A FUZZY BASED ASSESSMENT OF CAPACITOR EXCITED INDUCTION GENERATOR PERFORMANCE

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
ELECTRICAL ENGINEERING
(With Specialization in Power System Engineering)

By

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CANDIDATE'S DECLARATION

I hereby declare that the work, which is being presented in the dissertation, entitled **"A FUZZY BASED ASSESSMENT OF CAPACITOR EXCITED INDUCTION GENERATOR PERFORMANCE"** in partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** in Electrical Engineering with specialization in **Power System Engineering**, submitted in the department of Electrical Engineering, Indian Institute of Technology, Roorkee, is an authentic record of my own work carried under the guidance of Dr. E. Fernandez, Assistant Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee.

I have not submitted the matter embodied in this report for award of any other degree.

Dated: 29/6/06
Place: Roorkee

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(DEEPAK SINGH SYUNARI)

CERTIFICATE

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

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Deepak

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Abstract

The increasing importance of fuel saving, and the fast depletion of conventional energy resources is responsible to search for every other source of alternative energy. A higher emphasis is given to non-conventional and renewable energy resources such as wind energy, bio-gas, solar, micro-hydro, etc. The induction generators are being considered as an alternative choice to the well-developed synchronous generators for non-conventional sources because of their lower unit cost, rugged structure, and simplicity in maintenance. The induction generator's ability of self excitation by shunt capacitance is increased its use in remote and hilly areas.

This dissertation presents a fuzzy technique for the modeling of series compensated capacitor excited induction generator (short shunt). The rules of fuzzy system are composed by the data obtained from analytical method (iterative method). The steady state performances under different operating conditions are studied and explained the methodology for choosing appropriate values of series and shunt capacitors for voltage regulation.

With short shunt connection of capacitor excited generator, the load voltage dips at low load condition. To improve load voltage at low power outputs, method of ballast load which switching is done by fuzzy logic controller, is explained. The proposed system is simulated in MATLAB 6.5 and results are analyzed.

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Chapter -1

Introduction, Literature Survey and Outline of Chapters

1.1 Introduction

The self-excited induction generator (SEIG) is now a matured technology for isolated power generation in hilly and remote areas due to its number of advantages such as robustness, low cost, small size etc. They are being used in micro hydro and pico hydro electrical power generation. The synchronous generator has been very popular for stand alone and isolated generating systems as an energy converter to convert mechanical energy of the prime mover to electrical energy. But in comparison, the squirrel cage induction machine has enormous advantages like absence of DC excitation, low maintenance, low cost, high power/weight ratio, no synchronization requirement, brushless configuration etc. This can be a preferred option if it can effectively operate as a stand-alone generator. The capacitor self-excitation of the induction machine facilitates such an option. If an appropriate capacitor bank is connected across an externally driven three-phase squirrel cage induction machine, an EMF is induced in the machine winding due to excitation provided by capacitor bank if a residual magnetism exists in the rotor. This phenomenon is termed as "capacitor self-excitation" which can be exploited to operate the induction machine as a generator and is known as self-excitation induction generator (SEIG). Voltage and current thus induced would continue to rise, but due to magnetic saturation in the machine, equilibrium is reached and steady-state alternating voltage of frequency dependent on speed would result. [1, 2, 7-9]

The biggest hurdle in commercialization of self-excited induction generator is its poor voltage and frequency regulation, the latter, though is less significant if the prime mover speed is held constant. The SEIG demands continuous and varying reactive power (capacitive) with changing loads to maintain constant voltage but with drooping frequency. For the required power quality (constant voltage and frequency) suitable control scheme have to be developed for the SEIG to make it a viable commercial system and to meet customer requirements.

The performance of SEIG depends very much on the speed, consumer load and excitation systems. In constant speed prime mover, if consumer load is changed then generated voltage and frequency are also changed with constant excitation system [5]. Practically it is not possible to keep constant load on the SEIG without suitable controller. In nineteen eighties, fast switching devices have not been easily and economically available so that appropriate control system could not be designed to achieve good quality of power. Moreover, researchers have identified the parameters of the induction machine, which affect for the performance of the induction machine as a generator. They have made efforts and proposed different algorithms to redesign the induction machine so that as a generator it gives better performance. [10, 15, 20]

In micro or pico hydro systems the power in turbine is dependent on head and discharge. In large hydropower generation plants, turbine-governor is used to regulate the input power to the turbine by controlling the water flow through the turbine nozzle. This governor is a mechanical system, which is costly, complex in construction, requires skilled operator and demands frequent maintenance. The cost and size of the governor control of the turbine does not reduce much if a micro hydro plant is to be installed. Thus turbine–governor cost becomes a considerable part of the total system cost in small micro hydro units. Therefore, this mechanical governor system needs to be eliminated in small units to provide cost effective solution. Uncontrolled turbine operates at near constant power due to constant head and discharge. Hence, a constant voltage and frequency generation may be achieved by employing the uncontrolled hydro turbine driven SEIG if output generated power is maintained constant at varying consumer load. At such constant power operation, often called the ‘single point operation’, frequency, voltage, and capacitance are constant. [25]

The SEIG requires increase of reactive power with increase in load to maintain constant voltage. This reactive power can be fulfilled by using additional series capacitor either connected in short shunt or in long shunt. The series capacitance gives addition VAR to load as load increases. In low load condition VAR supplied by series capacitor is low so the voltage regulation is poor [16-18]. For controlling voltage, at low load condition, active components like saturable core reactor, thyristor controlled reactor (TCR), synchronous condenser and static compensator (STATCOM) can be used. But

Synchronous condenser, thyristor controller reactor and saturated core reactor are bulky, costly, and inject harmonics in the SEIG. Other method for achieving constant voltage and frequency is load controllers, in which total output power of SEIG is fixed with the help of ballast load. The ballast load can be varied either by controlling the firing angle of thyristor or by switching binary weighted resistors. [13, 19, 20]

For analyzing and controlling of any system, the most commonly used approach is to use a model of the system. However, because the different complex characteristics of the system, it is difficult to use the traditional quantitative techniques to build a quantitative model of the system. For this reason model builders have turned to more flexible methods based on various form of machine learning. These models are basically linguistic models which are based on the fuzzy IF-THEN rules and fuzzy inference. The fuzzy linguistic models can qualitatively describe two kinds of complex system behaviour, namely, the nonlinear relationship between the input and the output of the system, and the uncertainty in the system. Fuzzy systems can have two forms. One is the conventional linguistic model. Another is the functional representation of fuzzy IF-THEN rules. These functional representations are called fuzzy-neural systems which in fact are nonlinear deterministic functions. There are generally two kinds of fuzzy-neural systems: Mamdani type fuzzy model and Takagi-Sugeno type fuzzy model. [3, 4, 24]

For controlling any system a controller is needed, which compare the output from the process with that from a reference model. The error is then used for adjusting the parameters of the controller through a suitable algorithm, either based on physical or chemical laws or a parameter estimation method. These techniques are usually complex and required large amounts of computation time. The common difficulty with this approach lies in the attempt to formulate the input-output relationship by means of mathematical models, which may be difficult in many cases. Even when such models developed, they may be too complex to compute in real time.

Facing these problems, investigators realized that incorporating human intelligence into automatic control system would be a more efficient solution and this led to the development of fuzzy control algorithms. The fuzzy algorithm is based on intuition and experience, and can be regarded as a set of decision rules or "rules of thumb". Such nonmathematical control algorithm can be implemented easily in a computer. They are straightforward and should not involve any computational problems. [3, 4, 22-24]

1.2 Literature Survey

As already mentioned the self-excited induction generator has number of advantages over synchronous generator. Considerable work has been reported on different aspects of SEIG. The fact more than 200 research papers are published during last two decades on analysis, design, control, and application of SEIG, which reflects their importance and relevance to engineering developments. The induction machine is the most fascinated electromagnetic energy converter with certain unique features not found in other machines, which is due to the invention of Fortesque, Tesla and Pixii over hundred years ago. It is cheapest machine for a power rating due to simplicity, ruggedness, compactness, and manufacturing automation. While it is widely and almost universally used for motoring operation, it is indeed the main workhorse for industry, its use as a generator has received little attention [1, 2] . A major breakthrough in the application of an induction generator has been due to development of wind energy conversion system over last decades [5, 6]. But they are generally grid connected systems. Due to continuously and randomly varying wind speeds, the power input to the generator varies and the generator has to operate over a range of rotational speed decided by the power balance. Grid connected induction generator fitted this requirement, as it operates over a range of speed in the stable generating region with the negative slip corresponding to input power.

But an induction generator can also be used on stand-alone mode due to capacitor self-excitation. In SEIG selection of shunt capacitance for self excitation is a very important task. It is well known phenomenon that reactive power requirement of SEIG increases with load to maintain constant terminal voltage. Several authors have proposed the technique to compute minimum capacitance for self excitation [7, 8]. Elder et al [9] explained the process of self excitation in induction generators.

While the phenomenon of capacitor self-excitation has been known for long time, proper modeling and analysis to predict the performance of SEIG has been evaded solution. This issue has been addressed in early nineteen eighties with significant breakthrough which has led to series of research paper describing the methodology of modeling and predicting steady-state performance. The analysis of SEIG is more complicated compared to the grid-connected induction generator due to magnetic non-linearity. Murthy et al have reported the analytical technique for finding out the performance of SEIG under steady state conditions. The analytical technique is based on two unknown polynomials: magnetizing reactance and per unit frequency. The mathematical equation containing these unknown variables are very complex. The author solved this equation by iterative method like Newton Raphson [10]. Chan has proposed two technique of the steady-state analysis of the SEIG. The first technique employs a parameter elimination procedure to yield a seventh degree polynomial in the per unit frequency. The numerical solution of the polynomial then enables the prediction of performance of the SEIG. The second technique is based on the nodal admittance method where the symbolic programming method is employed for the derivation and solution of the higher-degree polynomial. Later on, the author proposed an iterative technique to include core loss effect and series capacitance compensation in the performance analysis of SEIG. The author also proposed a method for solving this equation by Hooke and Jeeves optimization method [11-13]. Alolah and alkanhal have reported the steady state analysis of an induction generator using multidimensional optimization technique. A constrained optimizer is used to minimize cost function of the total impedance or admittance of the circuit of the generator to obtain the frequency and other performance indices of the machine. Classical gradient optimizers are used for this purpose [14].

The inherent poor voltage regulation of the SEIG is a major drawback in isolated applications. Researchers have made efforts to improve the voltage regulation by redesigning the induction machine. Several authors have designed the induction machine using optimization technique and objective function are considered such as material cost, efficiency etc. Singh et al [15] have attempted optimum design of self-excited induction generator and have observed that an induction motor does not give good performance as an induction generator and for that a special design is required. They have concluded that low cage rotor resistance is desirable for an induction generator whereas for motor it affects the starting performance. They have further observed that an induction motor is generally designed for high leakage reactance to limit starting current whereas in a generator it may result in poor overload capacity, regulation and efficiency.

For controlling the voltage of SEIG, researchers use either passive elements or active elements. In passive elements voltage is improved by using short and long shunt capacitors, binary weighted switched capacitors, saturable core reactor, constant voltage transformers etc. In active components like thyristor controlled reactor (TCR), synchronous condenser and static compensator (STATCOM) are used. But these active element based control system generate harmonics in SEIG and produce heating, due to present of power electronic switches [16-21, 25-28].

For controlling purpose generally PID controllers or PI controllers are used but conventional PID controller requires quite a bit of tuning for obtaining a fast and dynamically acceptable response. Again, it is generally implemented using operational amplifier circuit whose parameters are adjusted for an operating point based on a piece wise linear model of the nonlinear system. These circuits have the tendency to drift with age and temperature causing degradation of the system performance. These types of controllers requires detailed mathematical model of the system. Facing these problems Mamdani used application of fuzzy set theory to control a small laboratory steam engine. The purpose was to regulate engine speed and boiler pressure by using heat applied to the boiler and the throttle setting on the engine. A fuzzy logic controller does not require a detailed mathematical model of the system and its operation is governed by a set of rules. Thus it is easy to implement and same performance is ensured over the years [22]. Hilloowala presents a rule base fuzzy logic controller to control the output power of a pulse width modulated (PWM) inverter used in a stand alone wind energy conversion scheme. The variable amplitude, variable frequency voltage at the induction generator terminals is first rectified in a diode bridge rectifier and the dc power is transferred over the dc link to a PWM inverter feeding a local load. By controlling the pulse width of the PWM inverter, it is possible to control its output voltage [23].

In this theses, fuzzy logic technique is used for modeling the series compensated capacitor excited induction generator. The effect of various parameters on the performance of capacitor excited induction generator is studied, which is necessary for design of generators for improving voltage regulation. In short shunt connection the load voltage is low at low power output, so a fuzzy based binary load controller is developed for improving this low voltage.

1.3 Outline of Chapters

Chapter 1: In this chapter background of capacitor excited induction generator (SEIG) are discussed in briefly. The chapter also deals the literature review, presents the studies related to capacitor excited induction generator, and different control strategies to maintain constant voltage.

Chapter 2: This chapter presents the fuzzy logic technique for modeling of series compensated capacitor excited induction generator. The input-output of fuzzy model and their linguistic labels are discussed in detail. Error in results obtained by fuzzy model and analytical model are also discussed.

Chapter 3: The composition of rules for fuzzy system is described in detail in this chapter. The effectiveness of a particular rule is also discussed.

Chapter 4: This chapter deals the steady state performance of capacitor excited induction generator, also compare short shunt SEIG to long shunt SEIG.

Chapter 5: The load voltage of capacitor excited induction generator varies with load. A voltage regulating scheme controlled by fuzzy controller is described in this chapter. Simulation result obtained from MATLAB 6.5 is also analyzed.

Chapter 6: This chapter concludes the whole dissertation work.

Chapter- 2

Fuzzy Model of Series Compensated SEIG

2.1 General

An induction machine will operate as a generator if a supply of reactive power is available to provide the machine's excitation. Self excitation can be achieved by the connection of capacitors across the machine terminals, allowing the induction machine to be used as a stand alone induction generator. Steady state analysis of induction generator is useful for both machine design and operation point of view. But for analyzing any system, system model is necessary. Once a model of a system is obtained, it is easy to predict the behaviour of the system, its performance, efficiency etc. But because of different complex characteristics of the system, it is difficult to use the traditional quantitative techniques to build a quantitative model of the system. The past few years have witnessed a rapid growth in the number and variety of applications of fuzzy logic. Fuzzy logic is a convenient way to map an input space to an output space. Some other techniques like linear systems, expert systems, neural networks, differential equations, interpolated multidimensional lookup tables etc, can also be used for input-output mapping. But in all of these, fuzzy is the best due to following reasons:

1. The mathematical concepts behind fuzzy reasoning are very simple. So it is conceptually easy to understand.
2. Fuzzy logic is flexible.
3. Fuzzy logic can model nonlinear functions of arbitrary complexity. It is easy to create a fuzzy system to match any set of input-output data.
4. Fuzzy logic can be built by the experience of experts who already understand about the system.
5. Fuzzy logic is based on natural language. The basis for fuzzy logic is the basis for human communication. [3, 4]

In this chapter the fuzzy model of series compensated SEIG is discussed in detail.

2.2 Fuzzy model of series compensated SEIG

Fuzzy logic of model building is generally a method of input-output mapping. For building a fuzzy model of a system first step is to identify the various variables which affect the output of the system. These variables are treated like fuzzy inputs. In SEIG the performances depends on many factors, like rotor resistance and reactance, magnetizing reactance, value of series and shunt capacitance, speed of prime-mover, shape of magnetizing curve, consumer load and its power factor etc. So in fuzzy model these various parameters which effect generator's performance is treated like fuzzy inputs, and generator performance, like load voltage, winding current, and load current etc., are fuzzy outputs. Figure2.1 shows the block diagram of fuzzy model of series compensated SEIG. Thus the output of SEIG is expressed as follows,

$$Y = f\,(R_2, X, X_m, K_1, K_2, K_3, p.f, N, P_{out}, C_{sh}, C_{se}). \qquad 2.1$$

Where,

Y = Output of SEIG, like load voltage, winding current, load current.

R_2 = Rotor resistance.

X = Rotor reactance.

X_m = magnetizing reactance.

p.f. = power factor of load.

