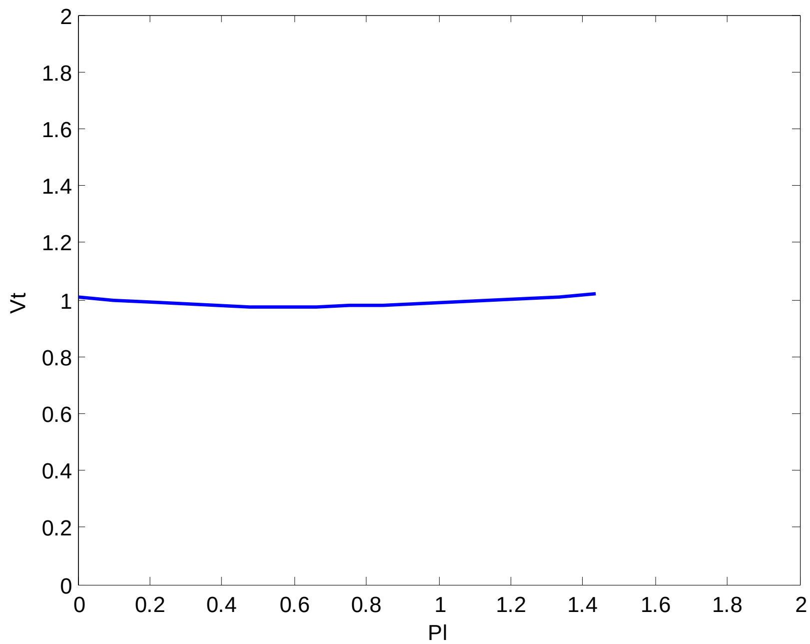

Figure 2.7 variation of terminal voltage with load power.

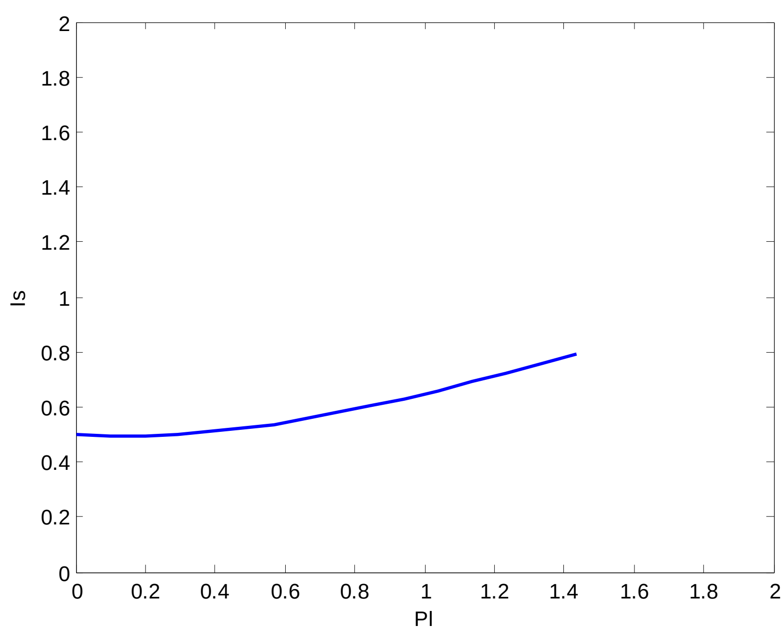

Figure 2.8: variation of stator current with load power.

Figure 2.8 shows the variation of the stator current with load power. It is seen that for the lower value of C_{se} the power capability of the SEIG reduces since at rated winding current it can deliver less than rated power, needing the machine to be de-rated. Where as in the case of higher C_{se}, the power capability of the SEIG increases at the cost of high capacitance, high cost and poor voltage regulation.

2.6.2 FOR REACTIVE LOAD

The next set of simulation results for the same set of capacitance values show the variation of the stator current, load voltage and terminal voltage with load power at a power factor of 0.9. This hence includes the reactive loading as the resistive loading is not commonly used in practice so analyses of reactive loading also become a paramount importance.

- Variation of load voltage and load power at 0.9 p.f.
- Variation of termninal voltage and load power at 0.9 p.f.
- Variation of stator current and load power at 0.9 p.f.

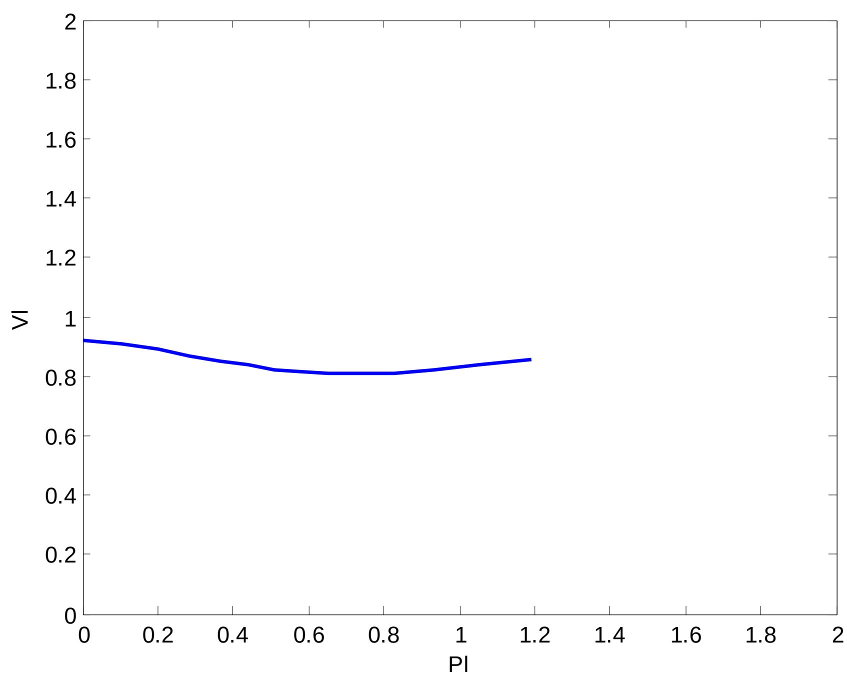

Figure 2.9 load voltage v/s load power at pf=0.9

Figure 2.9 shows the variation of load voltage and load power at 0.8 power factor. It is seen that there is not much variation for the optimum selected capacitance but if we want constant voltage curve, the value of capacitance must be increased. It is seen that the power capability reduces to some extent as the voltage regulation increases because the reactive power has been taken into account.

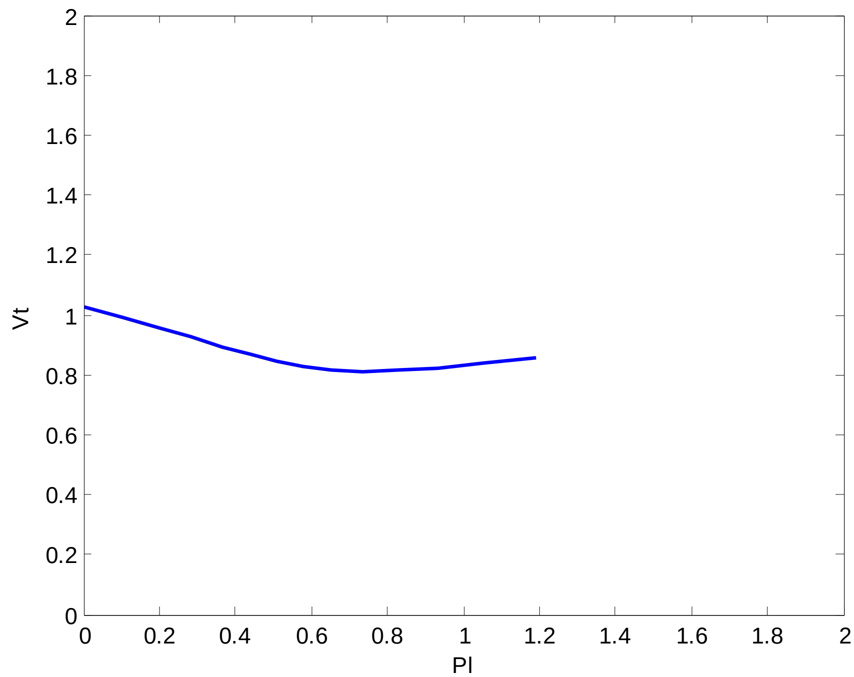

Figure 2.10 terminal voltage v/s load power at p.f.=0.9

Figure 2.10 depicts the variation of machine terminal voltage and load power. Here we see that the voltage initially goes down at load power=0.8 p.u. at a power factor of 0.9 and then slowly starts increasing. This shows that at a power factor of 0.9 also, the terminal voltage is highly affected much and such depreciation is not expected in case of machine terminal voltage as the voltage should rise.

Figure 2.11 shows the variation of stator current with load power at a power factor of 0.9. It is seen that in this figure that the power only rises up to 1.4 p.u. hence the power capability decreases as the reactive power is introduced in the machine.

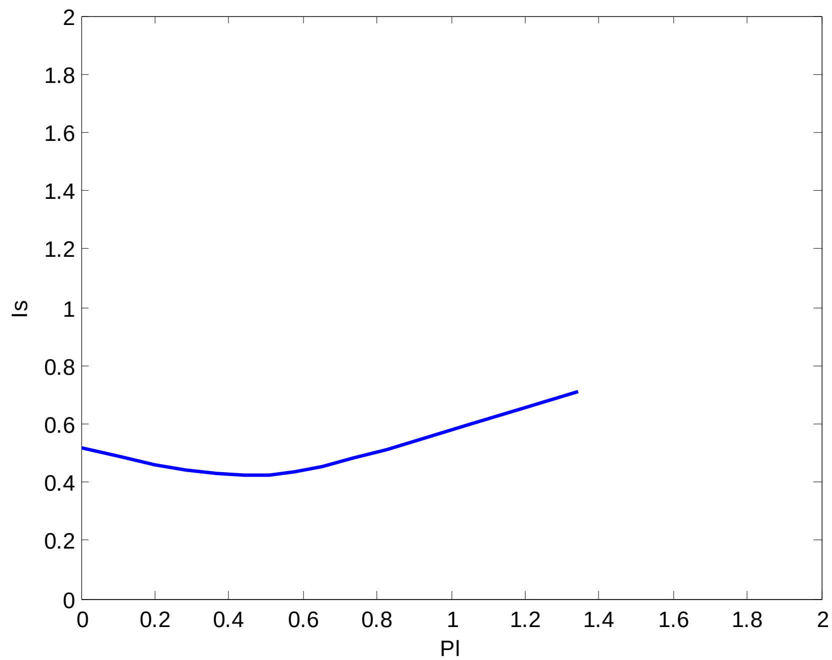

Figure 2.11 stator current v/s load power at p.f=0.9.

2.6.3 FOR REACTIVE LOADING AT VARIABLE SPEED

The next set of figures depict the variations in load voltage, machine terminal voltage and stator current at p.f. =0.9 and speed of 0.9 p.u Considerable differences in the voltage values can be seen when operated with speed other than rated speed at given power factor.

- Variation of load voltage and load power at speed 0.9 p.u. and p.f. 0.9
- Variation of terminal voltage and load power at speed 0.9 p.u. and p.f. 0.9
- Variation of stator current and load power at speed 0.9 p.u. and p.f. 0.9

Figure 2.12 shows the variation of load voltage and power. It is seen that the load voltage has gone down to 0.82 p.u. it is needed to enhance the series and shunt capacitance values to 180 μF and 18 μF respectively but this results in a high value of voltage regulation i.e.12% hence the series and shunt capacitance values need to be properly optimized to get a acceptable voltage regulation within the limits.