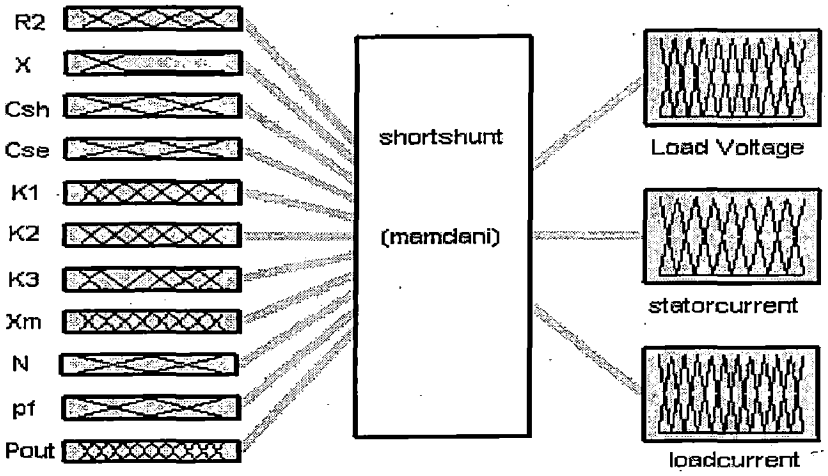
N = Speed of prime mover.

Csh = Shunt capacitance.

Cse= Series capacitance.

K_1, K_2, K_3 = Coefficient of equation 2.2, magnetizing characteristic of induction generator.

$$V_g/F = K_1 X_m^2 + K_2 X_m + K_3 \qquad 2.2$$



System shortshunt: 11 inputs, 3 outputs

Figure2.1: Fuzzy model of induction generator

A fuzzy logic system consists three main blocks:

1. Fuzzifier
2. Inference mechanism.
3. Defuzzification.

Automatic change in the design parameter of any of these elements creates an adaptive fuzzy system. Fuzzy system with fixed parameters are non adaptive.

2.2.1 Fuzzifier [3, 4, 24]

The fuzzy logic system requires that each input and output variables, which define the system, should be expressed in fuzzy set notations using linguistic labels. The linguistic labels for input and output variables for SEIG are shown in Figure2.3 and Figure2.4 respectively. These linguistic labels, which are characterized by degree of membership, are used to decompose each variable into fuzzy regions. The degree of membership shows the extent to which a variable belong to a particular label. This process of converting input and output variables into linguistic labels is called fuzzification. The shape of membership function is quite arbitrary and depends on the user's preference. For simplicity generally triangular or trapezoidal shapes are used. Here, triangular membership function is used for modeling. Overlap between adjacent labels should be taken such that the sum of the vertical points of the overlap will be always either one or less than one.

2.2.2 Inference mechanism [3, 4, 24]

The relation between fuzzy input and output variables are defined by a set of rules. These rules are represented as a set of IF-THEN rules, which are evaluated by an inference mechanism. The selected rules are evaluated by Mamdani algorithm during evaluation procedures. A typical fuzzy rule is like this

If (A is x and B is y), then (C is z)

Where: A, B and C are, respectively, the input and output system variables, 'x, y' are the antecedent linguistic terms (or fuzzy sets) in rule, 'z' is the conclusion of this particular rule.

When a set of input variables are given, each rule, which has nonzero value of membership grade for that set of inputs, is fired and contribute in system output. When all rules are fired, the resultant of the output of all rules gives system output for those particular values of input variables. The method of obtaining rule-base for series compensated SEIG is discussed in detail in next chapter.

2.2.3 Defuzzification [3, 4, 24]

The output obtained by fuzzy system is also fuzzy set in nature; this fuzzy output is converted into crisp value (number) by defuzzification techniques. Some commonly used defuzzification techniques are given below:

2.2.3.1 The Max Criterion Method

The max criterion method produces the point at which the possibility distribution of the fuzzy output reaches a maximum value.

2.2.3.2 The Mean of Maximum Method

The mean of maximum generates an output which represents the mean value of all local inferred fuzzy outputs whose membership functions reach the maximum. In the case of a discrete universe, the inferred fuzzy output may be expressed as

$$Z_0 = \sum_{j=1}^{l} \frac{w_j}{l}$$

Where w_j is the support value at which the membership function reaches the maximum value $m_z(w_j)$ and l is the number of such support values.

2.2.3.3 The Center of Area Method

The center of area generates the center of gravity of the possibility distribution of the inferred fuzzy output. In the case of a discrete universe, this method yields

$$Z_0 = \frac{\sum_{j=1}^{n} m_z(w_j) w_j}{\sum_{j=1}^{n} m_z(w_j)}$$

Where n is the number of quantization levels of the output.

2.2.3.4 Bisector of area

This method picks the abscissa of the vertical line the divides the area under the curve in two equal halves.

In these defuzzification techniques, center of area method of defuzzification is most accurate, so here, it is used for defuzzification process. The range of various parameters of fuzzy model is selected on the basis of different data of various induction machines. The block diagram of fuzzy system is like this.

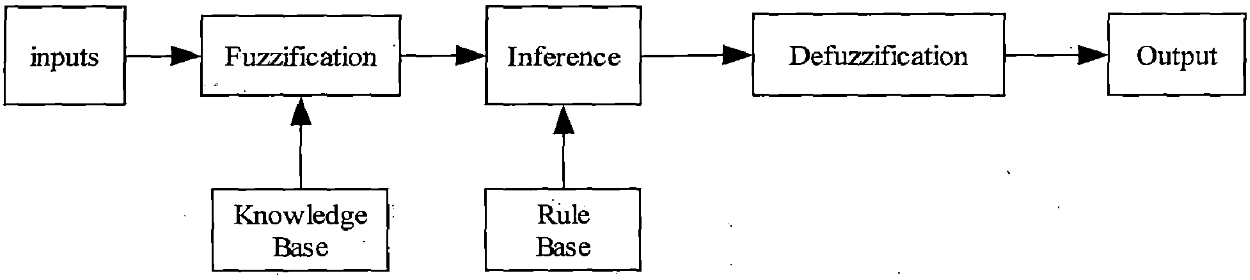
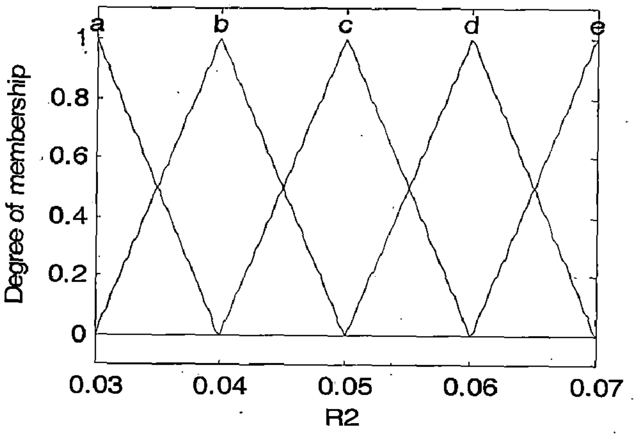
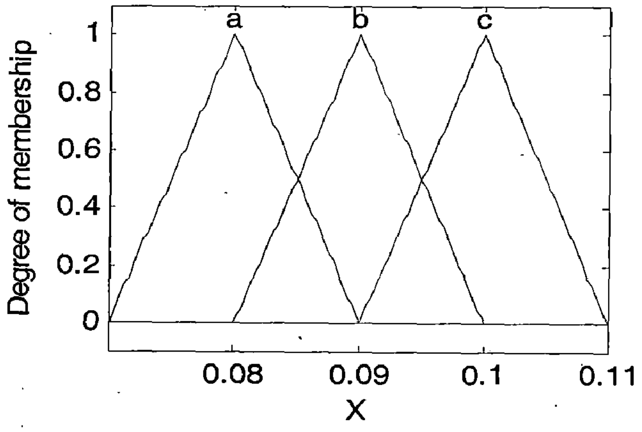


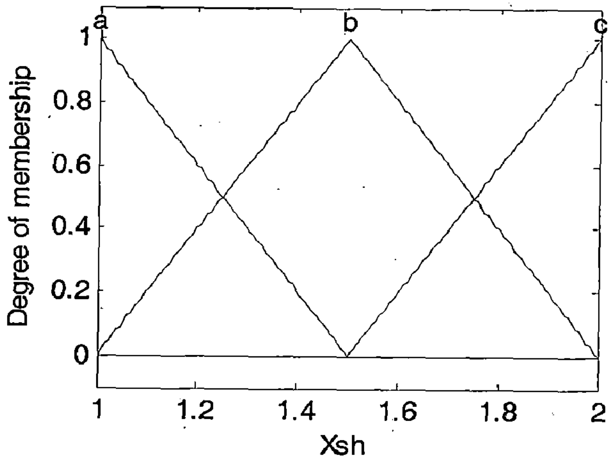
Figure 2.2: Block diagram of typical fuzzy logic system


a
b
c
d
e
Degree of membership
1
0.8
0.6
0.4
0.2
0
0.03
0.04
0.05
0.06
0.07
R2

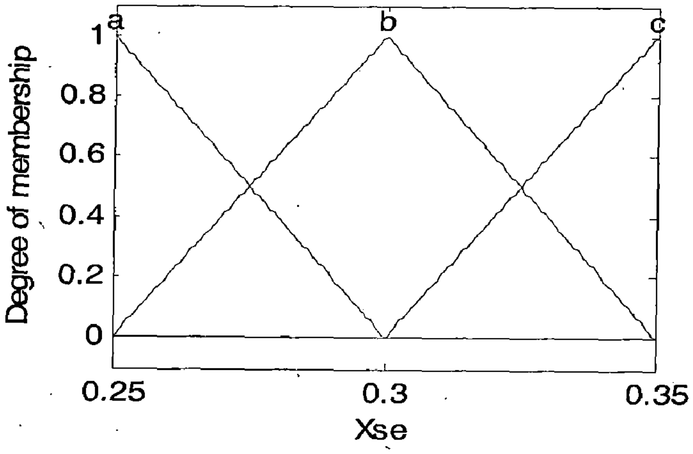
(a)


a
b
c
Degree of membership
1
0.8
0.6
0.4
0.2
0
0.08
0.09
0.1
0.11
X

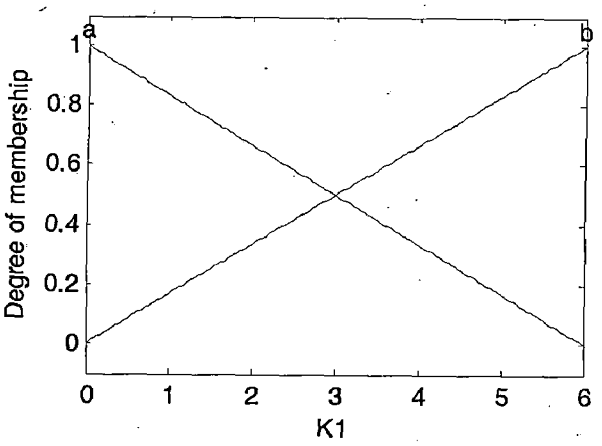
(b)


a
b
c
Degree of membership
1
0.8
0.6
0.4
0.2
0
1
1.2
1.4
1.6
1.8
2
Xsh

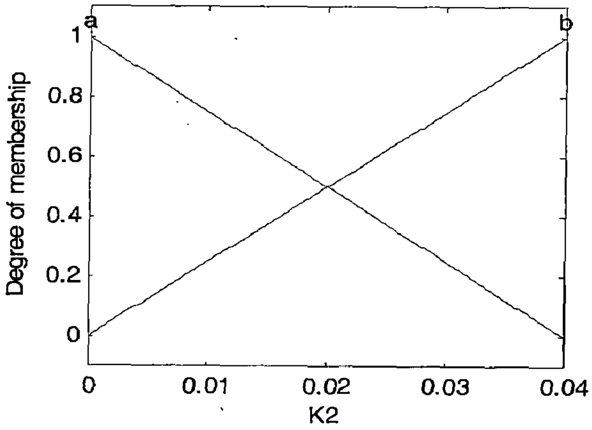
(c)


a
b
c
Degree of membership
1
0.8
0.6
0.4
0.2
0
0.25
0.3
0.35
Xse

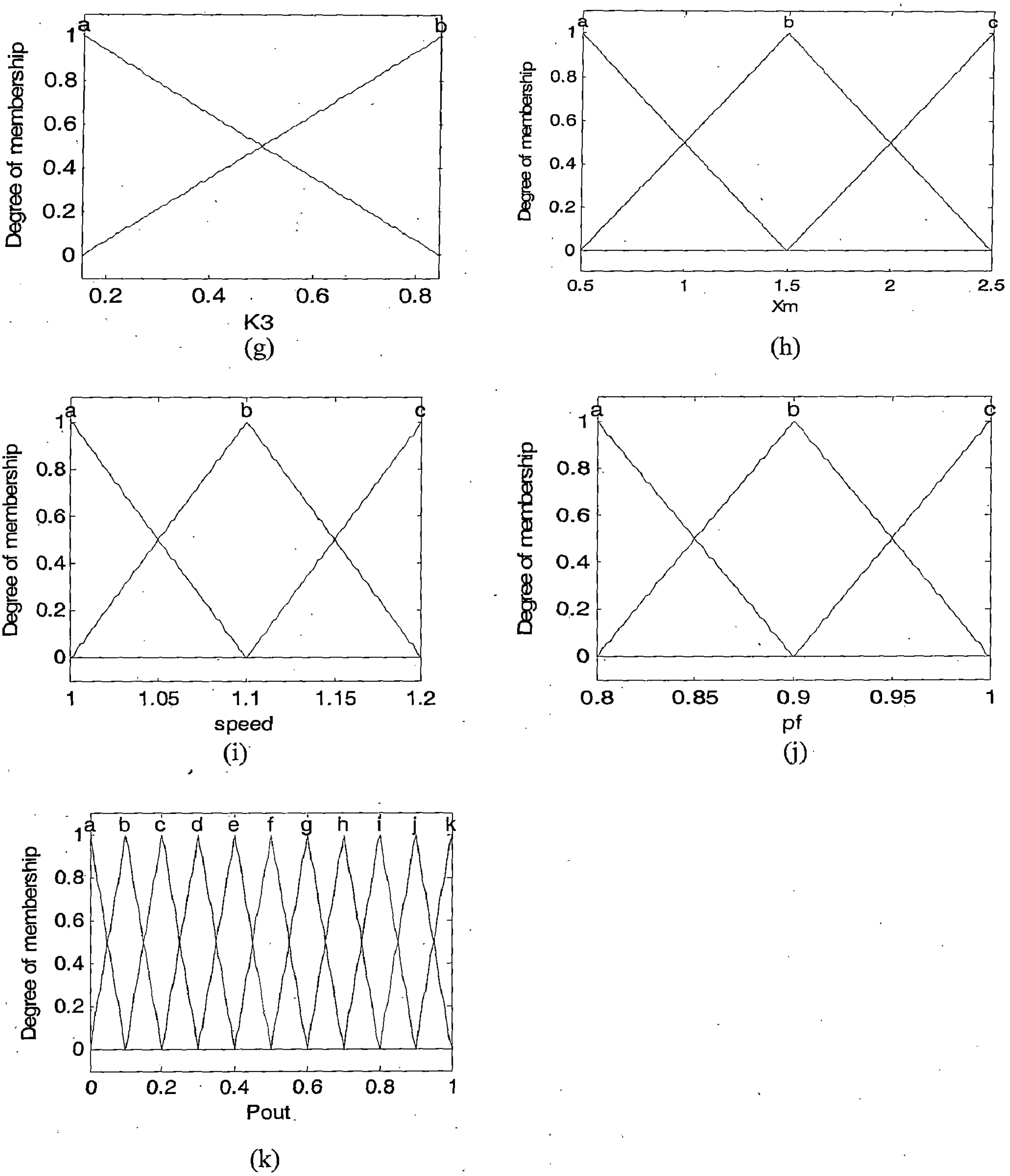
(d)


a
b
Degree of membership
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
K1

(e)


a
b
Degree of membership
1
0.8
0.6
0.4
0.2
0
0
0.01
0.02
0.03
0.04
K2

(f)