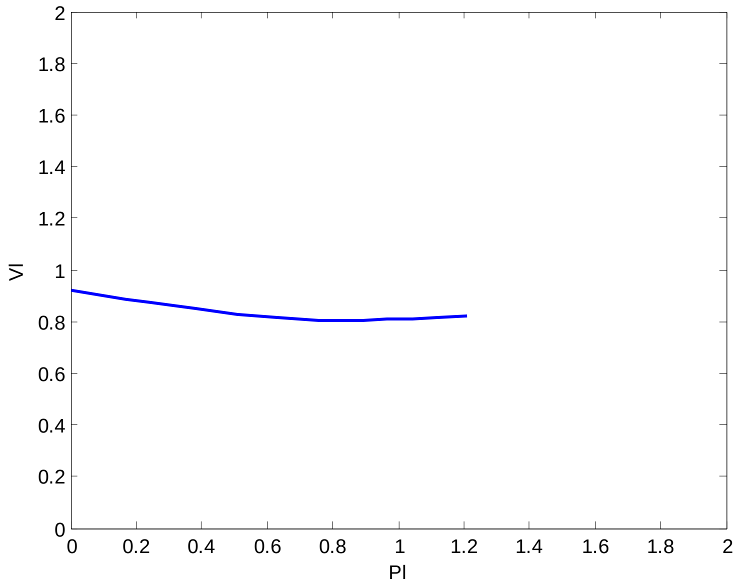

Figure 2.12 load voltage v/s load power at v=0.9 p.u.

Figure 2.13 shows the variation between machine terminal voltage and load power for speed 0.9 p.u. And power factor 0.9. it is seen that the terminal voltage also decreases and the voltage regulation can also violate in this case as it affects the load voltage also. So it can be inferred that if the prime mover speed decreases, it results in decrease of terminal voltage also.

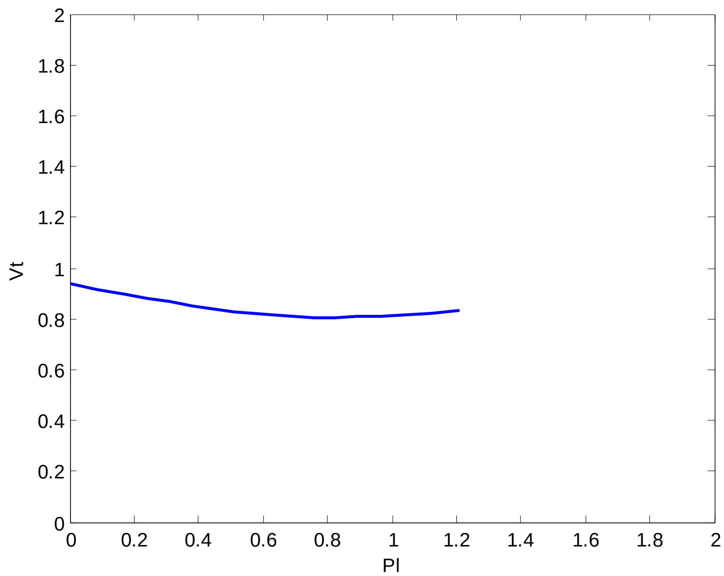

Figure 2.13 terminal voltage v/s load power at v=0.9 p.u.

Figure 2.14 shows the stator current variation with load power at the power factor of 0.9 and with a speed 0.9 p.u. if the speed is changed, it affects the slip of SEIG and hence due to this virtue, the stator current is affected.

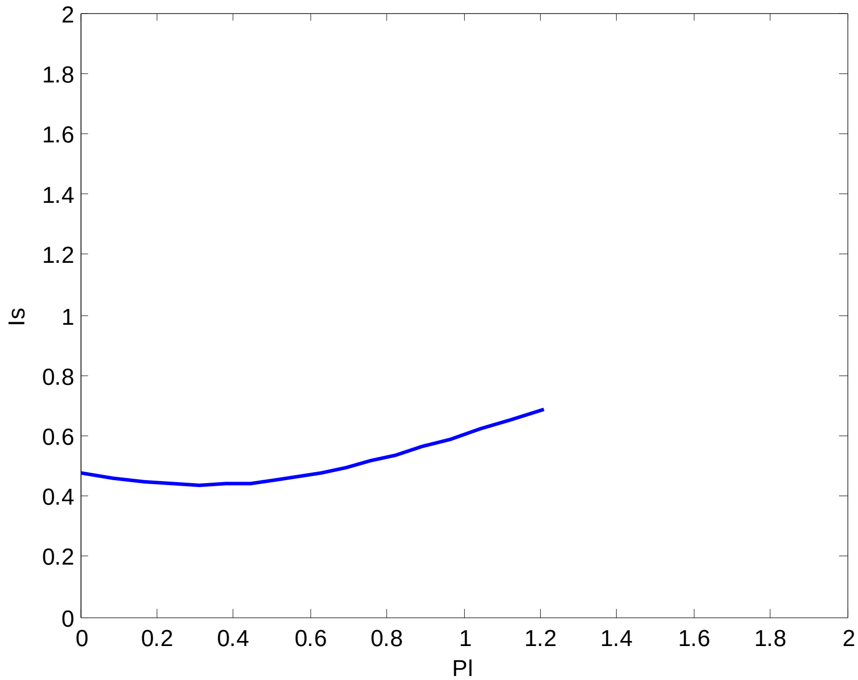

Figure2.14 stator current v/s load power at v=0.9 p.u.

The next set of graphs and simulation results depicts the various capacitance values used and the selection of capacitors done for the optimum voltage regulation. Various curves are plotted between v_t, v_l, i_s v/s load power for 3 different series capacitance values of 72.5μF, 165 μF, and 217.5 μF respectively.

- Variation of load voltage and load power for different series capacitors.
- Variation of terminal voltage and load power for different series capacitors.
- Variation of stator current and load power for different series capacitors.
- Effect of shunt capacitance on load characteristics.

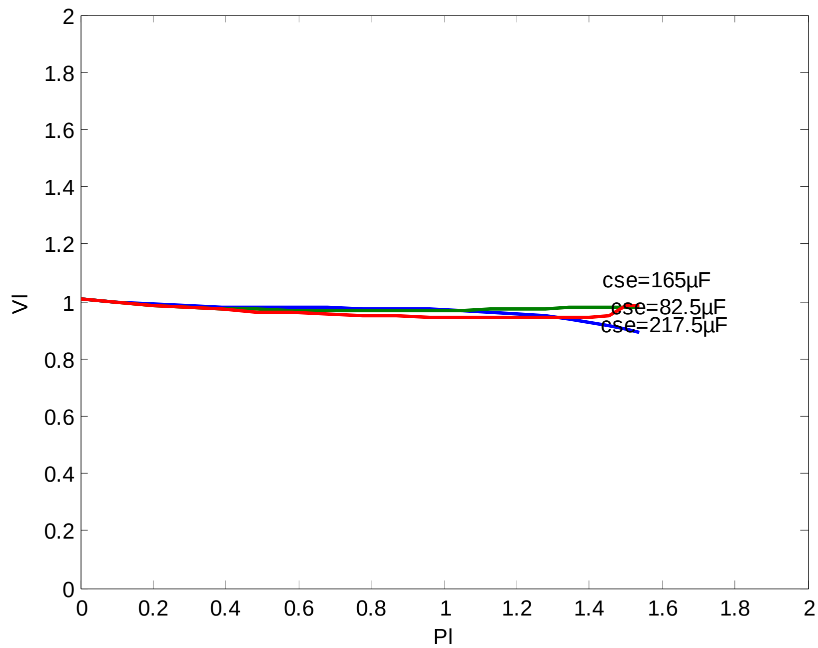

Figure 2.15 load voltage v/s power at different capacitors

Figure 2.15 shows the variation of load voltage and load power at different capacitor values and it is seen that as the capacitance values increase, the voltage falls down resulting in poor voltage regulation.

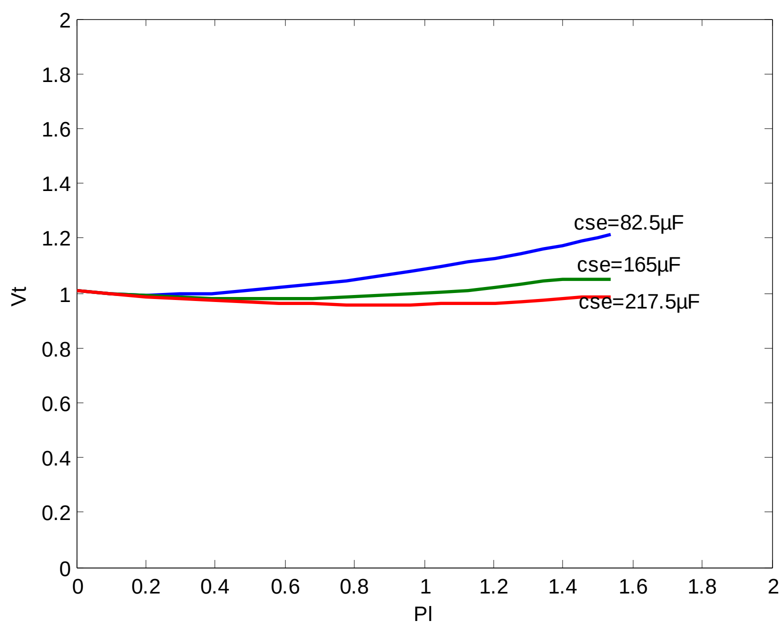

Figure 2.16 terminal voltage v/s load power at different capacitors

Figure 2.16 shows the variation between terminal voltage and load power for various capacitive loadings. It is seen that for the optimal selection, the terminal voltage rises but as the capacitance values is enhanced, the voltage starts falling and hence gives a poor regulation and the power capability of the machine also decreases.

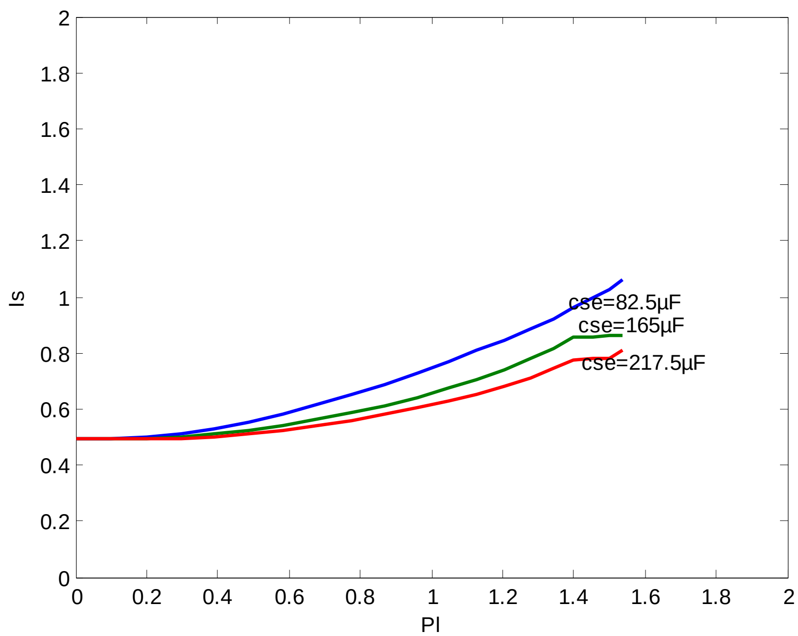

Figure 2.17 variation of stator current and load power at different capacitors

Figure 2.17 shows the variation between stator current and load power and it is seen that a lower values of series capacitance power capability reduces and at higher values it increases at cost of poor voltage regulation. But with C_{se} =165μF, the performance is not constrained.

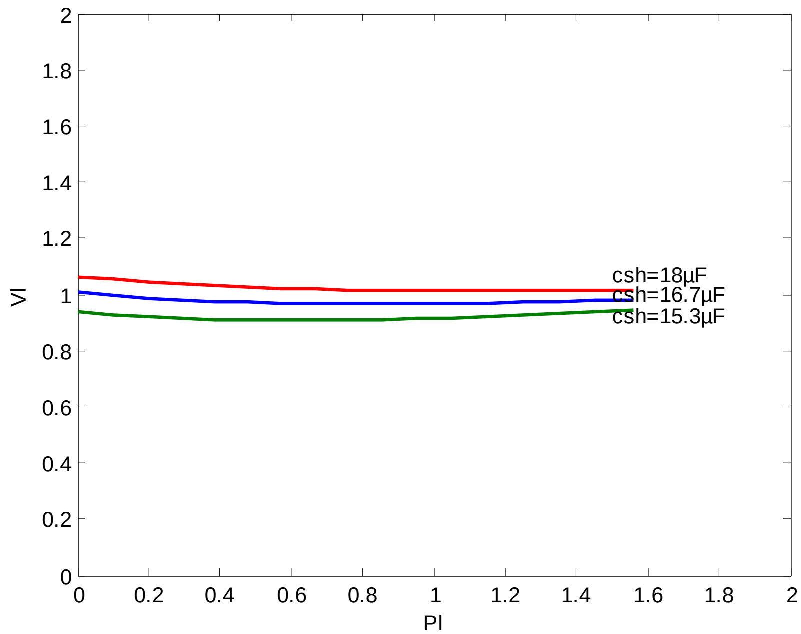

Figure 2.18 effect of shunt capacitance on load characteristics

Figure 2.18 shows the variation of load voltage with load power for different values of shunt capacitances. The C_{sh} is also said to have some effect on voltage at full load. For lower values, dips are noticed.

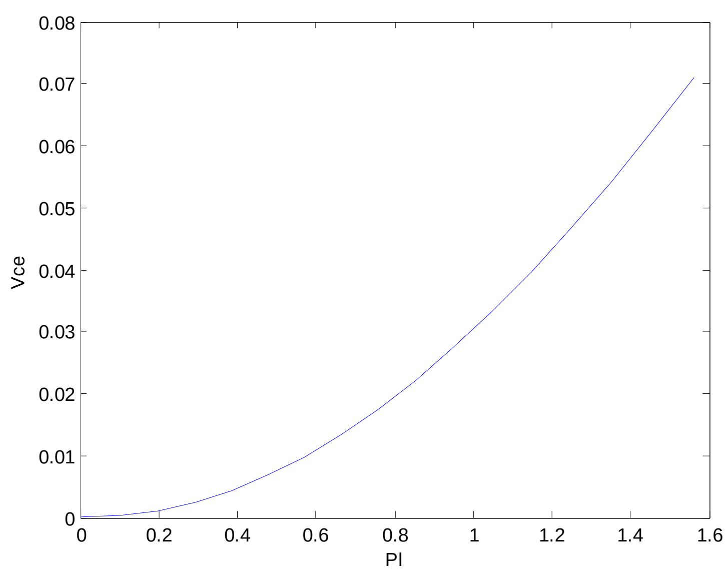

Figure 2.19 Variation of series capacitor voltage with load power

Figure 2.19 shows the variation between the voltage across the series capacitor with the load power and it is seen that the voltage increases almost linearly with the load power for the nominal selected capacitance.

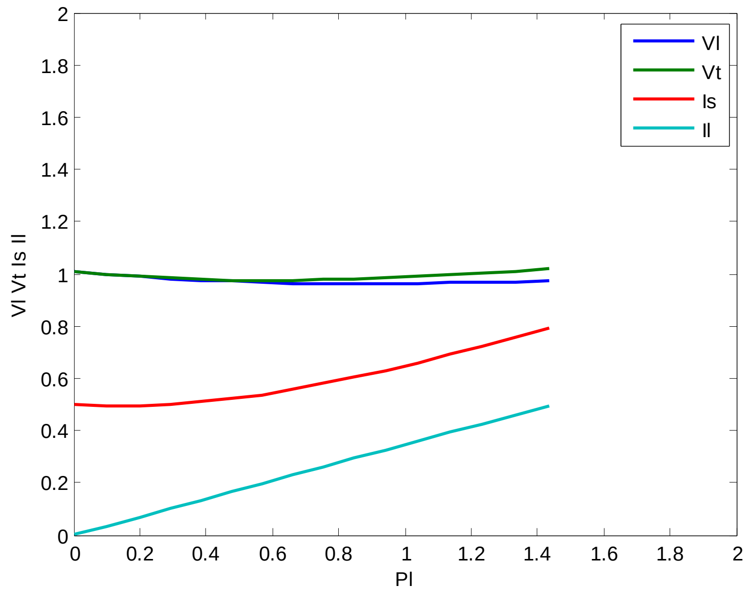

Figure 2.20 variation of different parameters with power

Figure 2.20 shows the combined results for stator current, load voltage, terminal voltage and load current for the optimum selection of capacitance values. The machine can be designed to withstand overvoltage and low voltage regulation is the main attractive feature of the machine. The variation of load current with the load power has also been shown.

2.7 CONCLUSIONS

Simulation results for optimum selection of capacitors as well as different capacitance values have been shown in this chapter using the 'fsolve' routine. We see that series capacitance values highly affect the voltage regulation but shunt capacitance doesn't affect it much. Different speed and power factor variation have also been presented in the proposed simulation.

CHAPTER 3

THEORY OF PARTICLE SWARM OPTIMIZATION

3.1INTRODUCTION

Particle swarm optimization is a stochastic, population-based search and optimization algorithm for problem solving. It is a kind of swarm intelligence that is based on social psychological principles and provides insights into social behavior, as well as contributing to engineering applications. The particle swarm optimization algorithm was first described in 1995 by Kennedy and Eberhart [86-88]. The techniques have evolved greatly since then, and the original version of the algorithm is barely used at present. Social influence and social learning enable a person to maintain cognitive consistency. People solve problems by talking with other people about them, and as they interacts their beliefs, attitudes, and behavior changes, the changes could typically be depicted as the individuals moving toward one another in a socio-cognitive space.

The particle swarm is an algorithm for finding optimal regions of complex search spaces through the interaction of individuals in a population of particles. Even though the algorithm, which is based on a metaphor of social interaction, has been shown to perform well, researchers have not adequately explained how it works. Further, traditional versions of the algorithm have had some undesirable dynamical properties, notably the particles' velocities needed to be limited in order to control their trajectories. The present analyses presents a particle's trajectory as it moves in discrete time (the algebraic view), then progresses to the view of it in continuous time (the analytical view). A five-dimensional depiction is developed, which describes the system completely. These analyses lead to a generalized model of the algorithm, containing a set of coefficients to control the system's convergence tendencies. Some results of the particle swarm optimizer, implementing modifications derived from the analysis, suggest methods for altering the original algorithm in ways that eliminate problems and increase the ability of the particle swarm to find optima of some well studied test functions.

3.2 THE PARTICLE SWARM CONCEPT

Particle swarm optimization is similar to a genetic algorithm in that the system is initialized with a population of random solutions. It is unlike a genetic algorithm, however, in that each potential solution is also assigned a randomized velocity, and the potential solutions, called particles, are then “flown” through hyperspace. Each particle keeps track of its coordinates in hyperspace which are associated with the best solution (fitness) it has achieved so far. (The value of that fitness is also stored.) This value is called pbest. Another “best” value is also tracked. The “global” version of the particle swarm optimizer keeps track of the overall best value, and its location, obtained thus far by any particle in the population; this is called gbest. The particle swarm optimization concept consists of, at each time step, changing the velocity (accelerating) each particle toward its pbest and gbest (global version). Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward pbest and gbest.

A population of particles ‘x_i’ is initialized with random positions and velocities and a function ‘f’ is evaluated, using the particle’s positional coordinates as input values [87]. Positions and velocities are adjusted and the function evaluated with the new coordinates at each time step. When a particle discovers a pattern that is better than any it has found previously, it stores the coordinates in a vector. The difference between ’p_i’ (the best point found by so far) and the individual’s current position is stochastically added to the current velocity, causing the trajectory to oscillate around that point. Further, each particle is defined within the context of a topological neighborhood comprising itself and some other particles in the population. The stochastically weighted difference between the neighborhood’s best position and the individual’s current position is also added to its velocity, adjusting it for the next time step. These adjustments to the particle’s movement through the space cause it to search it around two different positions.

The variables ’$Ø_1$’ and’$Ø_2$’ are random positive numbers, drawn from a uniform distribution and defined by an upper limit ’$Ø_{max}$’, which is a parameter of the system. In this version, the term variable is limited to the range $\pm Vmax$ for reasons that will be explained below. The values of the elements in the swarm are determined by comparing the best performances of all the members of particle’s topological neighborhood, defined by indexes of some other population members and assigning the best performer's index to the variable. Thus, represents the best position found by any member of the neighborhood.

The random weighting of the control parameters in the algorithm results in a kind of explosion or a "drunkard's walk" as particles' velocities and positional coordinates carried towards infinity. The explosion has traditionally been contained through implementation of a $Vmax$ parameter, which limits step size or velocity. In the literature, it has been demonstrated that the implementation of properly defined constriction coefficients can prevent explosion; however, these coefficients can induce particles to converge on local optima. An important source of the swarm's search capability is the interactions among particles as they react to one another's findings. Analysis of inter particle effects is beyond the scope of this thesis, which focuses on the trajectories of single particles.

3.3 THE BASIC PARTICLE SWARM OPTIMIZATION

Particle swarm optimization has roots in two main component methodologies. Perhaps more obvious are its ties to artificial life (A-life) in general, and to bird flocking, fish schooling, and swarming theory in particular. It is also related, however, to evolutionary computation, and has ties to both genetic algorithms and evolution strategies. Particle swarm optimization comprises a very simple concept, and paradigms can be implemented in a computer code. It requires only primitive mathematical operators, and is computationally inexpensive in terms of both memory requirements and speed. Early testing has found the implementation to be effective with several kinds of problems. Particle swarm optimization has also been demonstrated to perform well on genetic algorithm test functions, and it appears to be a promising approach for robot task learning.

Instead of using evolutionary operators to manipulate the individuals, like in other evolutionary computational algorithms, each individual in PSO flies in the search space with a velocity which is dynamically adjusted according to its own flying experience and its companions' flying experience. Each individual is treated as a volume-less particle (a point) in the dimensional search space. The ith particle is represented as $X_i = (x_{i1}, x_{i2}, \ldots,$

x_{iD}). The best previous position (the position giving the best fitness value) of the 'ith' particle is recorded and represented as Pi = (p_{i1}, p_{i2}, ….., p_{iD}). The index of the best particle among all the particles in the population is represented by the symbol g. The rate of the position change (velocity) for particle i is represented as Vi to the following equation:- (v_{i1}, v_{i2}, .. . , v_{iD}). The particles are manipulated according to the following equations:

$$\mathbf{V_{id} = V_{id} + C_1*rand(\,)*(P_{iD} - X_{iD}) + C_2*rand(\,)*(P_{gD} - X_{iD})} \quad \textbf{(3.1)}$$

$$\mathbf{X_{id(t+1)} = X_{id(t)} + V_{id}} \quad \textbf{(3.2)}$$

Where C_1 and C_2 are two positive coefficients and rand( ) is the random function in the range 0-1.