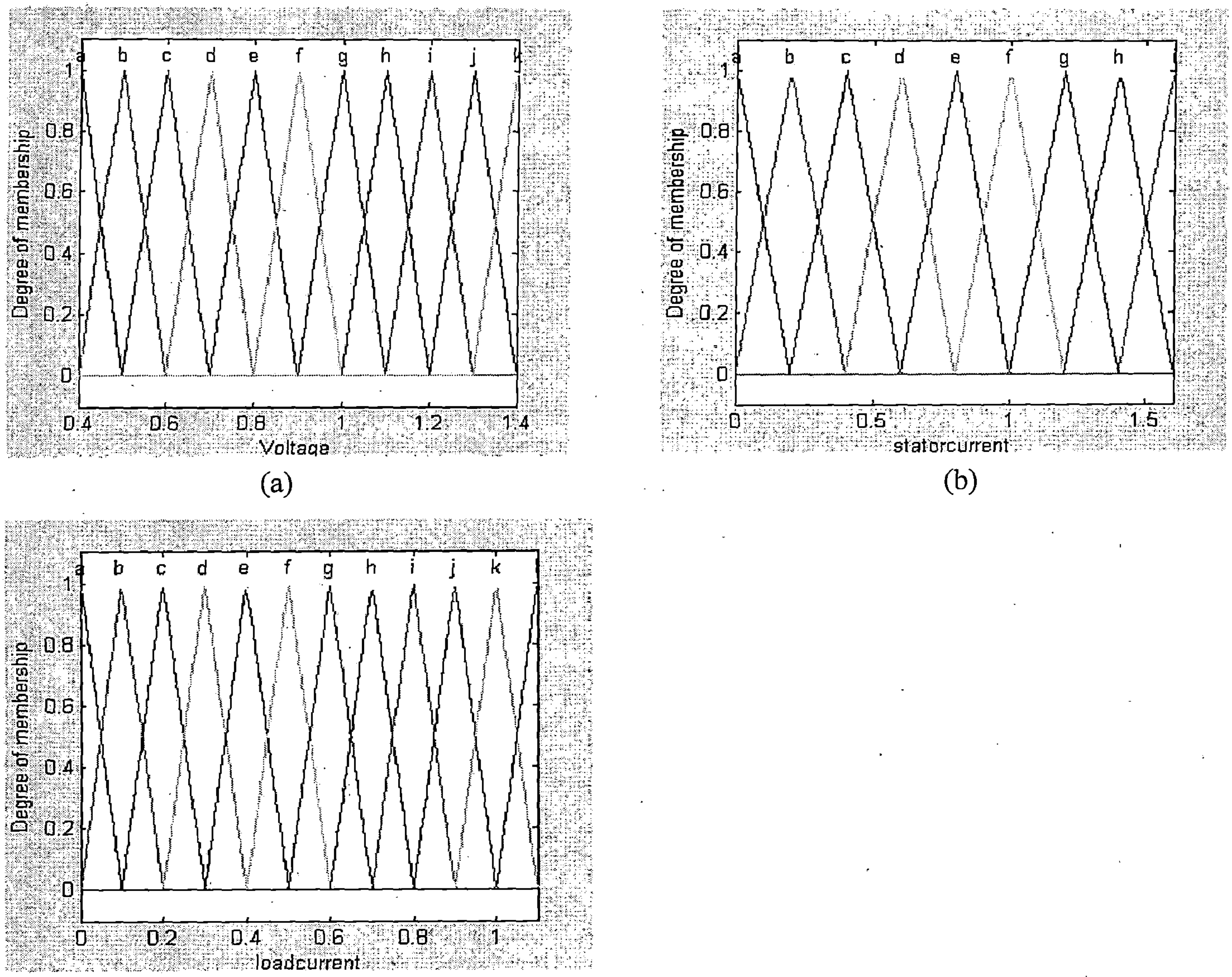


(g) (h)

(i) (j)

(k)

Figure 2.3: Membership function of input variables



(a)

(b)

(c)

Figure2.4: Membership function of output variables

Chapter- 3

Fuzzy Model of Series Compensated SEIG: Rule Base

3.1 General

A fuzzy system maps the input space variables to output space variables. Rule-base which tells relation between input and output variables is the heart of the system. Rules are determined from the past knowledge of system or any other method which gives relation between input and output variables. Composing fuzzy rules is a process natural to human brain, because the IF-THEN structure is part of our daily language and natural logic. Fuzzy subset theory involves very complicated theorems, but most of these theorems do not used in the development of fuzzy rules. The following three logic operators generally will be used in composing rules. [3, 4]

1. The union of two sets, $A \cup B$, corresponds to the OR function and is defined by

$$m\,(A\ \text{OR}\ B) = \max\,(m_A(x), m_B(x))$$

2. The intersection of two sets, $A \cap B$, corresponds to the AND function and is defined by

$$m\,(A\ \text{AND}\ B) = \min\,(m_A(x), m_B(x))$$

3. The complement of a set A corresponds to the NOT function and is defined by

$$m\,(\text{NOT}\ A) = 1 - m_A(x)$$

All rules are evaluated in parallel, and the order of the rules is unimportant. In this chapter the rules are developed with the help of steady state equivalent circuit of series compensated SEIG. For determining input-output relation iterative method is used. The effectiveness of a rule is also discussed, which is useful when for same LHS of the rule, the RHS is different. In such cases the rule which is less effective is ignored.

3.2 Equivalent circuit of series compensated SEIG

The performance of series compensated SEIG is affected by various parameters like shunt capacitance, series capacitance, power factor of the load and shape of magnetizing curve etc. The relation between these variables and performance can be easily seen by steady-state equivalent circuit of series compensated SEIG. Here, for determining input-output relation, a program in MATLAB is developed. The steady-state equivalent circuit of series compensated SEIG is shown in Figure 3.1.

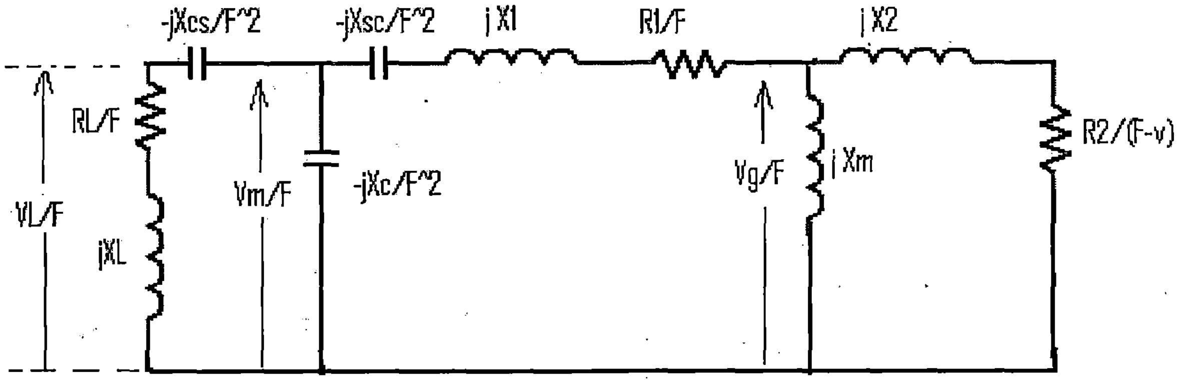


Figure 3.1: Generalized equivalent circuit of series compensated SEIG

There are two basic schemes by which a series capacitor may connect in induction generator.

1. Short shunt connection
2. Long shunt connection

For short shunt connection $X_{sc}=0$ and for long shunt connection $X_{cs}=0$.

3.3 Procedure for determining input and output relationship

Under self-excitation with no external voltage sources, the steady state diagram of SEIG is simplified to a closed circuit and summation of impedances equated to zero. Solution of this equation yields two unknown quantities, namely the saturated magnetizing reactance (Xm) and the p.u. generated frequency (F). This saturated magnetizing reactance (Xm) is used to obtaining air gap voltage. Currents, load voltage, output power, and magnetizing current etc. are easily calculated from equivalent diagram, after knowing air gap voltage. Based on the above procedure, the program in MATLAB has been developed and the following assumptions are made in the analysis:

1. All the equivalent circuit parameters except the magnetizing reactance are assumed to be constant (only the magnetizing reactance is assumed to be affected by saturation).
2. Core loss in the machine is neglected.

3. MMF space harmonics and time harmonics in the induced voltage and current waveform are neglected.
4. Stator and rotor leakage reactance are taken to be equal.
5. Speed of prime mover of the generator is constant.
6. Loads are balanced.

Saturation may have some effect on the values of the leakage reactance, but this is expected to have little effect on the results. Ignoring air gap harmonics means neglecting the effect of the 5th and 7th components, which are usually dominant in induction machines. Good winding designs may reduce or totally eliminate the effect of these components. Because isolated induction generators are characterized by their operation at variable frequencies, all parameters are referred to the operating per-unit frequency F. Core losses can be taken into account by placing a resistor in shunt with the magnetizing reactance, but the derivation will become lengthy.

From Figure 3.1, it can be seen,

$$Z_1^1 = \frac{R_1}{F} + jX_1 \tag{3.1}$$

$$Z_{SC} = -\frac{jX_{Sc}}{F^2} \tag{3.2}$$

$$Z_1 = Z_1^1 + Z_{SC} \tag{3.3}$$

$$Z_2 = \frac{R_2}{F - v} + jX_2 \tag{3.4}$$

$$Z_m = jX_m \tag{3.5}$$

$$Z_C = -\frac{jX_C}{F^2} \tag{3.6}$$

$$Z_l = \frac{R_L}{F} + jX_L \tag{3.7}$$

$$Z_{CS} = -\frac{jX_{CS}}{F^2} \tag{3.8}$$

$$Z_L = Z_l + Z_{CS} \tag{3.9}$$

If,

$$Z_3 = \frac{Z_L . Z_C}{Z_L + Z_C} \tag{3.10}$$

And,

$$Z_4 = \frac{Z_2 . Z_m}{Z_2 + Z_m} \tag{3.11}$$

Applying Kirchhof's voltage law in Figure 3.1,

$$I. (Z_1 + Z_3 + Z_4) = 0 \tag{3.12}$$

3.3.1 Method of Solution

For SEIG current (I) does not equal to zero. So summation of impedances will be zero. On substituting Z_1, Z_3, Z4 and rearranging equation 3.12, the following two non-linear equations with F and X_m as unknown quantities are obtained, by equating real and imaginary parts to zero separately.

$$f(X_m, F) = (C_1 X_m + C_2) F^4 + (C_3 X_m + C_4) F^3 + (C_5 X_m + C_6) F^2 + (C_7 X_m + C_8) F + C_9 \tag{3.13}$$

$$g(X_m, F) = (D_1 X_m + D_2) F^5 + (D_3 X_m + D_4) F^4 + (D_5 X_m + D_6) F^3 + (D_7 X_m + D_8) F^2 + (D_9 X_m + D_{10}) F + (D_{11} X_m + D_{12}) \tag{3.14}$$

Whose constants C1-C9 and D1-D12 are functions of constant machine parameters, load impedance, speed and connected capacitance, as listed in Appendix-1.

There are generally two techniques by which the value of Xm and F is determined. These methods are:

1. Iterative method.
2. Optimization method.

3.3.1.1 Iterative method [12]

From equation 3.13 & 3.14, it is seen that the degree of X_m is one. Hence it is possible to eliminate this variable from these two equations. So equation 3.13 & 3.14 can be rewritten as follows:

$$Xm = -\frac{C_2F^4 + C_4F^3 + C_6F^2 + C_8F + C_9}{C_1F^4 + C_3F^3 + C_5F^2 + C_7F} \tag{3.15}$$

$$Xm = -\frac{D_2F^5 + D_4F^4 + D_6F^3 + D_8F^2 + D_{10}F + D_{12}}{D_1F^5 + D_3F^4 + D_5F^3 + D_7F^2 + D_9F + D_{11}} \qquad 3.16$$

Since the value of X_m must satisfy both equations 3.15 & 3.16 simultaneously, the RHS of the both equations must be equal. So after doing cross-multiplication and expansion of the RHS of both equations, the following 9th degree polynomial in F is obtained:

$$K_1 F^9 + K_2 F^8 + K_3 F^7 + K_4 F^6 + K_5 F^5 + K_6 F^4 + K_7 F^3 + K_8 F^2 + K_9 F + K_{10} = 0 \qquad 3.17$$

The real coefficient K_1 to K_{10} can be expressed systematically in terms of the constant C and D derived earlier. Detailed expressions are given in Appendix-1.

Equation 3.17 may be solved for real roots to calculate the per-unit frequency F using a simple numerical procedure, e.g. Newton-Raphson method for a univariable polynomial. Having determined F, X_m can be evaluated using either equation 3.15 or 3.16.

3.3.1.2 Optimization method [13, 14]

Value of X_m and F is also determined by using a function minimization technique. It can be shown that the value of F and X_m that satisfy equation 3.12 will also result in a minimum value (of zero) in the following scalar impedance function:

$$f1(F,Xm) = \sqrt{\left((f(F,Xm))^2 + (g(F,Xm))^2\right)} \qquad 3.18$$

Any method of function minimization like Hooke and Jeeves method, cyclic coordinate method etc. may be used for calculating value of Xm and F from equation 3.18.

It will be noted that F<v, i.e. the slip s = (F-v)/F is always negative as it should be for generator operation.

3.3.1.3 Performance Equations

After calculating F and X_m under steady state, the next step is to calculate the air gap voltage Vg and terminal voltage. For this purpose information regarding variation of X_m with Vg/F is used which is obtained experimentally by driving the induction machine at synchronous speed corresponding to the line frequency, i.e. F=1, and measuring the magnetizing reactance for different input voltages at line frequency. A curve of Vg/F vs. X_m can be plotted using the experimental results. From this curve, Vg/F for the above calculated X_m is obtained. Knowing F, the air gap voltage Vg can be obtained []. After knowing Vg, load voltage, winding current, load current etc. are easily obtained from these performance equations, which is obtained from Figure 3.1.

$Is = (Vg/F)/\ (Z_1+Z_3)$ 3.19

$Ir = -\ (Vg/F)/Z_2$ 3.20

$I_L = Is\ Z_c /\ (Z_c + Z_L)$ 3.21

$V_L = I_L\ Z_l$ 3.22

$P_{out} = 3I_L^2\ R_L$ 3.23

Based on the analytical technique given here, a general computer program in MATLAB has been developed which gives the relation between input and output variables of SEIG. From these input-output relations, rule base for fuzzy system is composed. Here iterative method is used for finding relation between input and output variables. The flow chart of iteration method is given in appendix-2.

3.4 Effectiveness of a rule [3, 4]

Each rule is assigned a degree of effectiveness. A rule's effectiveness degree (E) is the product of its component fuzzy set membership degrees. For example suppose a rule is

If (A is x and B is y), then (C is z)

Then the effective degree of the rule is found using following expression,

$E = m(A)*m(B)*m(C)$ 3.24

Thus, the higher the total combined membership of the rule, the higher its composite effectiveness ranking relative to all other rules, with the same antecedent. This represents a filter on the conflict set. It not only solves ambiguity difficulties in the data but significantly reduces the total number of rules in the knowledge base. Thus if two rules are same LHS, then less effective rule is ignored. All rules which are used in modelling of series compensated induction generator are shown in appendix-3.

Chapter-4

Fuzzy Model of Series Compensated SEIG: Results

4.1 General

The basic scheme consists of an induction machine driven by a prime-mover having three phase shunt and series capacitors and load. The prime-mover can be oil engine, a micro hydel turbine. For oil engine and micro hydel turbines the speed can be maintained fairly constant and the voltage regulator has to maintain the terminal voltage constant at varying loads since frequency drop with load is found to be insignificant for a well designed machines. Any voltage regulating scheme has to affect increase in capacitive VAR with load. The series capacitor achieves this objective under certain conditions since additional VARs are added as load current increases. In chapter 2, fuzzy model of series compensated SEIG is discussed in detail. In this chapter a comparison is done between the results obtained from analytical method, which is discussed in chapter 3, and from fuzzy model and error between these two results is also discussed. After that effect of various parameters, like rotor resistance and reactance, shunt and series capacitance, power factor etc. on load voltage and winding current is discussed in detail.

4.2 Comparison in Fuzzy and Analytical Method

Load voltage, winding current, and load current obtained from fuzzy and analytical method (iterative method) at different power output at unity power factor for two machines is shown in Figure 4.1, Figure 4.2, and Figure 4.3 respectively. The main input variables, which changes the performance of induction generators are, saturated reactance (X_m), coefficient of magnetizing curve (K_1, K_2, K_3). The linguistic labels of these input variables are selected in such a way that maximum number of machines characteristic may fall in same linguistic label. It reduces number of rules, and become more generalized the fuzzy system. If rules are prepared for every possible combination of these variables, then the fuzzy system become a generalized model for checking the performance of all induction generators. Here rules are made form the data collected with the help of two machines whose ratings are given in Table 4.1 and Table 4.2. Table 4.3, Table 4.4 and Table 4.5 shows the values of load voltage, winding current and load current obtained by fuzzy and analytical methods, error between in these two methods are also indicated at different power output. Table 4.6 and 4.7 shows the rating of machine 3 and machine 4, the performance of these two machines are checked by the rule developed with the help of Machine-1 and Machine2. From Figure 4.4, Figure 4.5 and Figure 4.6, it can be seen that the performance of these two machine is also close its actual performance. Thus from fuzzy model it is easy to see the performance of any machine.

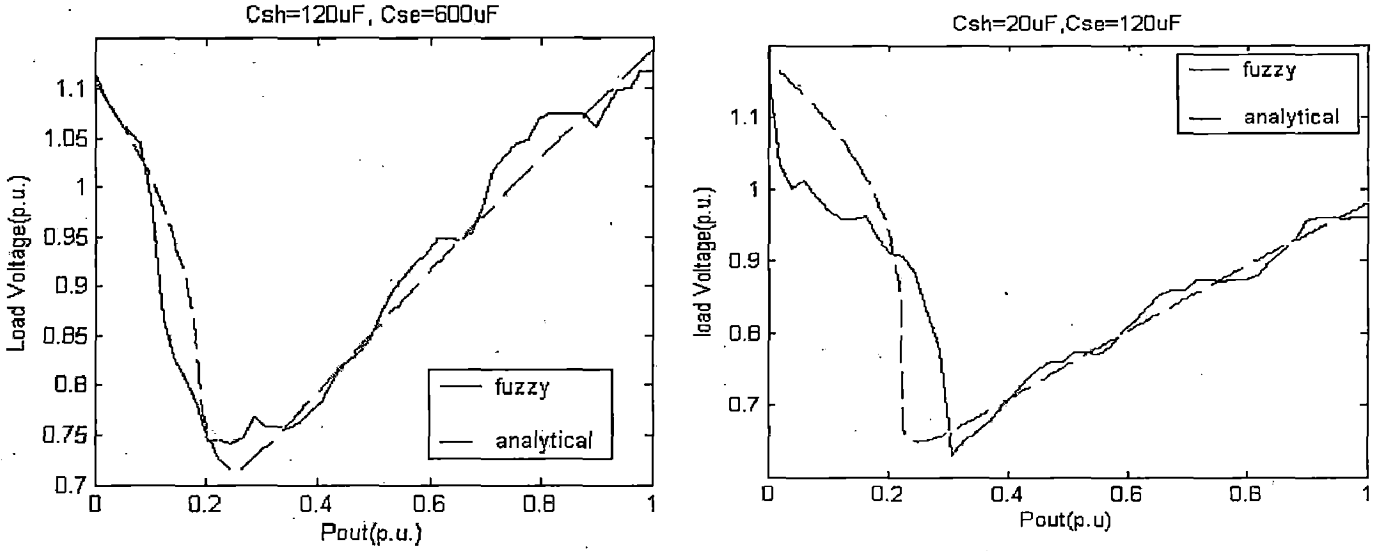
Table 4.1: Rating and equivalent circuit parameters of machines [27]

	power(kW)	type	line voltage(V)	line current(A)	R1(Ω)	R2(Ω)	X1=X2(Ω)	Xm(saturated)
M/c-1	22	delta	400	40	0.56	0.72	1.5	24.94
M/c-2	3.7	delta	415	7.6	5.53	5.86	9.6	120

Table 4.2: Coefficients of magnetizing characteristics of the machines [27]

$(V_g/F=K_1X_m^2+K_2X_m+K_3)$

	K1	K2	K3
M/c-1	-0.1741	9.8999	274.66
M/c-2	-0.0097	2.2926	320.75



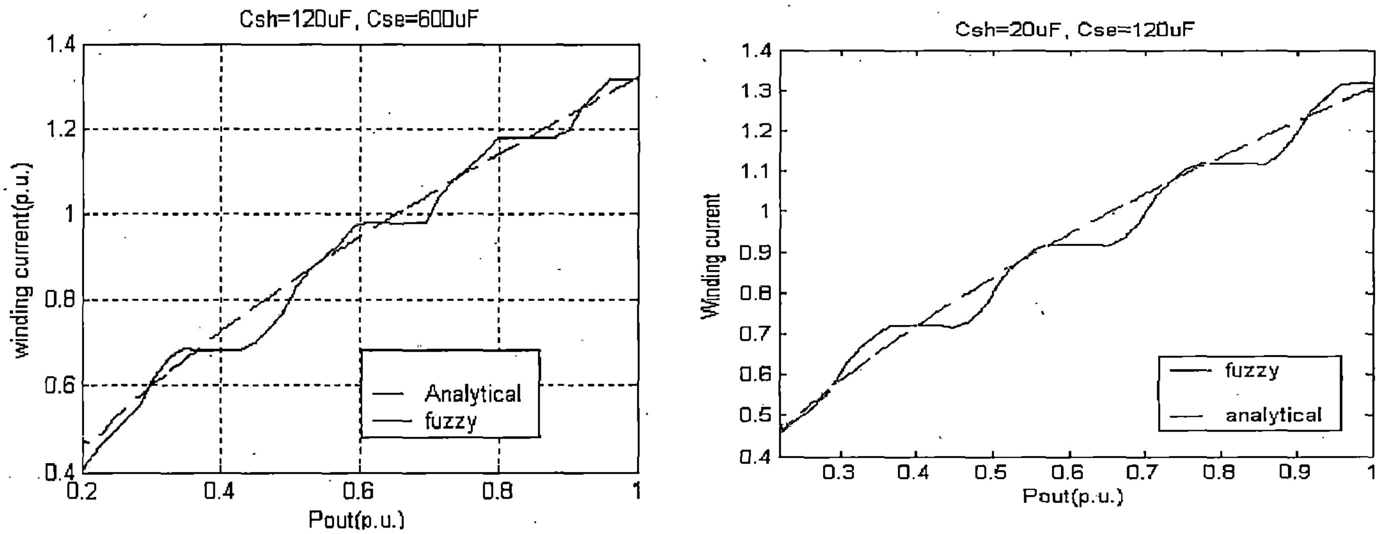
(a) Machine-1

(b) Machine-2

Figure 4.1: Load voltage obtained by fuzzy and analytical method

Table 4.3: Comparison between voltages obtained from fuzzy and analytical method.

	Machine-1			Machine-2		
Pout(p.u.)	VL(Analytical)	VL(fuzzy)	Error (%)	VL(Analytical)	VL(fuzzy)	Error (%)
0	1.105	1.114	-0.814	1.18	1.156	2.033
0.1	1.01	0.996	1.386	1.08	0.98	9.259
0.2	0.75	0.752	-0.266	0.935	0.915	2.139
0.3	0.735	0.76	-3.401	0.662	0.673	-1.661
0.4	0.793	0.78	1.639	0.707	0.708	-0.141
0.5	0.855	0.8575	-0.292	0.756	0.766	-1.322
0.6	0.915	0.937	-2.404	0.803	0.809	-0.747
0.7	0.974	0.991	-1.745	0.85	0.863	-1.529
0.8	1.03	1.07	-3.883	0.894	0.875	2.125
0.9	1.085	1.063	2.027	0.937	0.965	-2.988
1	1.138	1.118	1.757	0.98	0.96	2.040

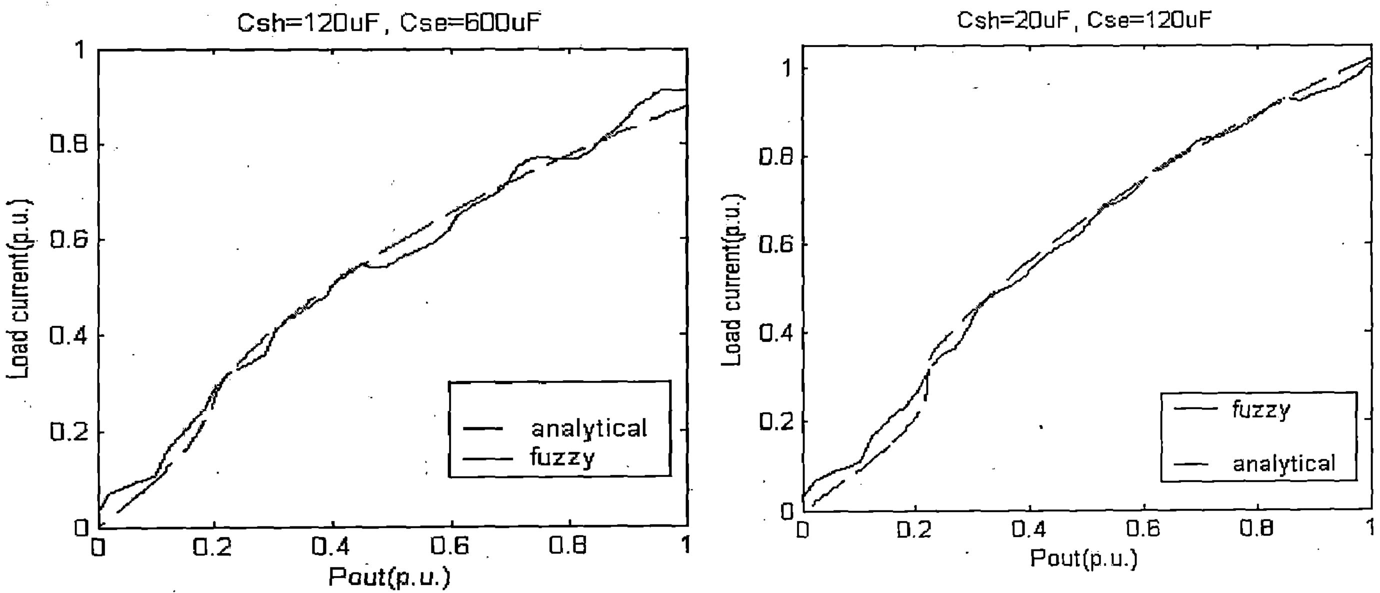


(a) Machine-1 (b) Machine-2

Figure 4.2: Winding current obtained by fuzzy and analytical method

Table 4.4: Comparison between winding current obtained from fuzzy and analytical method.

	Machine-1			Machine-2		
Pout(p.u.)	Is(Analytical)	Is(fuzzy)	Error (%)	Is(Analytical)	Is(fuzzy)	Error (%)
0.2	0.474	0.401	15.400	0.463	0.461	0.431
0.3	0.598	0.601	-0.501	0.58	0.6	-3.448
0.4	0.725	0.685	5.517	0.718	0.721	-0.417
0.5	0.84	0.8	4.761	0.84	0.8	4.761
0.6	0.945	0.975	-3.174	0.945	0.92	2.645
0.7	1.05	1	4.761	1.04	1	3.846
0.8	1.14	1.18	-3.508	1.138	1.121	1.493
0.9	1.234	1.2	2.755	1.22	1.2	1.639
1	1.32	1.316	0.303	1.31	1.32	-0.763



(a) Machine-1

(b) Machine-2

Figure 4.3: Load current obtained by fuzzy and analytical method

Table 4.5: Comparison between load currents obtained from fuzzy and analytical method.

	Machine-1			Machine-2		
Pout(p.u.)	IL(Analytical)	IL(fuzzy)	Error (%)	IL(Analytical)	IL(fuzzy)	Error (%)
0.1	0.1	0.107	-7	0.092	0.1	-8.695
0.2	0.264	0.282	-6.818	0.22	0.25	-13.636
0.3	0.409	0.395	3.422	0.45	0.435	3.333
0.4	0.504	0.5	0.793	0.542	0.565	-4.243
0.5	0.58	0.55	5.172	0.66	0.64	3.030
0.6	0.655	0.628	4.122	0.746	0.74	0.804
0.7	0.719	0.728	-1.251	0.825	0.835	-1.212
0.8	0.776	0.769	0.902	0.895	0.89	0.558
0.9	0.83	0.855	-3.012	0.96	0.94	2.083
1	0.88	0.91	-3.409	1.02	1.01	0.980

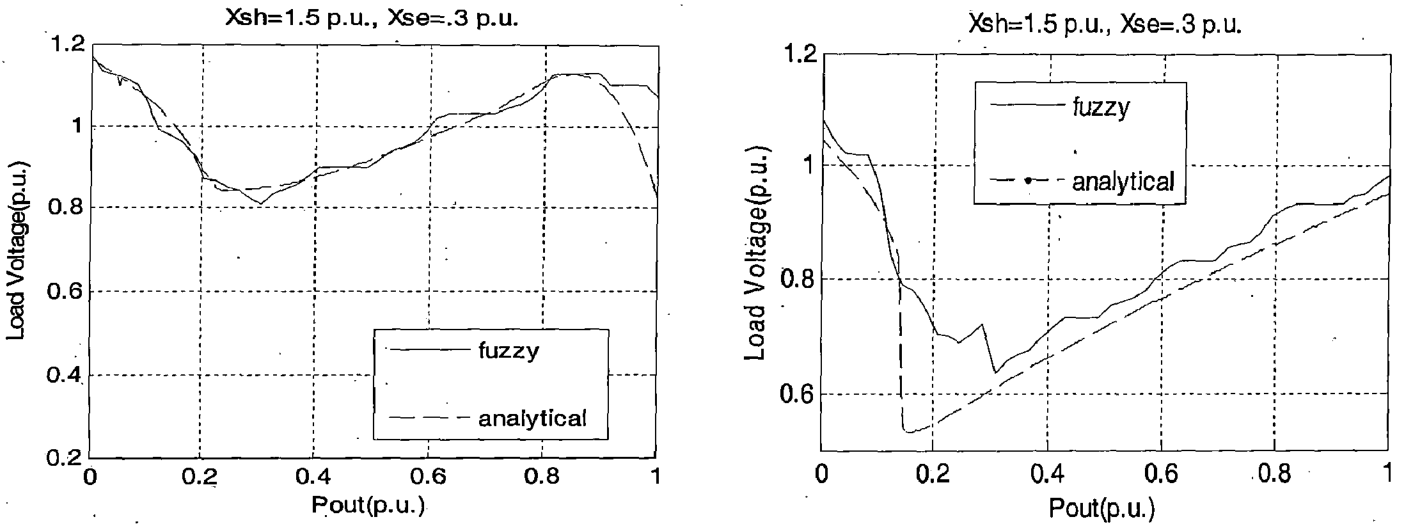
Table 4.6: Rating and equivalent circuit parameters of machines [27]

	power(kW)	type	line voltage(V)	line current(A)	R1(Ω)	R2(Ω)	X1=X2(Ω)	Xm(saturated)
M/c-3	15	delta	400	30	0.69	0.74	2.39	35
M/c-4	7.5	delta	230	26.2	0.76	1.03	1.5	30

Table 4.7: Coefficients of magnetizing characteristics of the machines [27]

$(V_g/F=K_1X_m^2+K_2X_m+K_3)$

	K1	K2	K3
M/c-3	-0.2185	14.082	203.37
M/c-4	-0.0622	4.0589	156.18

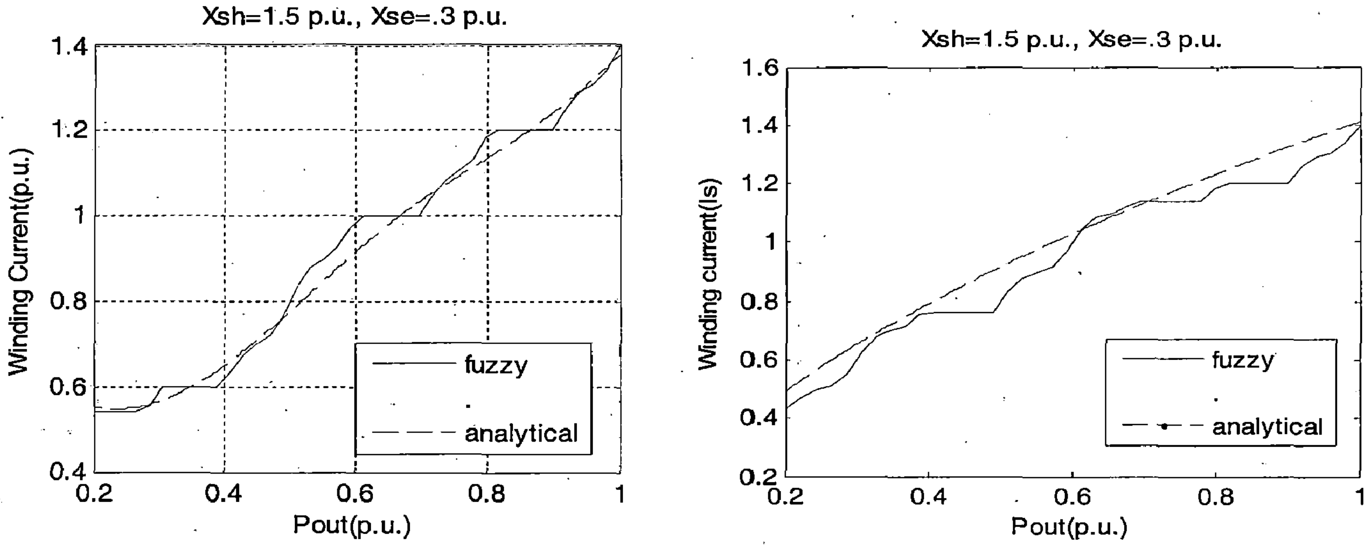


(a) Machine-3 (b) Machine-4

Figure 4.4: Load voltage obtained by fuzzy and analytical method

Table: 4.8 Comparison between voltages obtained from fuzzy and analytical method.