Unlike in genetic algorithms, evolutionary programming, and evolution strategies, in PSO, the selection operation is not performed [89]. All particles in PSO are kept as members of the population through the course of the run (a run is defined as the total number of generations of the evolutionary algorithms prior to termination) [90]. It is the velocity of the particle which is updated according to its own previous best position and the previous best position of its companions. The particles fly with the updated velocities. PSO is the only evolutionary algorithm that does not implement survival of the fittest [89].

By considering equation (3.1) as similar to a mutation operation, the PSO algorithm is similar to the evolutionary programming algorithm since neither algorithm performs a crossover operation. In evolutionary programming, each individual is mutated by adding a random function (the most commonly used random function is either a Gaussian or Cauchy function) [91], while in PSO each particle (individual) is updated according to its own flying experience and the group's flying experience. In other words, at each generation, each particle in PSO can only fly in a limited number of directions which are expected to be good areas to fly toward according to the group's experience; while in evolutionary programming, each individual has the possibility to "fly" in any direction which is a "conscience" [92]. Theoretically speaking, evolutionary programming has more chance to "fly" into an area around the global optimal position while the PSO has more chance to "fly" into the better solution areas more quickly when the "conscience" provides helpful information. In evolutionary programming, the balance between the global and local search is adjusted through adapting the variance (strategy parameter) of the Gaussian random function or step size, which can even be encoded into the chromosomes to undergo evolution itself. In PSO, a parameter called inertia weight is brought in for balancing the global and local search and equation (3.1) is changed to:

$$\mathbf{V_{id} = w^* V_{id} + C_1{*}rand(\,){*}(P_{iD} - X_{iD}) + C_2{*}rand(\,){*}(P_{gD} - X_{iD}) \ldots\ldots \quad (3.1a)}$$

$$\mathbf{X_{id(t+1)} = X_{id(t)} + V_{id} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.2a)}$$

where ‘w’ is the inertia weight [94]. The inertia weight has characteristics that are reminiscent of the temperature parameter in the simulated annealing [89]. A large inertia weight facilitates a global search while a small inertia weight facilitates a local search. By linearly decreasing the inertia weight from a relatively large value to a small value through the course of the PSO run, the PSO tends to have more global search ability at the beginning of the run while having more local search ability near the end of the run.

The simulation results on the benchmark problem of Schaffer’s F6 function illustrate that an inertia weight starting with a value close to 1 and linearly decreasing to 0.4 through the course of the run will give the PSO the best performance compared with all fixed inertia weight settings In [93], Angeline compared the philosophy and performance differences between the evolutionary programming algorithm and PSO algorithm by conducting experiments on four non-linear functions well studied in the evolutionary optimization literature. The evolutionary programming algorithm employed is the one with a combination of Gaussian and Cauchy functions as strategy parameters’ update function. This version of algorithm was first reported in [94] and has been shown to be superior to other update functions for the strategy parameters [95]. The PSO algorithm employed is the original one described by equation (3.1a) and (3.2a). Through adapting the strategy parameters to adjust the mutation step size, the evolutionary programming algorithm employed ideally has the ability to fine tune the search area around the optima. Since only the original version of PSO algorithm is involved in the comparison, no mechanisms are utilized in the PSO to adjust its velocity step size, therefore the PSO may lack some fine tuning ability. The experimental results reported in [93] shows that generally speaking the PSO has quick convergence ability but a slow fine tuning ability while the evolutionary programming algorithm is the opposite. From the results, it can be accepted that by employing a dynamically adapting velocity step size approach, the PSO performance can be improved to have better fine tuning ability similar to that of evolutionary programming. By introducing a linearly decreasing inertia weight into the original version of PSO, the performance of PSO has been greatly improved through experimental study on the benchmark problem of Schaffer's F6 function [92].

3.4 PSO ALGORITHM AND FLOWCHART

There are two categories the algorithm can be divided on the basis of the speed of convergence and susceptibility to local minima.

- Local best PSO
- Global best PSO

For the local best or the individual best version, the steps are as follows. The algorithm uses the ring topology.

1. Initialize the swarm, $x_i(t)$, of particles such that the position P_{iD} of each particle. $x_i(t)$ is random within the hyperspace, with $t = 0$.
2. Evaluate the performance of each particle, using its current position $x_i(t)$.
3. Compare the performance of each individual to its best performance as

   if $F(x_i(t)) < pbest_i$ then

   $$pbest_i = F(x_i(t)) \quad \ldots\ldots (3.3)$$

   $$xpbest_i = x_i(t) \quad \ldots\ldots (3.4)$$

4. Change the velocity vector for each particle using

   $$V_{id} = w * V_{id} + C_1 * rand() * (P_{iD} - X_{iD}) + C_2 * rand() * (P_{gD} - X_{iD}) \quad \ldots\ldots (3.5)$$

   where *p* is a positive random number.

5. Move each particle to a new position.

   $$X_{id(t+1)} = X_{id(t)} + V_{id} \quad \ldots\ldots (3.6)$$

   $$t = t + 1$$

6. go to step 2 repeat until convergence.

For the global best version, the steps carried out are:

The global best, gbest, of PSO reflects the star topology. The social knowledge used to drive the movement of particles includes the position of the best particle from the entire swarm. In addition, each particle uses its history of experiences in terms of its own best solution thus far. In this case the algorithm changes to:

1. Initialize the swarm, P_{iD}, of particles such that the position of each particle $x_i(t)$ which is random within the hyperspace, with $t = 0$.
2. Evaluate the performance of each particle, using its current position *xi (t)*.
3. Compare the performance of each individual to its best performance thus far:

   if F(xi(t)) < pbesti , then

   pbesti = F(xi(t))……………………………………………(3.7)

   pbesti = xi(t)………………………………………………….. (3.8)
4. Compare the performance of each particle to the global best particle:

   if F (xi(t)) < gbest then

   xgbest = F(xi(t))……………………………………………… (3.9)

   xgbest = xi(t)…………………………………………… (3.10)
5. Then the velocity is updated as:

$$V_{id} = w * V_{id} + C_1 * rand(\ ) * (P_{iD} - X_{iD}) + C_2 * rand(\ ) * (P_{gD} - X_{iD}) \quad \ldots\ldots\ldots \quad (3.11)$$

Where C_1 and C_2 are random variables. The second term above is referred to as the cognitive component, while the last term is the social component.

6. Then the corresponding positions are updated

$$X_{id(t+1)} = X_{id(t)} + V_{id} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.12)$$

$$t = t + 1$$

7. Go to step 2, repeat until convergence.

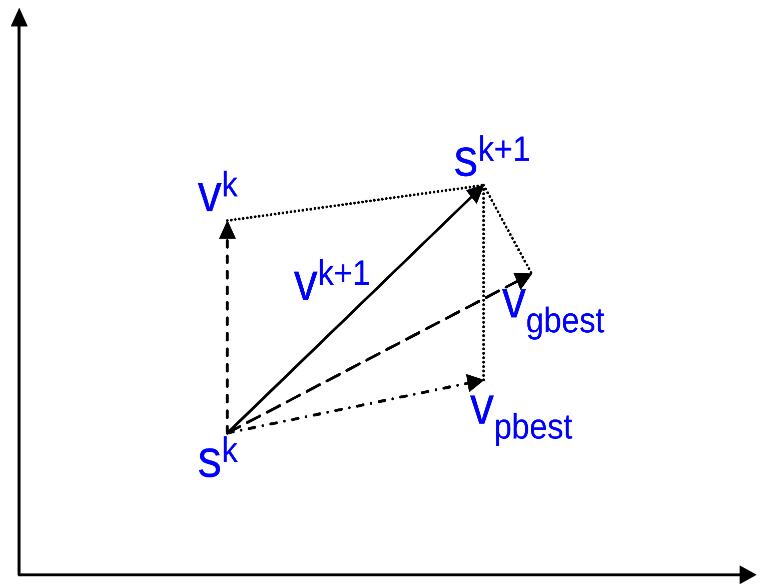

Figure3.1 update process during the PSO

The algorithms above continue until convergence has been reached. Usually, a PSO algorithm is executed for a fixed number of iterations, or fitness function evaluations. Alternatively, a PSO algorithm can be terminated if the velocity changes are close to zero for all the particles, in which case there will be no further changes in particle positions. Figure 3.1 shows the update process during the as the swarms moves towards their best positions. The following figure (figure 3.2) shows the flowchart of the proposed PSO algorithm.

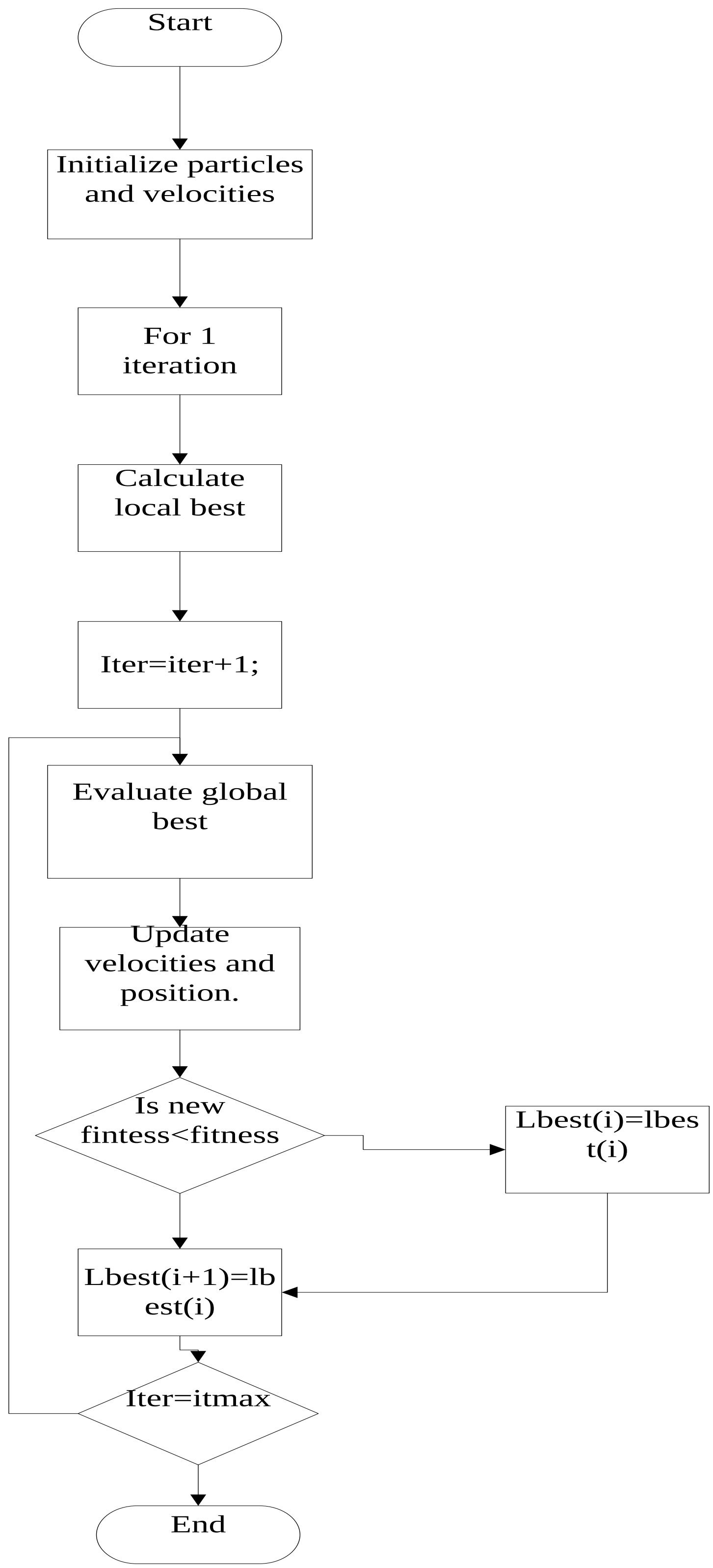

Figure3.2 flowchart for PSO

3.5TEST FUNCTION

The effectiveness of PSO is demonstrated using a test example to show how it optimizes and the particles reach a global best as shown in figure 3.3.