	Machine-3			Machine-4		
Pout(p.u.)	VL(analytical)	VL(fuzzy)	Error (%)	VL(analytical)	VL(fuzzy)	Error (%)
0	1.16	1.17	-0.862	1.045	1.08	-3.349
0.1	1.0685	1.064	0.421	0.92	0.96	-4.347
0.2	0.896	0.882	1.562	0.55	0.714	-29.818
0.3	0.848	0.815	3.891	0.6	0.66	-10
0.4	0.875	0.892	-1.942	0.66	0.71	-7.575
0.5	0.919	0.9085	1.142	0.715	0.74	-3.496
0.6	0.975	1	-2.564	0.765	0.81	-5.882
0.7	1.032	1.029	0.290	0.815	0.835	-2.453
0.8	1.108	1.099	0.812	0.86	0.91	-5.813
0.9	1.1	1.125	-2.272	0.906	0.93	-2.649
1	1.05	0.84	20	0.95	0.98	-3.157

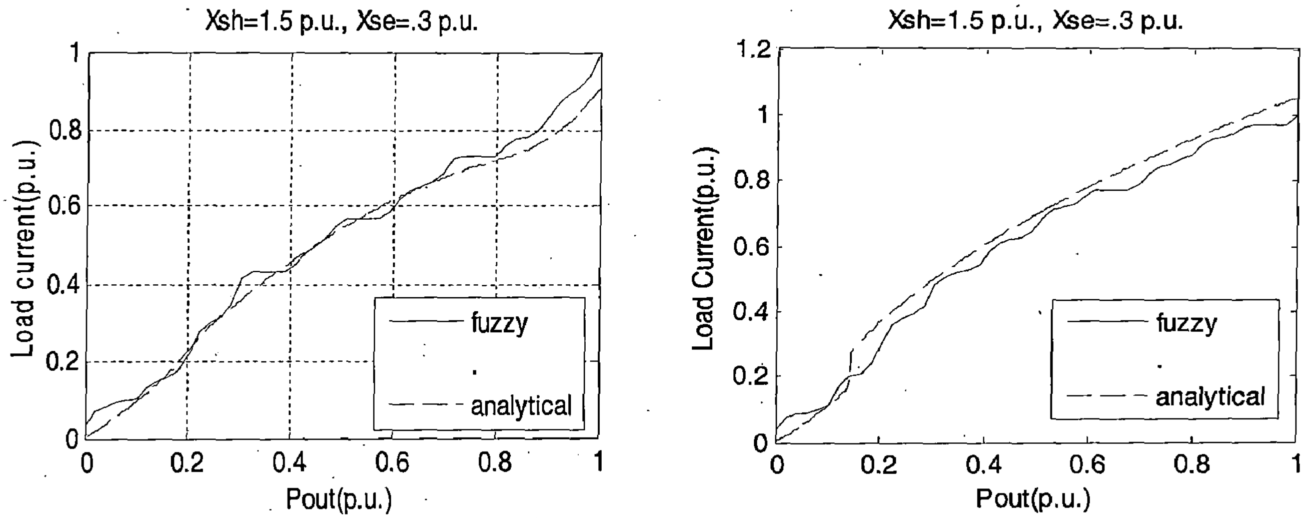


(a) Machine-3 (b) Machine-4

Figure 4.5: Winding current obtained by fuzzy and analytical method

Table 4.9: Comparison between winding current obtained from fuzzy and analytical method

	Machine-3			Machine-4		
Pout(p.u.)	Is(analytical)	Is(fuzzy)	Error (%)	Is(analytical)	Is(fuzzy)	Error (%)
0.2	0.55	0.54	1.818	0.49	0.43	12.244
0.3	0.565	0.585	-3.539	0.65	0.6	7.692
0.4	0.616	0.65	-5.519	0.79	0.76	3.797
0.5	0.8	0.775	3.125	0.92	0.8	13.043
0.6	0.98	0.92	6.122	1.03	1	2.912
0.7	1.015	1.038	-2.266	1.13	1.138	-0.707
0.8	1.19	1.135	4.621	1.23	1.19	3.252
0.9	1.205	1.24	-2.904	1.32	1.2	9.090
1	1.4	1.38	1.428	1.41	1.395	1.063



(a) Machine-3 (b) Machine-2

Figure 4.6: Load current obtained by fuzzy and analytical method

Table 4.10: Comparison between load currents obtained from fuzzy and analytical method.

	Machine-3			Machine-4		
Pout(p.u)	IL(analytical)	IL(fuzzy)	Error (%)	IL(analytical)	IL(fuzzy)	Error (%)
0.1	0.094	0.104	-10.638	0.108	0.109	-0.925
0.2	0.222	0.21	5.405	0.36	0.29	19.444
0.3	0.355	0.39	-9.859	0.49	0.46	6.122
0.4	0.456	0.44	3.508	0.605	0.57	5.785
0.5	0.545	0.56	-2.752	0.7	0.666	4.857
0.6	0.618	0.6	2.912	0.78	0.76	2.564
0.7	0.68	0.7	-2.941	0.86	0.8	6.976
0.8	0.72	0.735	-2.083	0.93	0.885	4.838
0.9	0.78	0.83	-6.410	0.99	0.965	2.525
1	0.91	1	-9.890	1.05	1	4.761

4.3 Variation of load voltage, winding current and load current with power output

As power output (load) of series compensated SEIG is increased, the variation in load voltage, winding current and load current is discussed in this section. As load increases, how the load voltage is vary, is important for voltage regulation studies.

4.3.1 Variation of load voltage with output power

Fig 4.7 shows the variation of load voltage with output power at unity power factor and 1.01 p.u speed, obtained from fuzzy model of SEIG. The value of shunt capacitance and series capacitance are 120uF and 600uF respectively. At low load condition the load voltage decreases with increase in load, but after a point it begin to increase as load is increased. Thus shape of voltage curve is like 'V' curve. At no load condition the current in series capacitance is zero, so no load voltage is totally determined by shunt capacitance. So value of shunt capacitance is selected on the basis of no load condition.

4.3.2 Variation of Winding current with output power

Figure 4.8 shows that the stator current or winding current of SEIG at unity power factor, obtained from fuzzy model. The winding current increases as load are increased. At no load condition the value of winding current is not zero, it is due to self excitation of induction generator. The value of shunt and series capacitance is respectively 120 uF and 600 uF.

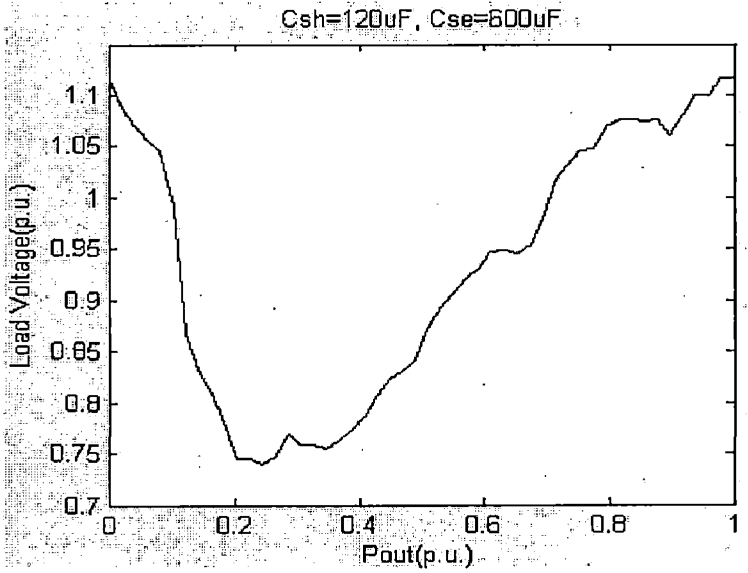


Figure 4.7: Variation of load voltage with output power

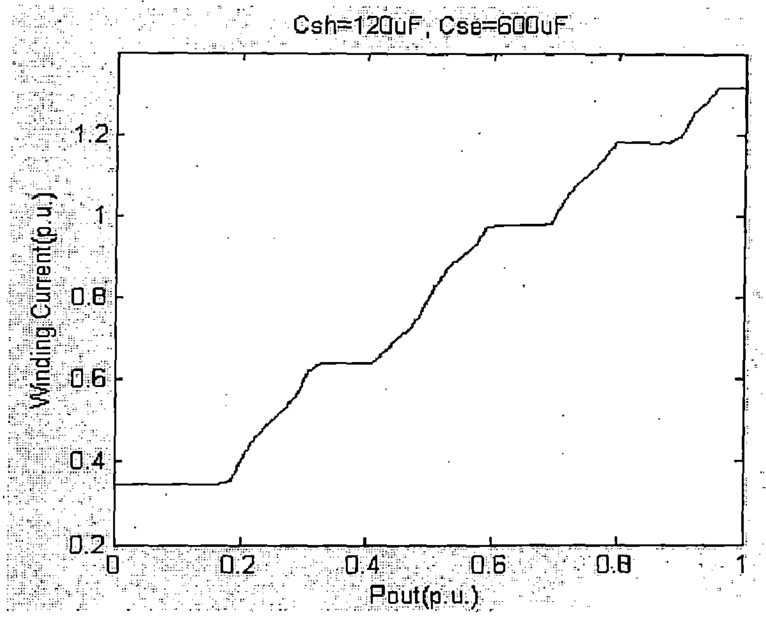


Figure 4.8: Variation of winding current with output power

4.3.3 Variation of load current with output power

Figure 4.9 shows variation of load current at unity power factor as output power is increased. The load current is increases as the load is increased.

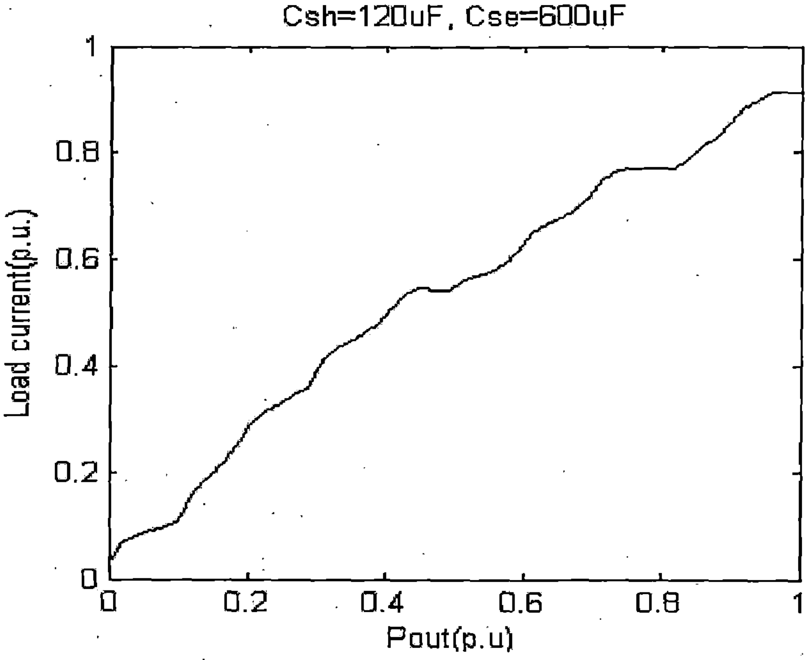


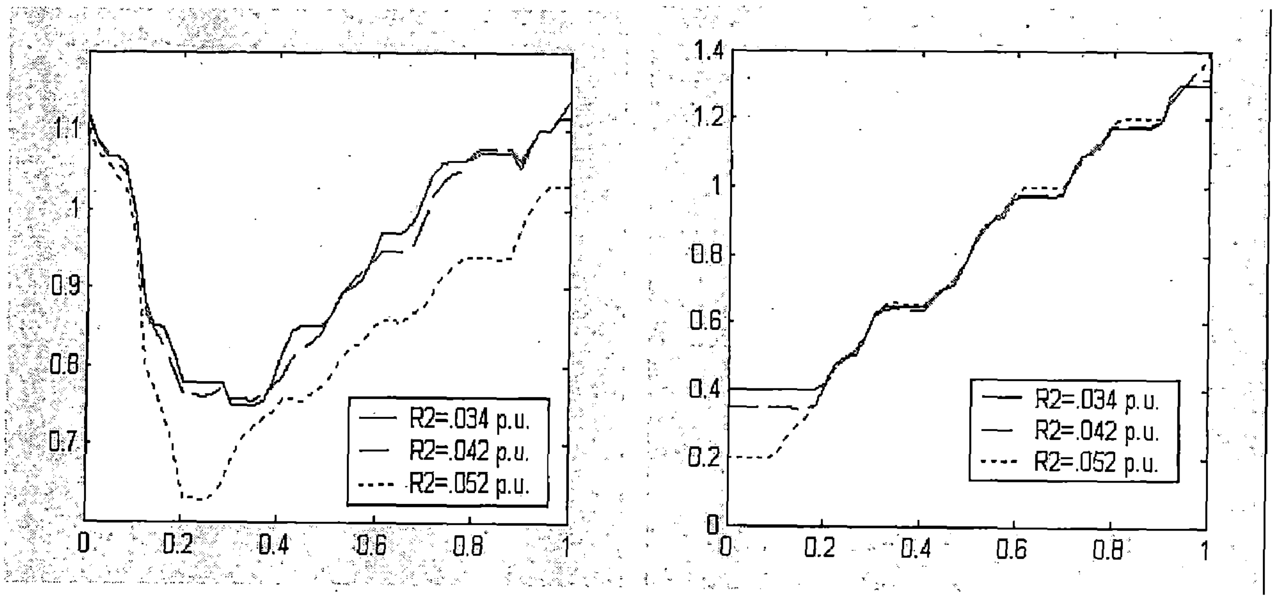
Figure 4.9: Variation of load current with output power

4.4 Effect of various parameters on series compensated SEIG performance

Rotor resistance and reactance, shunt capacitance, series capacitance etc. effect the load voltage very much. The effects of these parameters (rotor resistance and reactance) are important for designing an efficient induction generator, whereas effect of shunt or series capacitance gives the information about values of shunt or series capacitors for improved voltage regulation. In this section effect of various parameters on induction generator performance is discussed.

4.4.1 Effect of rotor resistance

Fig. 4.10(a) and Fig 4.10 (b) shows the variation of load voltage and winding current with output power at different values of rotor resistance at resistive load condition. It is seen that at high cage rotor resistance the voltage regulation is poor in compare to low cage rotor resistance. Thus low cage rotor gives better performance in the case of induction generator whereas for a motor it adversely affects the stating performance. Winding current is almost constant at different value of rotor resistances.



(a) (b)

Figure 4.10 Effect of rotor resistance on load voltage and winding current

4.4.2 Effect of leakage reactance

Figure 4.11 shows the variation of load voltage with output power at different values of leakage reactance at resistive load condition. From the Figure 4.11 it is seen that at low value of leakage reactance the voltage dip is less in compare to high value of leakage reactance. Thus for better voltage regulation in induction generator the leakage reactance should be less whereas in motor case high leakage reactance is desirable to limit stating current.

4.4.3 Effect of shunt capacitance

Fig 4.12(a) and Fig 4.12(b) shows, the effect of shunt capacitance on load voltage and winding currents, for a fixed value of series capacitance, load voltage and winding current is more for high value of shunt capacitance for same power output. It is seen that for higher value of shunt capacitance the power capability of SEIG reduces since at same winding current it delivers less output power but voltage regulation is improved.

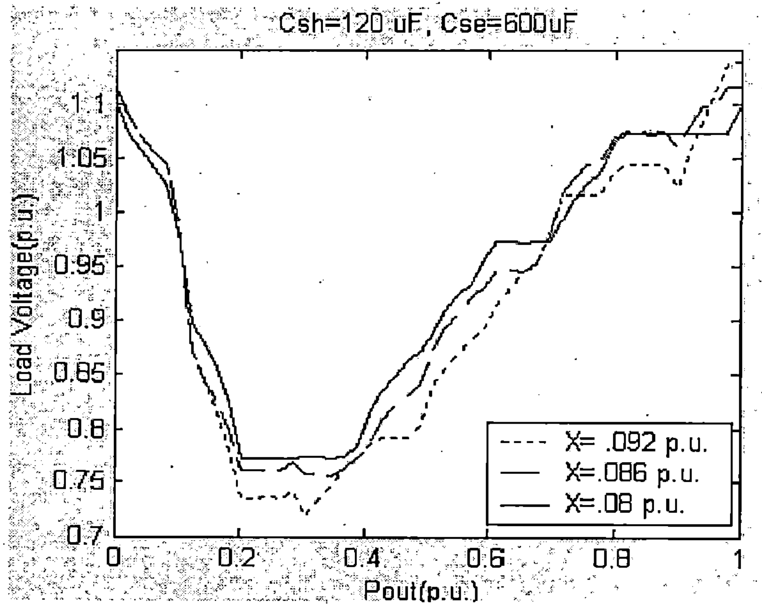
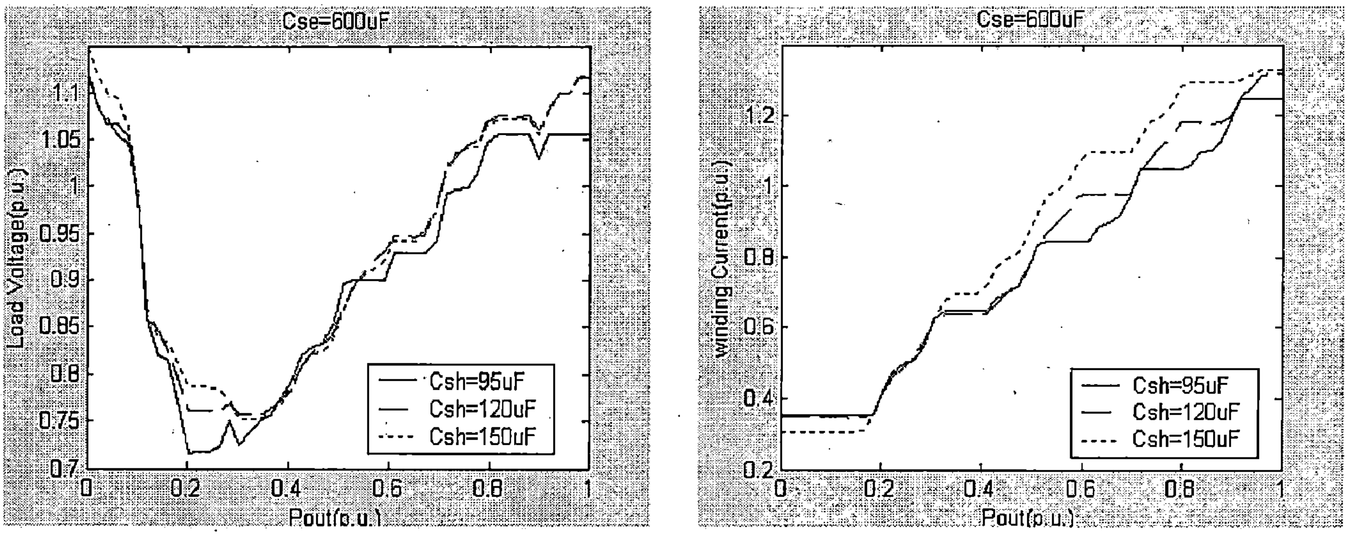


Figure 4.11: Effect of leakage reactance on load voltage



(a) (b)

Figure 4.12: Effect of shunt capacitance on load voltage and winding current

4.4.4 Effect of series capacitance

Fig 4.13 shows the load characteristic at different values of series capacitance. It can be seen that at higher value of series capacitance voltage drops is more than low values of series capacitance. Based on these curve (Fig 4.12(a) & Fig 4.13) suitable value of series and shunt capacitance are selected for better voltage regulation.

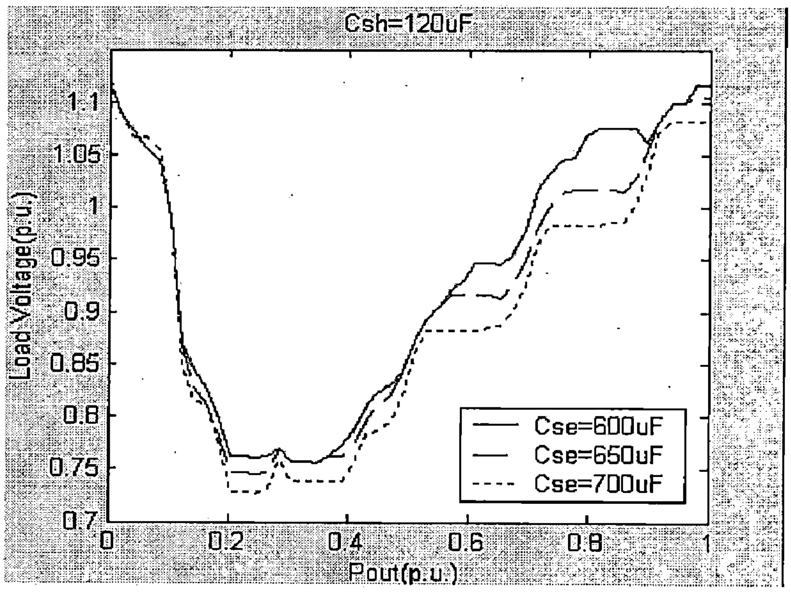


Figure 4.13: Effect of series capacitance on load voltage

4.4.5 Effect of speed

From Fig 4.14 it can be seen that for fixed value of series and shunt capacitance, voltage is more for higher speed and drop in voltage is also low.

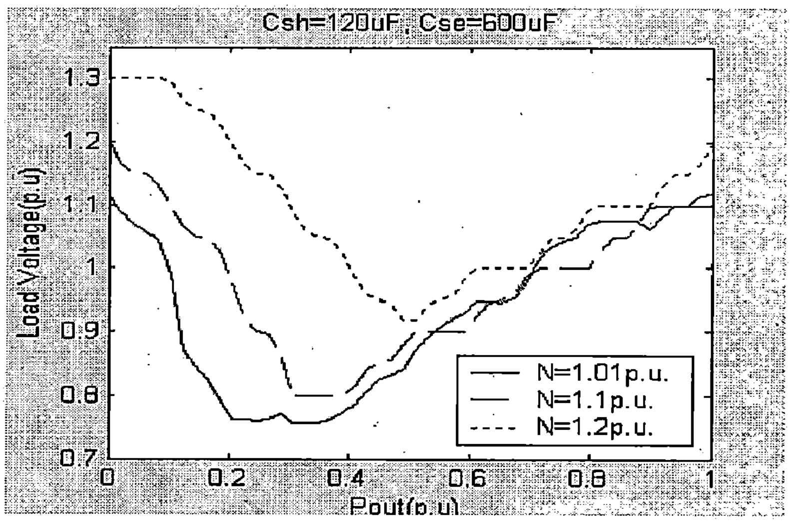
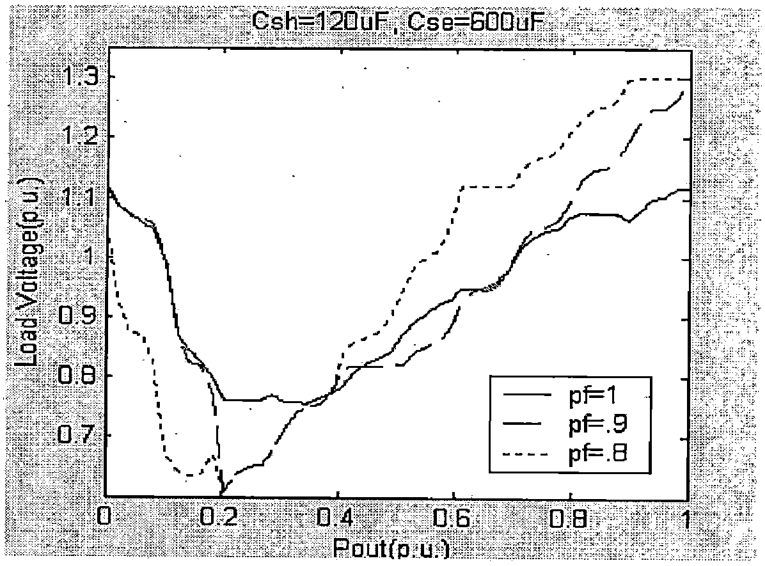


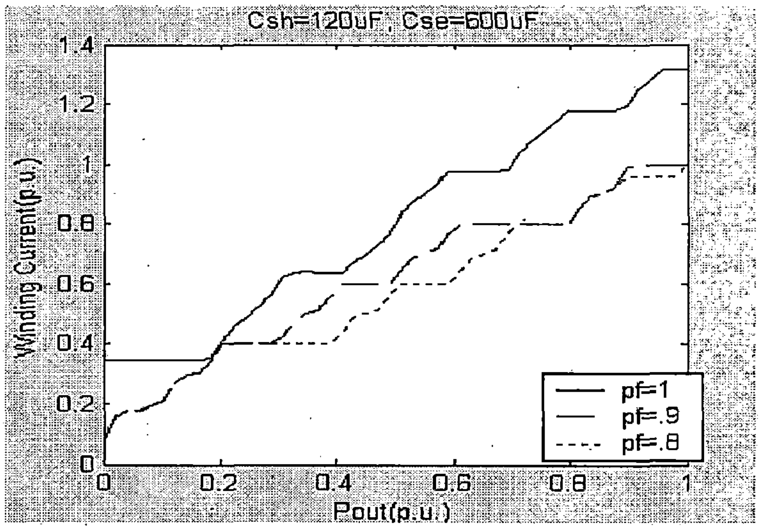
Figure 4.14: Effect of speed on load voltage

4.4.6 Effect of power factor

From Fig 4.15(a) it is clear that power factor of load effects the load voltage very much. At low load condition, load voltage is lower at lagging loads whereas as load increases the load voltage rise more rapidly in lagging loads rather than resistive loads. Winding current is less for lagging loads as shown in Fig 4.15(b).



(a)



(b)

Figure 4.15: Effect of power factor on load voltage and winding current

Chapter-5

Analysis of Fuzzy Load Controller for Three-Phase SEIG

5.1 General

In the previous chapters, steady state analysis of SEIG under balanced load condition is presented in detailed. From these chapters it is observed that in short shunt series compensated SEIG the terminal (load) voltage is low at low load condition. The terminal voltage may be maintained constant under following conditions (a) load, capacitor and speed are constant, or (b) excitation capacitance is increased with load at constant speed to kept voltage constant. In the first case, total load should be kept constant at constant capacitance and speed of the SEIG. Hence SEIG generates constant voltage of fixed frequency under rated load and this is called 'single-point operation' where all parameters of the system are fixed. This operating condition is a most appreciate option if the prime mover for the SEIG is having constant input power as an uncontrolled hydro turbine. If the prime mover is a fuel driven engine, constant power operation is wasteful and voltage regulation using control of excitation capacitor is appropriate. But practically it is not possible to constant load at all times. If load on SEIG decreases, the speed will go high due to constant input power and hence the voltage and frequency will shoot up. The increase in voltage and frequency will be harmful to the connected appliances. Suitable scheme has to be developed to maintained constant load on the SEIG in such power applications.

Under low power ratings(less than 10kW) uncontrolled turbines are preferred, which maintain the input hydro power constant needing the generator output power to be held constant at varying consumer loads. This requires a controllable dump (ballast) load connected in parallel with the consumer load so that the total power consumed is held constant. The two commonly employed technique used for load governing are:

1. The phase delay action, where the ballast load comprises a permanently connected single resistive load circuit of magnitude equal to (or slightly greater than) the full load rated output of the generator. As a result of the detection of a change in the consumer load, the firing angle of a power electronic switching device, such as a

triac, is adjusted, thus altering the average voltage applied, and hence the power dissipated by, the ballast load.

As with all power electronic switching of this nature, this technique introduces harmonics onto the electrical system. It is to note that these harmonics are continuously present to some extent as long as the ballast load is energized. The presence of these harmonics will cause overheating of electrical equipment connected to the system and of the generator and this is usually counteracted by derating of the generator plant. To compensate for the waveform distortion, the generator should be oversized.

2. The binary load action where the ballast load is made up from a switched combination of a binary arrangement of separate resistive loads. The value of these resistors is binary weighted so as to achieve the maximum number of loads with minimum number of resistors and switches. The main advantage of this approach is that waveform distortion is not produced and the ballast load is resistive. Because the ballast load is only varied by steps, the voltage is only controlled within a range or 'window'. This switching operation occur during the transient period only, thereafter full system voltage is applied to the new fraction of the ballast load and hence harmonics are not produced at all by this method in the steady-state.

In this chapter, the terminal voltage of short shunt SEIG is controlled with the help of binary weighted switched resistors, the switching of these resistors is done by fuzzy logic controller. Here, it is assumed that the consumer loads are resistive.

5.2 Principle of operation

The SEIG load controller system consist of a three-phase delta connected induction generator driven by uncontrolled pico hydro turbine and ballast loads. Suitable value of series and shunt capacitance is chosen to generate rated voltage near rated load. Since the input power is nearly constant, the output power of the SEIG must be held constant by varying ballast load such that the summation of consumer load and ballast load is constant; i.e.

$P_{out} = P_d + P_c$

Where,

P_{out} = Generated power of the generator.

P_d = Ballast load power.

P_c = Consumer power.

The ballast load power P_d may be used for space heating, water heating, cooking etc.

5.3 Fuzzy control of series compensated SEIG

There are a number of reasons for using fuzzy logic in control application; the primary advantage of fuzzy controller is its flexibility. The backbone of any fuzzy logic controller is its set of rules. Advantages of fuzzy controller over other conventional controllers are:

1. In fuzzy controller, the control strategy is represented by a set of rules and not on set of equations. So the basic characteristic of the controller is changed simply by redefining the rules.
2. The fuzzy rules are dealing with the imprecise definition of the system. This eliminates the need for a well-defined mathematical model of the system. Model with reduced complexity can be employed for analyzing the functional characteristic of the fuzzy logic controller.
3. The conventional PI controller generally requires operational amplifier circuits. These circuits have the tendency to drift with age and temperature causing degradation of the system performance, whereas fuzzy controllers are implemented with microprocessors. So fuzzy controllers gives same performance over the years.

5.3.1 Control Block

Figure5.1 shows the block diagram of fuzzy load controller and a SEIG set. There are two inputs to the fuzzy logic controller. The load voltage is compared with reference voltage, which generates an error in load voltage. With the help of delay circuit change in error is obtained. These two, error or change in error are used as the input to the fuzzy logic controller. The fuzzy logic controller inputs vary from one application to other. But more number of inputs produce problem in rule composing. The basic control strategy is to maintain the load voltage within a small range, over varying consumer loads. The control output is used for switching of ballast loads.

So the task involved in designing a fuzzy logic controller can be summarized as follows:

1. Identify the input and output variables.
2. Define membership function for the variables.
3. Composite a fuzzy rule base.
4. Choose the method of inference.
5. Choose defuzzification technique.

This is general design technique and can vary from one design to another depending upon on the requirements.