The function is: **x^0.5 * y^0.5**

Number of dimensions: 2

Number of particles: 50

C1=C2=2

Inertia weight ‘w’: 0.9 to 0.4

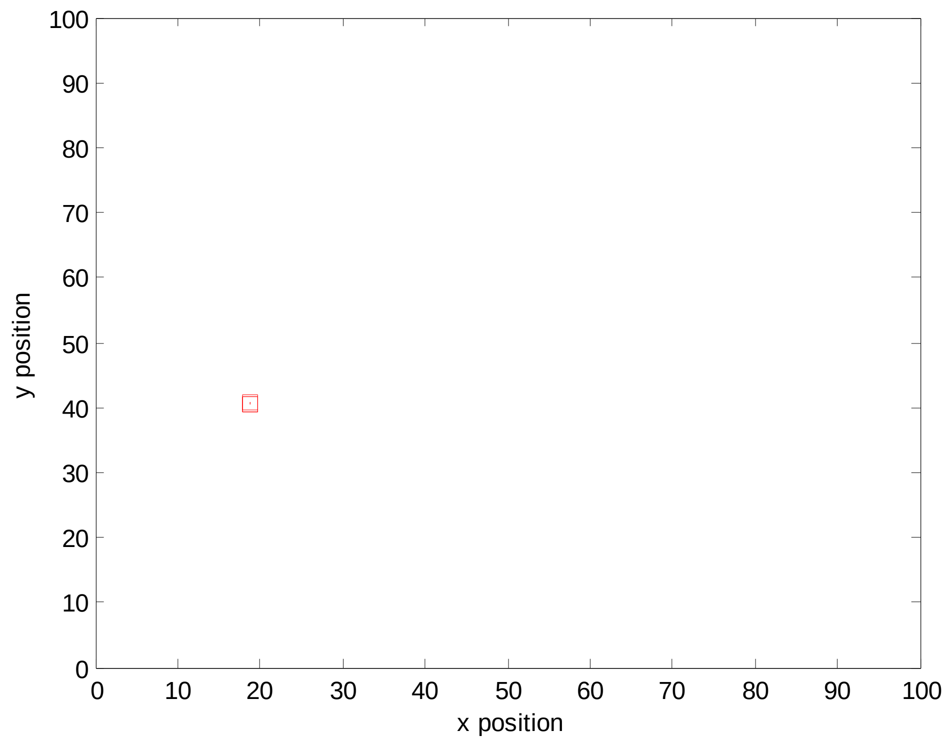

Figure3.3 optimized positions after the global best

Number of iterations=400

Constraint applied: 100=x+2y

Figure 3.4 shows the fitness minimization with the iterations. It is seen that as the iterations proceed, the above given fitness is minimized to global optima i.e. zero.

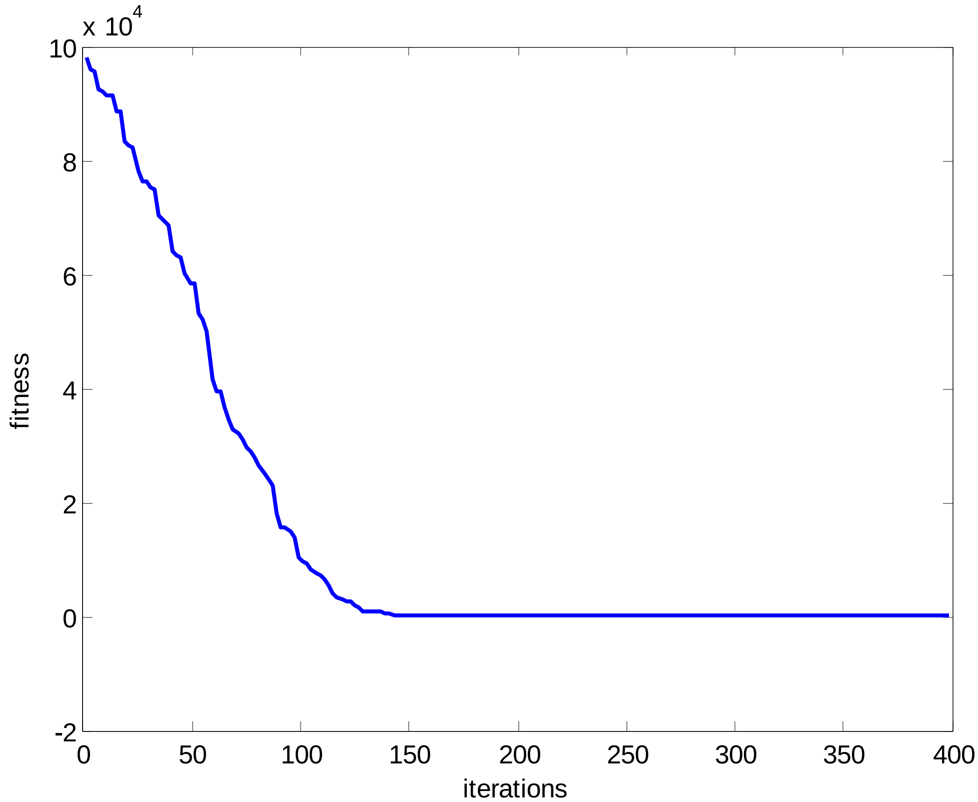

Figure 3.4 variation of fitness with iterations

3.6 LATEST MODIFICATIONS IN PSO

Variants of basic PSO can be generally classified into four categories: in the first category several researchers discussed the parameter selection issues in PSO. The introduction of inertia and constriction factors into the basic velocity expression and strategies for time dependent variation of algorithm parameters are remarkable results of studies in this category [96]. Variants of the second category involve the applications of PSO to different problem areas including the optimization of multimodal functions, integer programming, min-max problems, constraint handling, multi objective optimization problems, combinatorial optimization problems, etc. [97-103]. This is certainly the largest category among the four, in which many successful applications together with problem specific considerations in quite diverse problem domains are presented by many authors. Studies that can be put into the third category deal with the generation of different

Algorithmic strategies, analysis of convergence behavior, and strategies developed using inspirations from other meta-heuristics. In this respect, hierarchical PSO, dissipative PSO, co-evolutionary PSO, parallel PSO, and PSO with dynamic population strategies are some of the frequently studied subjects within this category. Finally, hybrid algorithms combining PSO with other meta-heuristic methods are classified into the fourth category. Hybrid methods combining PSO with genetic algorithms, differential evolution, and mass extinction are built and successfully applied for the solution of provably difficult optimization problems for which it is demonstrated that the hybrid approaches perform better than the individual component algorithms.

3.7CONCLUSIONS

Thereby it can be concluded that the particle swarm optimization technique serves as a powerful tool to optimize functions and to find a global optimum point. Hence this algorithm is used in this thesis work to get optimum selection of series and shunt capacitance using short shunt SEIG configuration.

CHAPTER 4

SELECTION OF CAPACITORS IN SHORT SHUNT SEIG USING PSO

4.1 INTRODUCTION

Here, the self regulating feature of SEIG using additional capacitors is examined. A system consisting of both series and shunt capacitors is analyzed. A Meta heuristic approach is used for the selection strategy of the series and shunt capacitors to get optimum voltage regulation. The connection scheme taken is the short shunt scheme as it has performance superiorities as compared to long shunt connections. The two unknowns X_m and f have been found out using the conventional MATLAB routine namely 'fsolve' and these values are used for the further calculations to find out the optimum set of the series and shunt capacitance values for SEIG to give minimum voltage regulation. This requires evaluating the generator characteristics under constant voltage operation. The method employed is the particle swarm optimization method which has a population of random solutions and here the series and shunt capacitances have been kept as the random values. The idea behind using this method is that the method is more effective and is not complex and more accurate results are obtained using this method as the 'fsolve' method doesn't converge to a perfect zero.

The chapter deals with the implementation of the PSO approach, unlike the conventional approach such as newton- raphson method or the nodal admittance method, lengthy derivations and accurate initial estimates are not required. And moreover, the objective function is irrespective of the unknown parameters. Hence this method can be used for evaluating the performance characteristics of SEIG as well as for the selection of capacitors for optimum voltage regulation.

4.2 PROBLEM FORMULATION

The steady-state performance of an induction generator is usually determined from its equivalent circuit. To simplify the analysis, the circuit of figure 4.1 is represented by three series impedances as shown in figure 4.2.

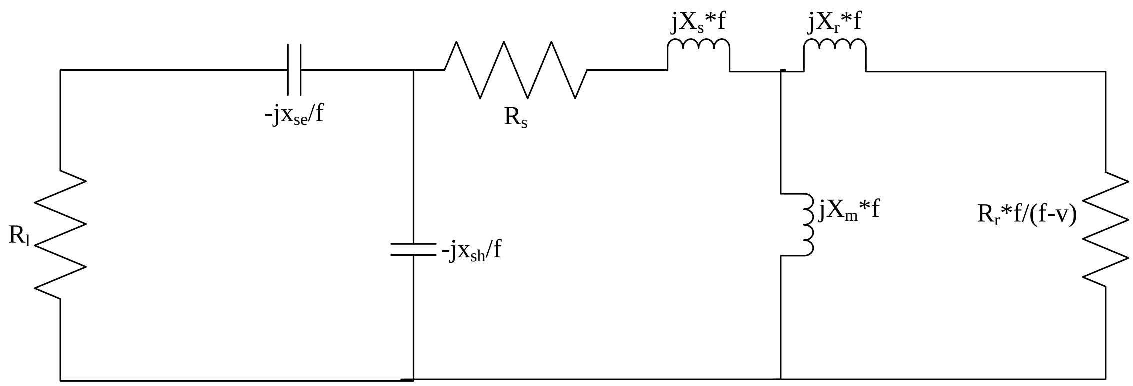

Figure 4.1 Equivalent circuit of short shunt SEIG.

This is the per-phase equivalent circuit of a three-phase short-shunt induction generator with its excitation capacitors and an R load is shown in the figure, where R_s, X_s, R_r, X_r, and X_m represent the stator resistance, stator leakage reactance, rotor resistance, rotor leakage reactance and magnetizing reactance, respectively. f and v represent the per unit (p.u.) frequency and speed, respectively.

In the previous chapter, the voltage regulation optimization and the process of capacitance selection for this short shunt configuration was made through the MATLAB routine ‘fsolve’ and now the same work is carried out using PSO.