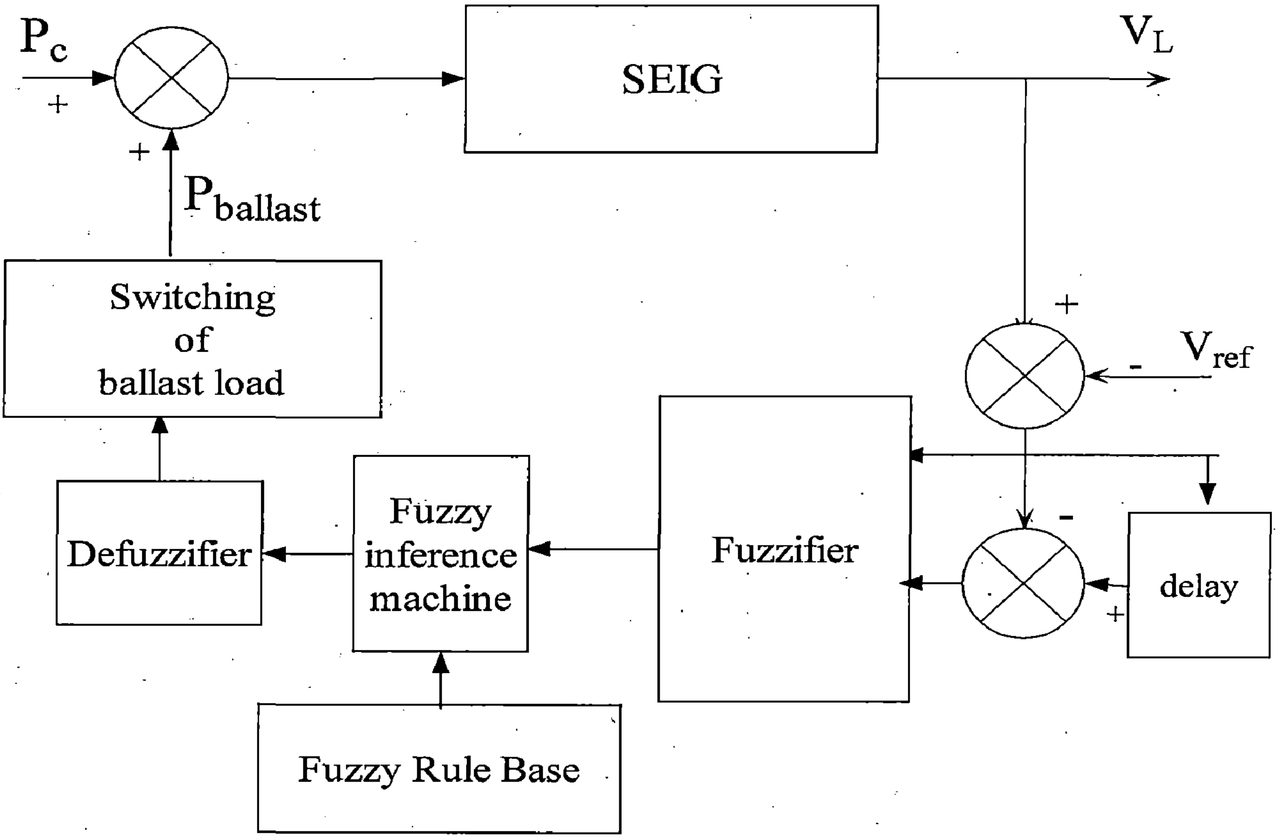


Figure 5.1: Block diagram of Fuzzy load controller and SEIG system.

5.3.2 Membership function

The crisp value of input is changed into fuzzy by membership function. Here triangular membership function is used. The inputs of fuzzy logic controller are respectively, error, which is equal to the set point minus the process output (load voltage) and, error change, which is error from the process output minus the error from last output.

The universe of disclose of the input variables is partitioned into 13 linguistic labels, while the output is in two, ON or OFF of the switches. Linguistic labels for error or error change is shown in Figure5.2.

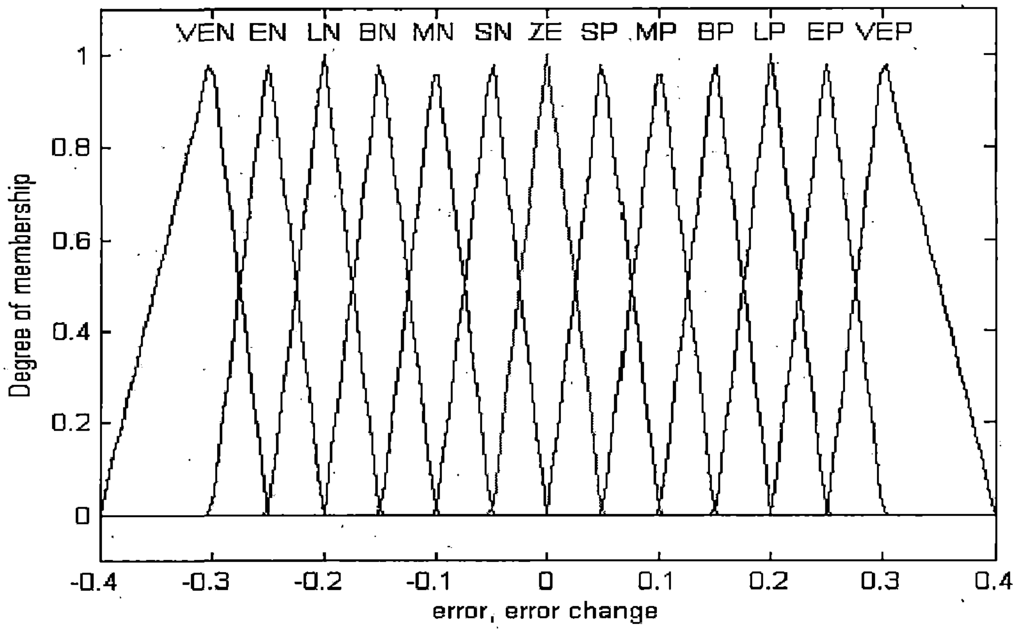


Figure5.2: Degree of membership of fuzzy controller inputs

5.3.3 Fuzzy rule base

Each input variable can take any of the 13 linguistic values; therefore total 169 rules are possible for these two inputs. Here, 33 rules are used for controlling the load voltage of series compensated SEIG. Rules are expressed in IF-THEN manner as discussed in chapter2.

5.3.4 Inference engine

Fuzzy logic controller in this project incorporates Mamdani's implication method of inference, which is one of the most popular methods in fuzzy control application. The first phase of Mamdani's implication involves min-operation since the antecedent pairs in the rule are connected by a logical 'AND'. If kth rules are like this:

If (x_1 is A_1^k and x_2 is A_2^k), then (y is C_k)

Then all the rules are aggregated using a max-operation as shown in equation 5.1.

$$m_c(y) = \max_k \left[\min \left[m_{A_1^k}(x_1), m_{A_2^k}(x_2) \right] \right] \qquad k = 1, 2, \ldots\ldots, n \qquad 5.1$$

Where,

n= Number of fuzzy rules.

5.3.5 Defuzzification technique

The output of fuzzy controller is changed into crisp value by defuzzifier. Different type of defuzzification technique is discussed in detail in chapter 2. Here, in fuzzy logic controller, center of area method of defuzzification is used.

5.4 Rule base design

For composing rules, some level of understanding about system is necessary. The most basic way of the constructing the rule base is by trial and error. The design of fuzzy logic controller can also be based on conventional controllers such as PID. Here, for governing the load voltage of series compensated SEIG fuzzy logic controller is designed based on PI controllers. The rule base is constructed from the control law of PI system.

5.4.1 PI control

The proportional-integral (PI) controller is a lag compensator characterized by the transfer function

$$G(s) = K\left(1 + \frac{1}{T.s}\right) \qquad 5.2$$

Where,

G(s) = gain

K = control parameter

T = time constant

The control action of a PI controller is defined by the following equation:

$$u_{PI} = K_p.e + K_I.\frac{1}{T}\int_0^t e.dt \qquad 5.3$$

Where,

K_p = proportional sensitivity or gain

T = integral time

u = control signal

e = error

Differentiating of equation gives

$$\frac{du}{dt} = K_p.\frac{de}{dt} + K_I.e \qquad 5.4$$

In discrete-time system, equation can be written as

$$u(kT) - u(kT - T) = K_p.\{e(kT) - e(kT - T)\} + K_I.e(kT) \qquad 5.5$$

Or,

$$\Delta u = k_p.\Delta e + K_I.e \qquad 5.6$$

So by using two inputs one error and other error change fuzzy logic controller can build like PI.

5.4.2 PI-like fuzzy control

The control low in equation 5.6 is not in fuzzy terms. In order to design a fuzzy controller these two inputs error and error changed are changed in linguistic labels. The control output is also changed in linguistic labels. The corresponding PI control law in IF-THEN rule has the form:

If (e is A and Δe is B), then (u is C)

Where,

A is any linguistic value in e

B is any linguistic value in Δe

C is any linguistic value in u

The table 5.1 shows all the fuzzy rules used for controlling the load voltage of series compensated capacitor excited induction generator.

Table5.1: Fuzzy rule base for fuzzy logic controller

							Δe							
		VEN	EN	LN	BN	MN	SN	ZE	SP	MP	BP	LP	EP	VEP
	VEN													
	EN													
	LN							A' B C				A B C'		
	BN				A' B' C									
	MN			A' B C	A' B C	A' B' C								
e	SN			A' B C'	A B' C		A' B C'		A' B C'	A' B' C'				
	ZE			A' B C'		A' B C	A' B' C	A' B' C'		A' B' C'				
	SP							A' B' C'		A' B C'	A' B' C			
	MP	A' B' C'		A' B C'		A' B C		A' B' C'	A'B' C'		A'B' C	A' B' C'	A' B' C'	A' B' C'
	BP		A B' C'			A B' C'		A B' C		A' B C'				
	LP							A' B' C'						
	EP	A B' C				A'BC		A B C						
	VEP													

Where,

A, B, C mean switch ON the switch A, B, C respectively.

A’, B’, C’ mean switch OFF the switch A, B, C respectively.

5.5 System Configuration

The proposed scheme consists of a series compensated capacitor excited induction generator driven by uncontrolled hydro turbine. The series capacitance is connected in short shunt. The capacitor excited induction generator has two types of loads one consumer load which is variable and other is ballast load. The ballast loads are the binary weighted resistors which are connected parallel to the consumer load. The switching of these ballast loads are done by fuzzy controller such that total power output of generator remain constant so that voltage and frequency controlled. A brief discussion of each is as follows:

5.5.1 Series compensated capacitor excited induction generator

Here, fuzzy model of series compensated SEIG is used for analysis. For a particular set of inputs it gives value of load voltage. The inputs of this fuzzy model of induction generator are speed, power factor, consumer load, value of shunt capacitance and series capacitance etc. Output of fuzzy SEIG is load voltage. For uncontrolled hydro turbine the speed of turbine is constant, and assuming the consumer loads is resistive. So for fixed value of series and shunt capacitance, all the input of this fuzzy SEIG is constant except power output which depends on consumer loads. The detail of building fuzzy model of series compensated SEIG is discussed in previous chapters. The fuzzy model of SEIG is shown in Figure 5.3. It is builded in MATLAB fuzzy logic toolbox.

5.5.2 Ballast load

The SEIG has two types of loads, first consumer load which is variable and other ballast load which is varied such that total load seen by generator terminal is constant. The ballast loads are resistive in nature. These are binary weighted and connected in parallel. The values are binary weighted so that number of different combinations can be achieved by this. The switching of these ballast loads is controlled by fuzzy logic controller, which sense error and error change in load voltage. The value of binary loads used here are 2.5, 5, and 10 per unit.

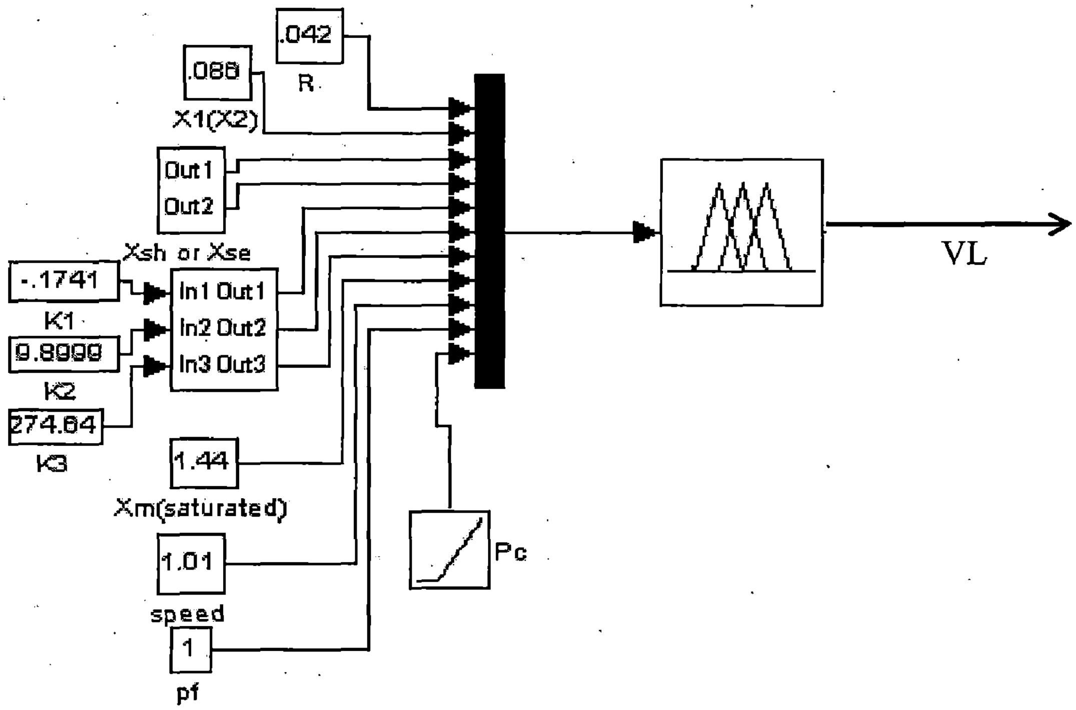


Figure5.3: Fuzzy model of series compensated SEIG

5.6 Simulation results

The fuzzy based series compensated capacitor excited induction generator with ballast load is shown in Figure 5.4. The whole system is simulated in MATLAB 6.5. There are three ballast load connected parallel to consumer load by switch 1, 2 and 3 respectively. The ON/ OFF of this switch is done by fuzzy controller. When fuzzy controller output is greater than a particular value, then these switches become ON, otherwise these ballast loads are open circuit i.e. delivering zero power.

Figure5.5 shows the variation of load voltage for short shunt capacitor excited induction generator without ballast load for machine-1. The values of p.u. series and shunt capacitive reactance is 0.31 and 1.5 respectively. Speed is assumed 1.01 p.u. where base speed is taken synchronous speed of the machine. From Figure5.5 it is clear that load voltage dips at low load condition, after that it increases. Figure5.6 shows the load voltage after using fuzzy logic controller. Without ballast load the voltage dips up to 0.74

p.u, but after using ballast load dip is reduces to 0.85 p.u. Thus significant improvement can see in load voltage.

Figure 5.7 and Figure 5.8 shows the variation of load voltage with output power. In first case ballast load are not used, but in other ballast loads are switched ON/OFF by fuzzy logic controller. The values of series and shunt capacitive reactance used for analysis are .3 and 1.55 respectively. Speed of prime mover remains constant equal to 1.01 p.u. and consumer loads are assumed purely resistive in nature. Without ballast load control the voltage dips to 0.6 p.u. after using ballast load it improves to 0.75 p.u.