The simplified representation of the equivalent circuit can be seen in figure 4.2 which comprises of three impedances whose formulations are given below in the following equations.

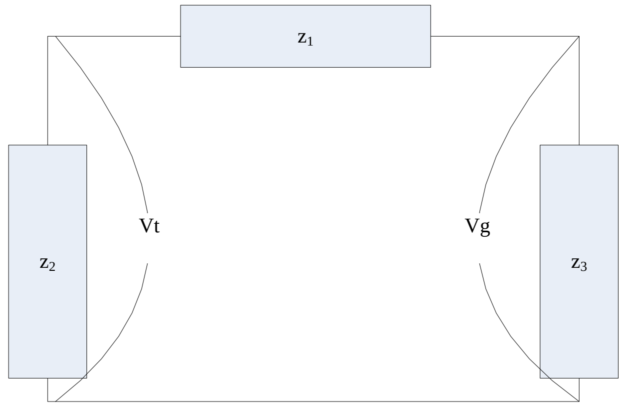

Figure 4.2 Simplified representation of the circuit.

The impedances are given as:

$Z_1 = R_s + (j*X_s*f)$……………………………………………………………………(4.1a)

$Z_2 = (j*f*X_m)*((R_r*f/(f-v)) + (j*X_r * f)))/(R_r * f/(f-v) + (j*f*(X_m + X_r))$……… (4.1b)

$Z_3 = (-j*X_{sh}/f)*(R_L-(j*X_{se}/f))/(R_L-((j*X_{sh}/f)+(j*X_{se}/f)))$………………………… (4.1c)

The loop equation in the figure 4.2 is

$I_s (Z_1 + Z_2 + Z_3) = 0$……………………………………………………………..(4.2)

Under normal running conditions, the stator current I_s cannot be zero hence the impedance in the equation 4.2 has to be zero. Now this equation can be segregated into real and imaginary parts.

Hence the two equations can be written as

G1= real $(Z_1 + Z_2 + Z_3) = 0$……………………….. (4.3)

G2= imag $(Z_1 + Z_2 + Z_3) = 0$……………………………………………………… (4.4)

These two equations(4.3) and (4.4) can be solved for the values of X_m and f using ‘fsolve’ routine which is an optimization toolbox in MATLAB and the detailed formulation has been described in chapter 2.

After the computation of X_m and f, we other parameters such as air gap voltage, terminal voltage, load voltage and load power can be calculated from the following equations:

$V_g/f = k_1 - k_2 * X_m$ ………………………………………………………………………… (4.5)

Where k_1 and k_2 are coefficients of the polynomial which are obtained from the synchronous speed test whose curve and constants are given in appendices A and B.

From equation (4.6), V_t can be evaluated.

$V_t = V_g * Z_3/(Z_1 + Z_3)$ …………………………………………………………………… (4.6)

The stator current can be obtained from the equation (4.7)

$I_s = V_g / (Z_1 + Z_l Z_{ch}/(Z_l + Z_{ch}))$ ………………………………………………………… (4.7)

As the stator current has been calculated, the load component of current can easily be obtained from equation (4.8)

$I_l = I_s * Z_{ch} / (Z_l + Z_{ch})$ ……………………………………………………………… (4.8)

Hence the load voltage can be obtained by multiplying the load current by R_l as given in equation (4.9)

$V_l = I_l * R_l$ …………………………………………………………………………… (4.9)

Z_l and Z_{ch} are given in equations (2.14) and (2.15)

After the values have been calculated for the power counter, the series and shunt capacitances are generated randomly. The PSO optimization hence is followed by generating velocities for the capacitors respectively. The objective function is summarized which is to be optimized as given in equation (4.10).

$$\text{Minimize } V_d = \sum_{i=0.1}^{\text{Pout}} \left(\frac{\text{Vl} - \text{vlsp}}{vl}\right)^2 \quad \ldots\ldots(4.10)$$

Where 'V_d' is the fitness function to be optimized and V_l is the load voltage and V_{lsp} is the specified value of the load voltage and is kept constant at 1.00 p.u. This fitness is evaluated for each particle if all the decision variables are within the search ranges. Then correspondingly the velocities and hence the particles are updated using the equations (4.11) and (4.12)

$$V_{id} = w * V_{id} + C_1 * rand(\,) * (P_{id} - X_{id}) + C_2 * rand(\,) * (P_{gd} - X_{id}) \quad \text{……(4.11)}$$

$$X_{id(t+1)} = X_{id(t)} + V_{id} \quad \text{……(4.12)}$$

Where w(i) is the inertia weight which is in the range of 0.9 to 0.4. C_1 and C_2 are acceleration coefficients of social and cognitive components respectively.

4.3 ALGORITHM AND FLOWCHART

1) Read the machine data.
2) Assume initial values of X_m and f.
3) Initialize particles for series and shunt capacitance.
4) Generate velocities for the same.
5) For the power counter, evaluate X_m and f and hence evaluate the load voltage using the equations, the value of pre specified load voltage already been given.
6) For one iteration/ generation, find the fitness function as given in equation (4.10) in the current population.
7) Calculate the local best and compare the particles' fitness evaluation with the local best. Hence the local best is set to current value and location or dimension equal to the current location.
8) Calculate the particles' global best and compare best current fitness with global best, if current value is better than global best, then reset global best to current best position.
9) Update velocities and positions.
10) Repeat steps 5-9 until a best solution is reached until a maximum number of iterations.
11) Record the global best results.
12) Stop.

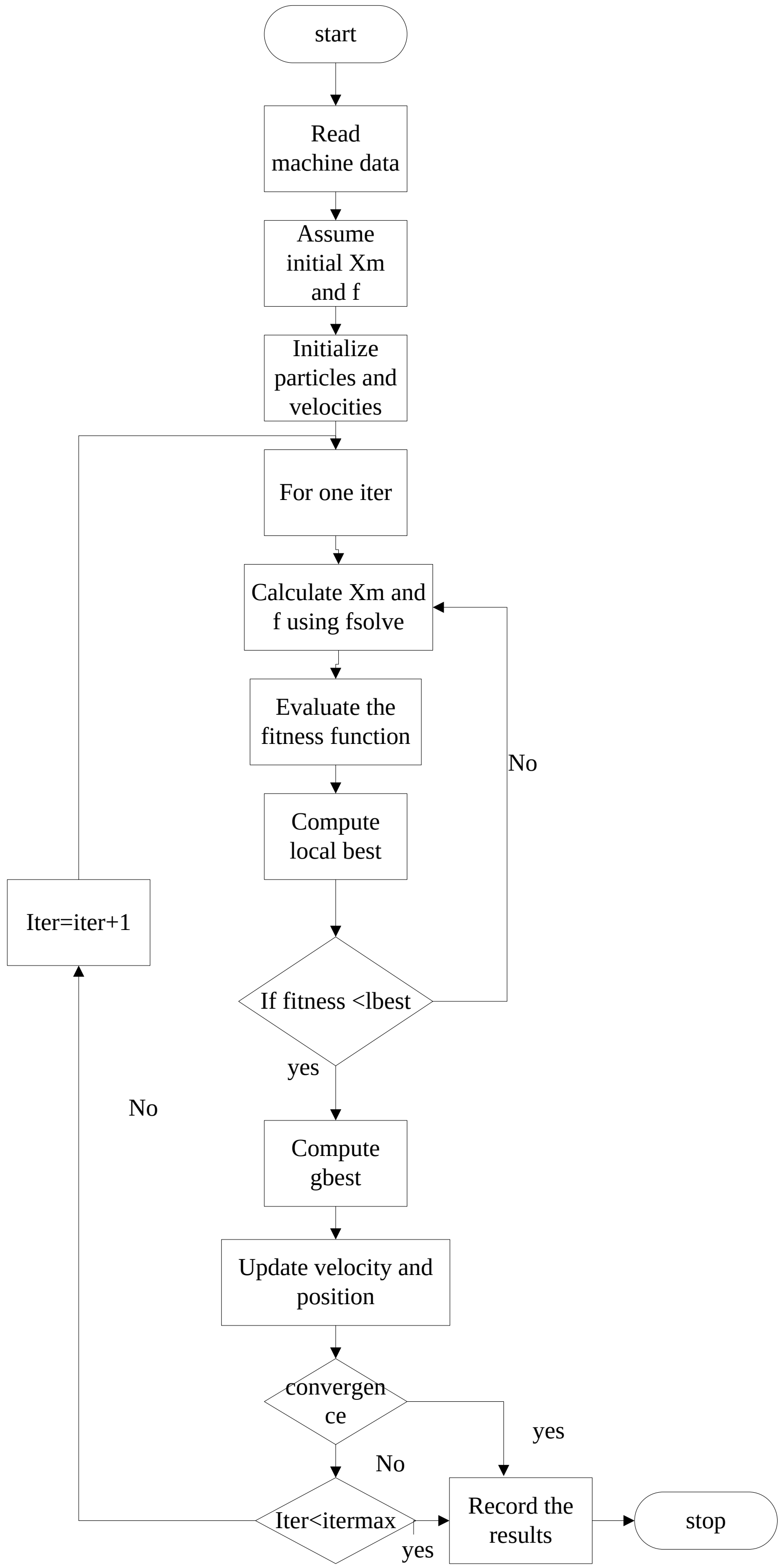

Figure 4.3 flowchart for selection of capacitors using PSO

4.4 RESULTS AND DISCUSSION

In this portion of the chapter, the various graphs at different capacitor values at various power factors will be studied. First the simulation results for the resistive load are emphasized. The results simulated are compared with the 'fsolve' results.

4.4.1 RESULTS FOR RESISTIVE LOADING

The graphs for resistive loading have been shown in the chapter for various machine parameters:

- Variation of load voltage and load power.
- Variation of terminal voltage and load power.
- Variation of stator current and load power.

method	Shunt capacitance	Series capacitance
fsolve	16.7 µF	165 µF
PSO	16.83 µF	160.5 µF

Table 4.1 selection at unity p.f. load

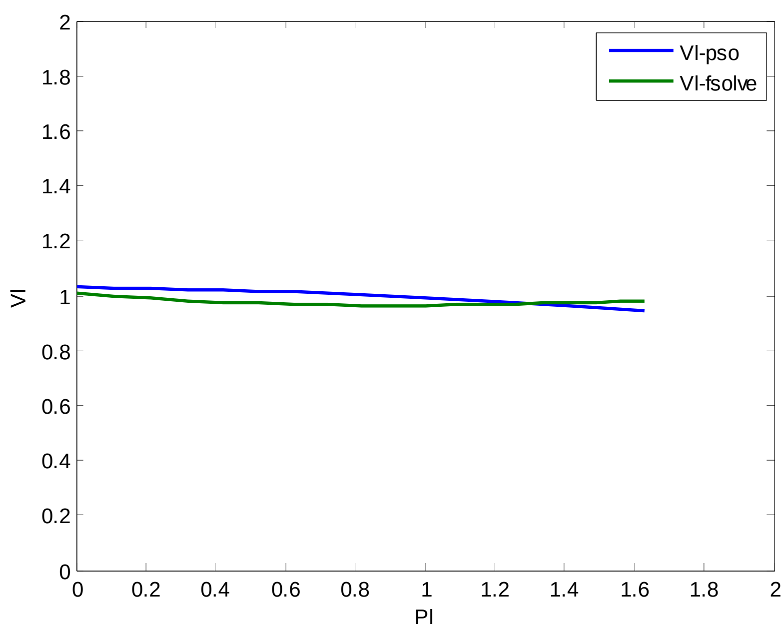

Figure 4.4 variation between load voltage and load power compared

Figure 4.4 shows the variation between load voltage and load power at unity power factor and speed 1.00 p.u. The series and shunt capacitances are taken here as 160.50μF as the series capacitance and 16.83 μF as the shunt capacitance. The voltage regulation obtained is 4% in case of PSO and 4.3% in case of the 'fsolve' results. Hence PSO serves as a better option in maintaining a better voltage regulation.

Figure 4.5 shows the variation between machine terminal voltage and load power at unity power factor and speed and the results are compared with the 'fsolve' results. It is seen that in case of the PSO results, the terminal voltage almost remains constant and there is a slight rise in the voltage with the 'fsolve' technique. However such a slight rise is not a matter of concern.

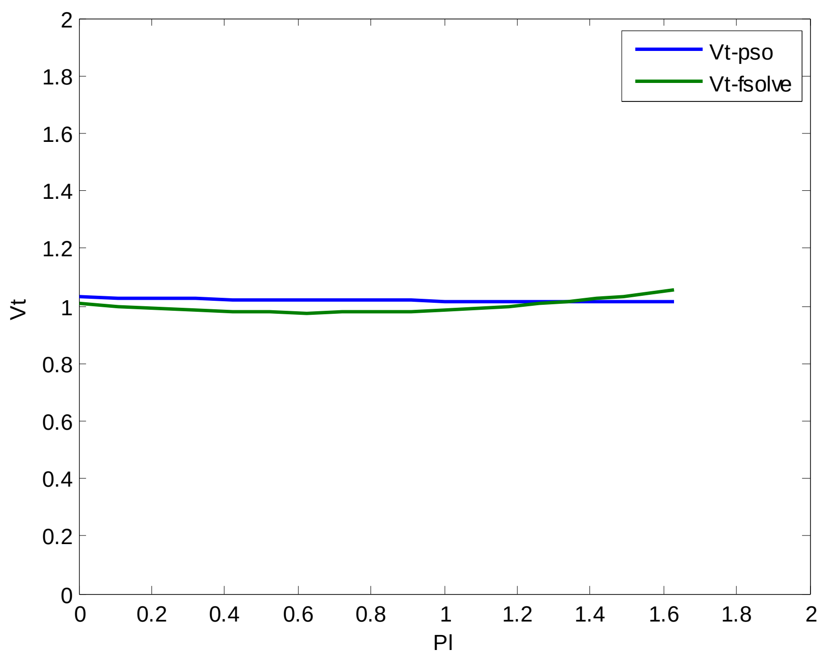

Figure 4.5 variation between terminal voltage and load power compared

Figure 4.6 shows the variation between stator current and load power. For the optimum selection of the capacitance values as given with minimum voltage regulation, performance is not much constrained.

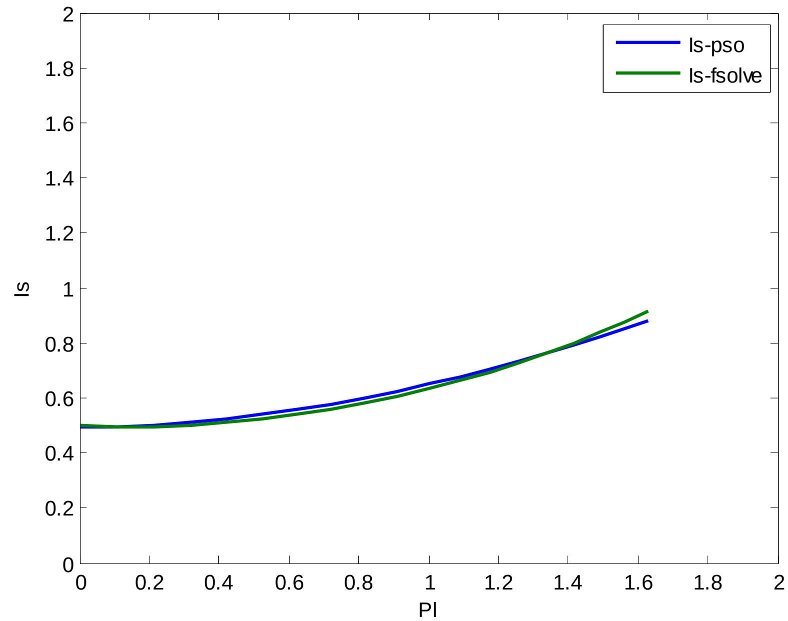

Figure 4.6 variation of stator current with load power compared

It is seen that at rated stator current, the output of the generator is more than its rated value. Hence it can be said that the power handling capability of SEIG is good and the overload capability enhances the robustness of SEIG. The comparison between the performances using 'fsolve' and PSO has also been exposed. It is seen that the results with PSO are better.

4.4.2 RESULTS FOR RESISTIVE- INDUCTIVE LOADING AT 0.98 p.f.

- Variation of load voltage and load power at 0.98 p.f.
- Variation of terminal voltage and load power at 0.98 p.f.
- Variation of stator current and load power at 0.98 p.f.

Method	**Shunt capacitance**	**Series capacitance**
Fsolve	16.1 µF	110 µF
PSO	15.9µF	98 µF

Table 4.2 selection at 0.98 p.f.

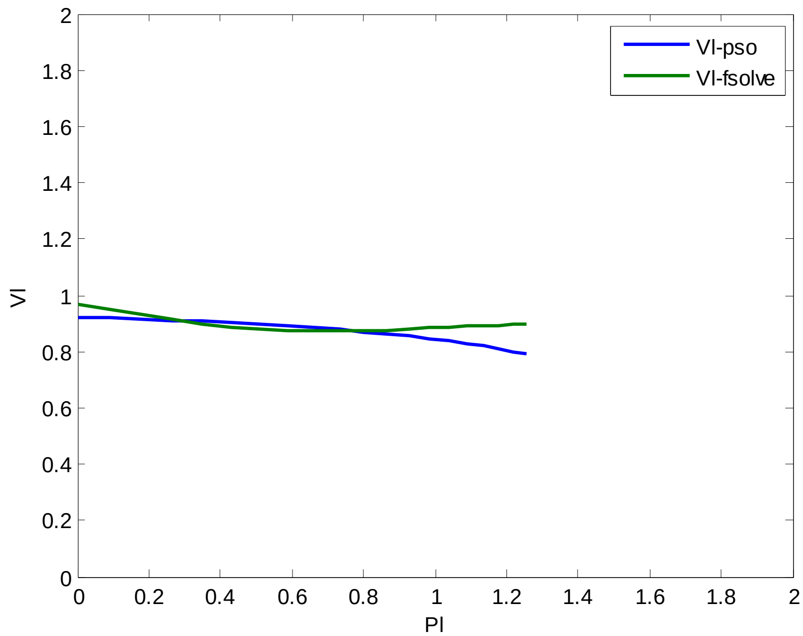

Figure 4.7 variation between load voltage and power compared at pf=0.98

The figure 4.7 shows variation of load voltage and load power at a power factor of 0.98. It is seen that as the power factor is taken into account and as the reactive power is also considered, there is depreciation in the load voltage to 0.79 p.u, the series capacitor values needed to maintain constant voltage becomes higher.

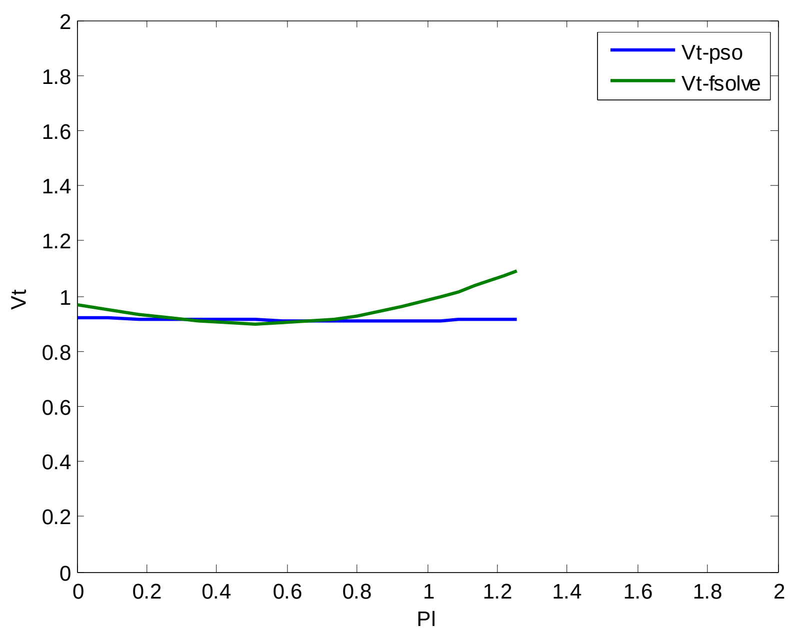

Figure 4.8 variation between terminal voltage and load power compared at pf=0.98

Figure 4.8 depicts the variation of terminal voltage with the load power at 0.98 power factor for the optimum placement of capacitors. From the comparison, it is seen that for PSO, the terminal voltage remains constant and in case of 'fsolve', there is a slight rise in terminal voltage but that rise is within the acceptable limits, the rise is only 3%. For lower values of series capacitors, there is much rise in the terminal voltage and for higher values; it results in poor voltage regulation.

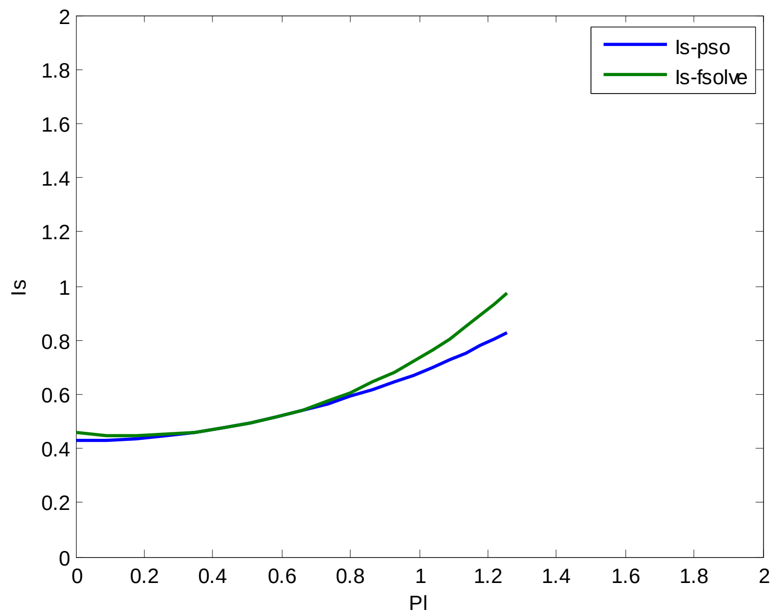

Figure 4.9 variation of stator current with load power compared at pf 0.98

Figure 4.9 shows the variation of stator current and load power for a power factor of 0.98. for PSO, the rated wining current is 0.8 p.u. whereas the 'fsolve' results give the stator current as 1.00 p.u. for the same loading, hence it can be seen that the performance with PSO is less constraines.

Figure 4.10 shows the variation of load voltage with load power for 3 different series capacitor values viz 160 µF, 187 µF and 215 µF and different shunt capacitor values viz 16.8 µF , 17.3 µF and 17.8 µF. It is seen that for the capacitor 160.5 µF, the voltage regulation comes out to be minimum. The maximum load voltage at no load is seen at the combination of 215 µF and 17.8 µF i.e. nearly 1.2 p.u. which violates the limits of voltage regulation.

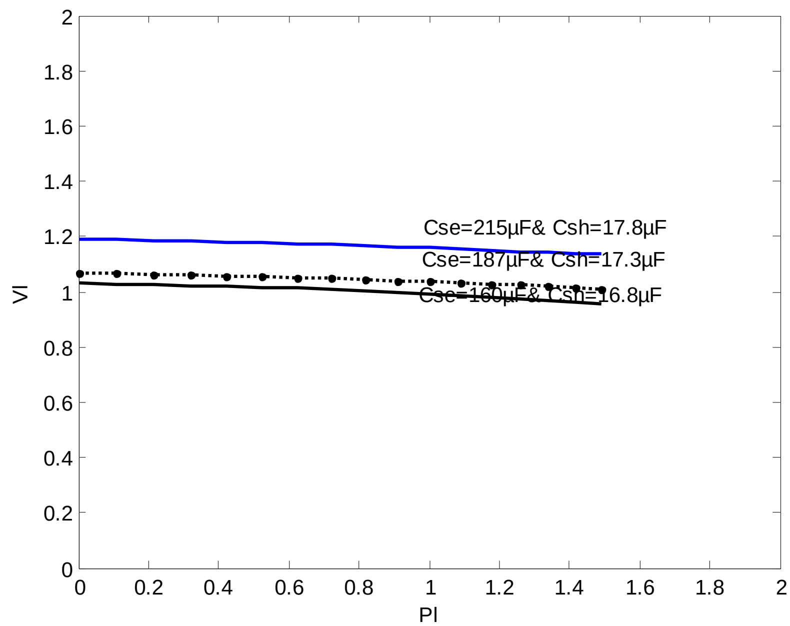

Figure 4.10 variation of load voltage and load power for different capacitors

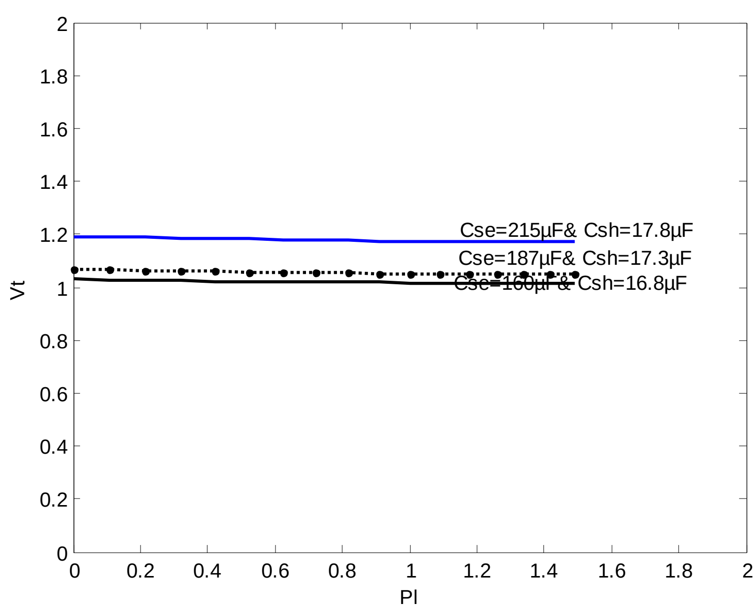

Figure 4.11 variation of terminal voltage with load power for different capacitors

Figure 4.11 shows the variation of load power with machine terminal voltage for these set of series and shunt capacitors. It is seen that the terminal voltage is almost constant throughout the loading range.

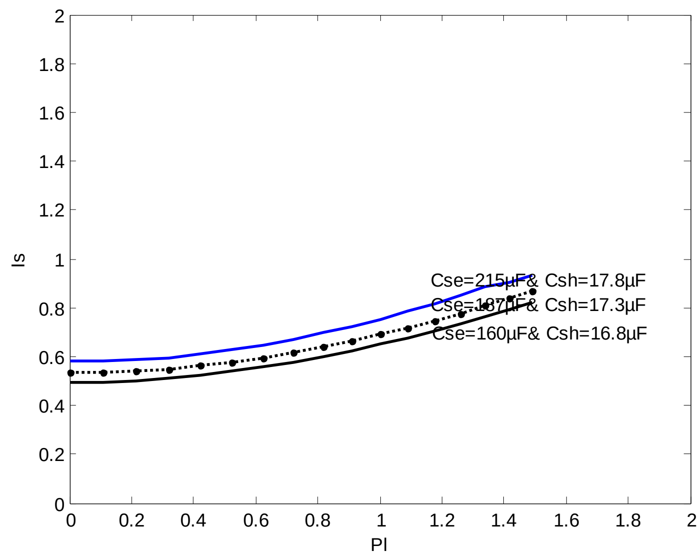

Figure 4.12 variation of stator current with load power for different capacitors

Figure 4.12 shows the variation of stator current with load power for different sets of series and shunt capacitors. For Cse=215 µF and Csh=17.8 µF, the stator current is nearly 1.00 p.u and for such current, it is delivering same amount of power as the other selected capacitors are delivering hence a higher value of series and shunt capacitor can reduce the power capability of the machine.

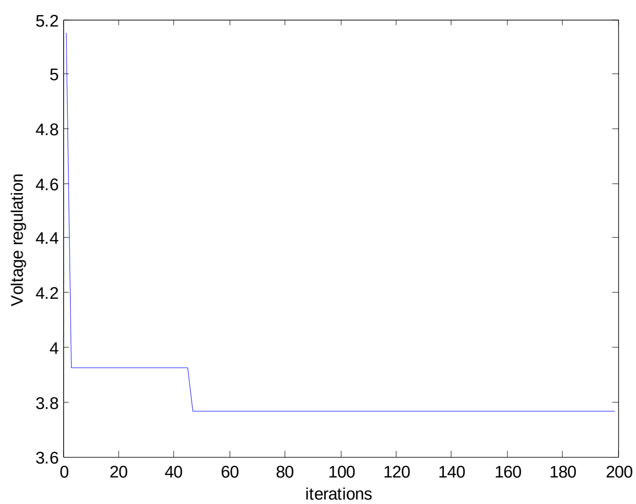

Figure 4.13 fitness minimization with iterations

figure 4.13 shows the fitness minimization graph of the voltage regulation that has been considered as the fitness function with the number of iterations which are taken to be 200. It is seen that as the number of iterations increase, the voltage regulation decreases to a global optimum point showing the effectiveness of PSO.

4.5 CONCLUSIONS

The performance of short shunt SEIG has been studied in detail and the results with 'fsolve' have been compared with the PSO results and the results have been simulated for different values of power factors i.e. for resistive and reactive loading. It is seen that the combination of shunt and series capacitor affects the generator performance, the optimum placement of the capacitors has hence been done to maintain almost constant load voltage using the two simple techniques. It is seen that a voltage regulation within reasonable limits is possible by selecting suitable values of series and shunt capacitors by the proposed methodology.

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

5.1 CONCLUSIONS

The increasing rate of depletion of conventional energy sources and the ability of induction generators to convert mechanical power over a wide range of rotor speeds has given rise to an interest in the study of SEIGs. The SEIG suffers from poor voltage regulation which can be improved by using series capacitors. Here the short shunt connection of SEIG has been studied in detail and a novel method has been developed for the selection of capacitor elements for minimum voltage regulation and better self excitation without the possibility of voltage collapse.

Two methods have been presented in this thesis work for the selection strategy of series and shunt capacitors namely the conventional MATLAB routine ‘fsolve’ and the artificial intelligence method ‘particle swarm optimization’ which is a meta-heuristic search technique based on Artificial-life which mimics the behavior of bird flocking or the fish schooling. The simulation results of the two methods have been compared and it is seen that reasonable voltage regulation is achieved as the voltage regulation has been one of the main issues with the performance of SEIGs. First the value of shunt capacitor is kept fixed such that the no load voltage does not exceed the voltage deviation limits. The size of series capacitors is then selected to obtain minimum voltage regulation at full load condition. The analysis is then extended to different power factors and for the different values of shunt capacitors to see the effect on the terminal voltage, stator current and the load voltage.

5.2 SCOPE OF FUTURE WORK

The study of short shunt SEIG for selection of series and shunt capacitors have been presented here. This study can be extended to long shunt SEIG also and a comparison of the two configurations can be established. There are many applications of self regulating SEIG to which this study can be extended such as this work can be extended to variable speed machine where the speed parameter can also be embedded in the objective for further analyses. The studies can be established by the use of PSO which makes the problem formulation easier and the lengthy calculations are exempted from.

The study of series damping resistors with the series capacitors feeding dynamic load such as induction motor for the voltage regulation optimization can also be carried out by this method. The voltage regulation can also be improved by using power electronic circuitry and the performance of SEIG can be studied using STATCOM (static compensator), a voltage source inverter with PWM control and SVC (static VAR compensator).

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APPENDIX A

MACHINE DATA

The machine data [21] used in the thesis work is as follows:

- 3-phase, Δ-connected, squirrel cage induction machine specifications

  Power – 3.7kW

  Voltage/ phase – 415 Volts

  Current/ phase – 4.39 Amp

  Frequency – 50 Hz

  Speed – 1430 rev/min

- Equivalent circuit parameters:

  R_s = 0.053 p.u.

  R_r = 0.061 p.u.

  X_s =X_r = 0.087 p.u.

- Magnetizing characteristic coefficients using synchronous speed test

  K_1 = 1.6275

  K_2 = 0.3418

APPENDIX B

The induction machine magnetizing characteristic as obtained from the synchronous speed tests which gives the curve between air gap voltage and magnetizing reactance is as follows

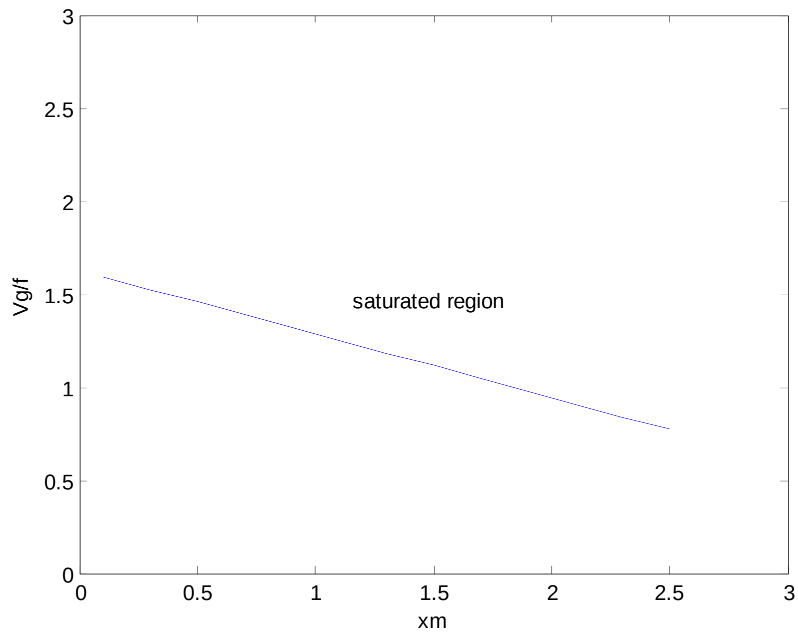

Figure B: variation of V_g/f with X_m

The equation is given as follows:

$$\mathbf{V_g = K_1 - K_2 * X_m}$$