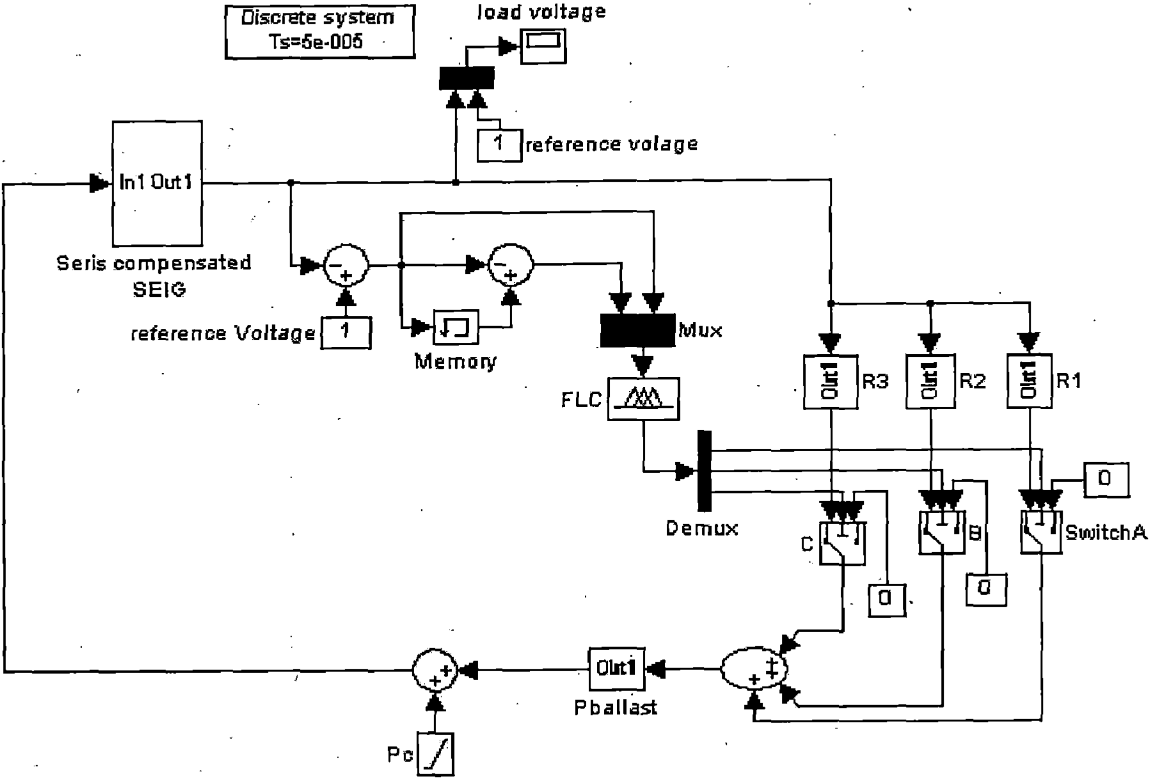


Figure5.4: SEIG with ballast load controller

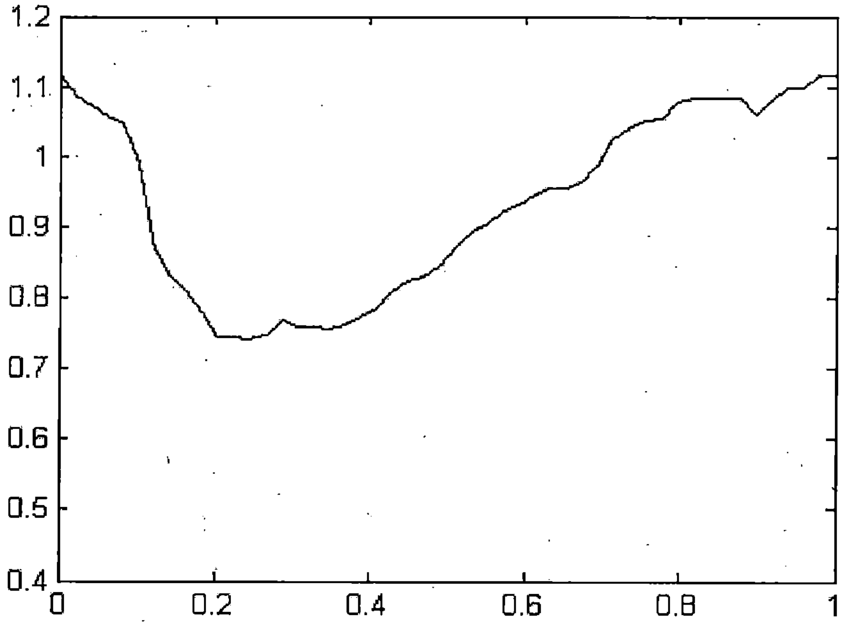


Figure 5.5: Load voltage variation without ballast load control

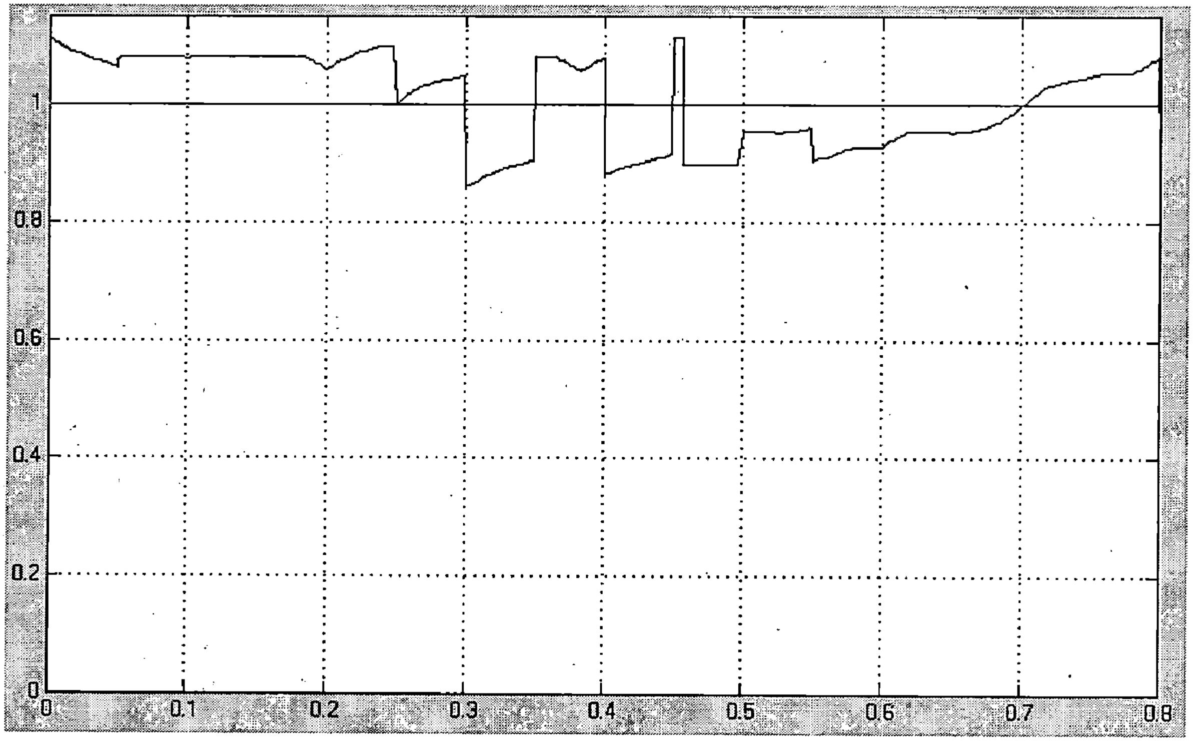


Figure 5.6: Load voltage variation of Machine1with ballast load control

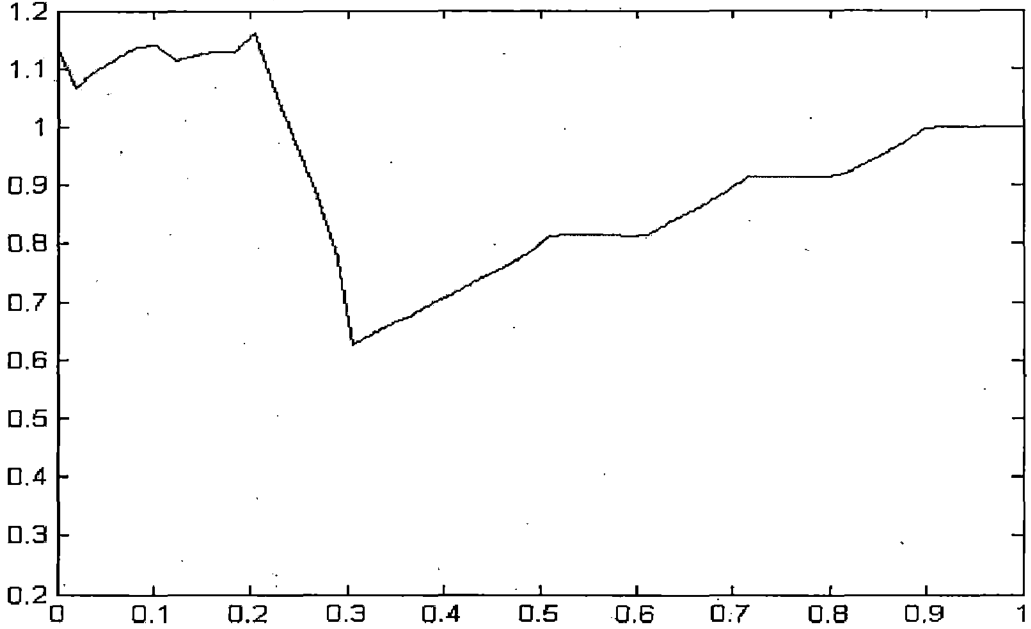


Figure 5.7: Load voltage variation of Machine 2 without ballast load.

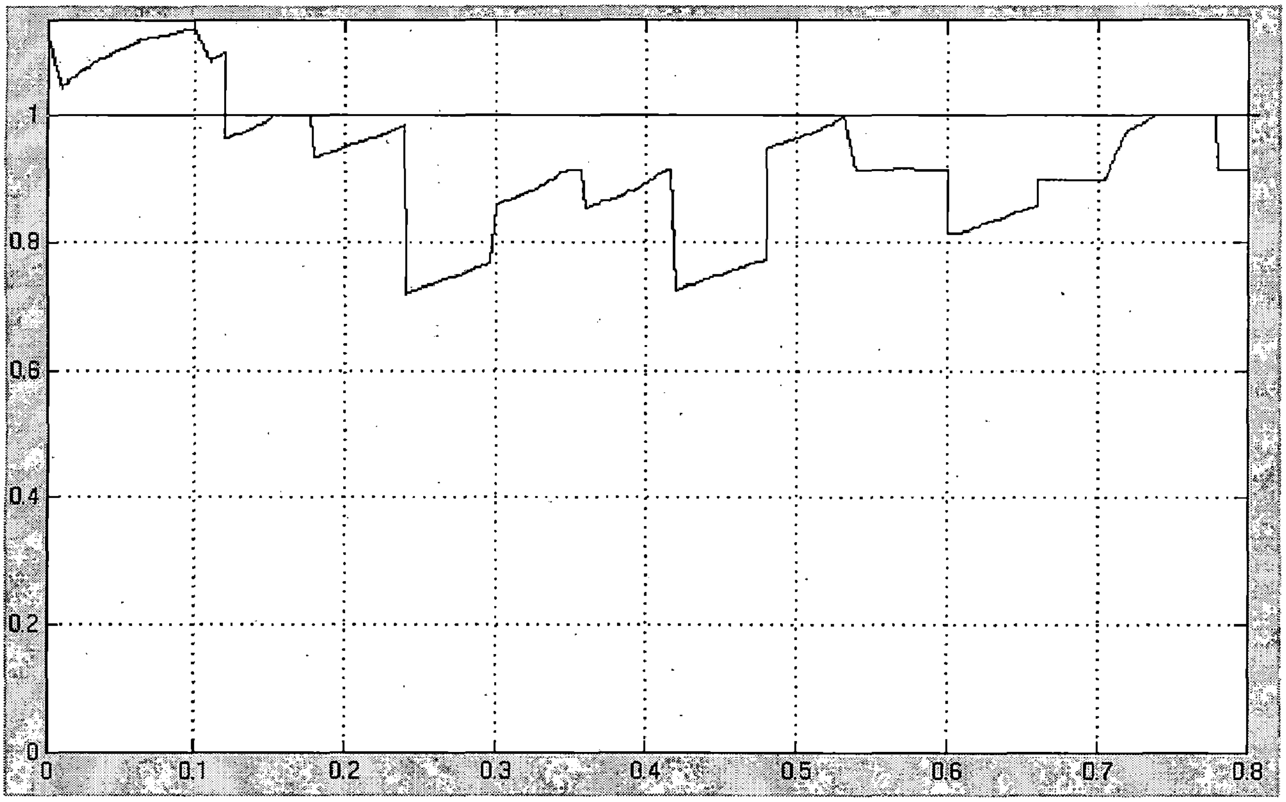


Figure 5.8: Load voltage variation of Machine 2 with ballast load

Chapter 6

Conclusion and Future Scope

6.1 Conclusion

The project presents modeling, simulation results of series compensated capacitor excited induction generator. The series compensated capacitor excited induction generator is modeled by using fuzzy logic, which is easy to model and suitable for analyzing the steady state performance of SEIG. The steady state performance of series compensated capacitor excited induction generator gives many important aspects for designing an induction generator for suitable voltage regulation. These are:

1. The high cage rotor resistance the voltage regulation is poor in compare to low cage rotor resistance. So in induction generator the rotor resistance should be low for better voltage regulation. In motors high rotor resistance is necessary for starting purpose.
2. In capacitor excited induction generator, voltage dip is less for low value of leakage reactance in compare to high value of leakage reactance. Thus for better voltage regulation in induction generator the leakage reactance should be less whereas in motor case high leakage reactance is desirable to limit stating current.

The variation of load voltage with output power in series compensated SEIG has a characteristic like 'V' curve. The voltage is low in low load condition but in high load the load voltage is increases with output power. The voltage varies with series and shunt capacitor variation. Therefore it is important to take suitable value of series and shunt capacitors for better voltage regulation.

The low voltage in low load condition in SEIG is controlled by fuzzy controller, which switch ON/OFF the ballast load such that the total output power of SEIG remains constant. A fuzzy controller offers following advantages:

1. They don't require a detailed mathematical model for algorithm.
2. By using different sets of control rules, fuzzy controller can operate for large range of inputs.

6.2 Future Scope

1. In present work only the fuzzy based short shunt induction generator is modeled and analyzed .In future long shunt model can be developed or can be use of adaptive fuzzy model which is not used here.
2. Protection scheme should be developed for more utilization of induction generator in non-conventional energy sources.

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Appendex-1

Values of coefficients C_1-C_9, D_1-D_{12} and K_1 –K_{10}

$C_1 = -R_L (X_1 + X_2) + X_L (R_1 + R_2)$

$C_2 = -R_L X_1 X_2 + X_L (-R_2 X_1 + R_1 X_2)$

$C_3 = v (R_L (X_1 + X_2) + X_L R_1)$

$C_4 = v X_2 (R_L X_1 + X_L R_1)$

$C_5 = X_c (R_L + R_1 + R_2) + X_{cs} (R_1 + R_2) + R_L X_{se}$

$C_6 = X_C (R_2 (X_L + X_2) + X_2 (R_L + R_1) + X_{cs} (R_2 X_1 + R_1 X_2) + R_1 R_2 R_L) + R_L X_{se} X_2$
$+X_L R_2 X_{se}$

$C_7 = -v (X_c (R_L + R_1) + X_{cs} R_1) – v R_L X_{se}$

$C_8 = -v X_2 (X_c (R_L + R_1) + X_{cs} R_1) – v R_L X_2 X_{se}$

$C_9 = -X_c X_{cs} R_2 - X_c R_2 X_{se}$

$D_1 = -X_L (X_1 + X_2)$

$D_2 = -X_1 X_2 X_L$

$D_3 = v X_L (X_1 + X_2)$

$D_4 = v X_1 X_2 X_L$

$D_5 = X_c (X_L + X_1 + X_2) + X_{cs} (X_1 + X_2) + R_L R_2 + R_1 R_L + X_L X_{se}$

$D_6 = R_L (R_2 X_1 + R_1 X_2) + X_L (R_1 R_2 + X_c X_2) + (X_{cs} + X_c) X_2 X_1 + X_2 X_L X_{se}$

$D_7 = -v (X_c X_L + (X_{cs} + X_c) (X_1 + X_2) + R_L R_1) - v X_L X_{se}$

$D_8 = -v X_2 ((R_1 R_L + X_c X_L) + (X_{cs} + X_c) X_1) – v X_2 X_L X_{se}$

$D_9 = -X_c X_{cs} - X_c X_{se}$

$D_{10} = -X_c R_2 (R_L + R_1) + X_{cs} (R_1 R_2 + X_c X_2) – R_L R_2 X_{se} - X_c X_2 X_{se}$

$D_{11} = v X_c X_{cs} + v X_c X_{se}$

$D_{12} = v X_c X_{cs} X_2 + v X_c X_2 X_{se}$

$K_1 = -C_1 D_2 + D_1 C_2$

$K_2 = - (C_1 D_4 + C_3 D_2) + (C_4 D_1 + D_3 C_2)$

$K_3 = - (C_1 D_6 + C_3 D_4 + C_5 D_2) + (C_6 D_1 + C_4 D_3 + C_2 D_5)$

$K_4 = - (C_1 D_8 + C_3 D_6 + C_5 D_4 + C_7 D_2) + (C_8 D_1 + C_6 D_3 + C_4 D_5 + C_2 D_7)$

$K_5 = (C_1D_{10} + C_3D_8 + C_5D_6 + C_7D_4 + D_2) + (C_9D_1 + C_8D_3 + C_6D_5 + C_4D_7 + C_2D_9)$

$K_6 = (C_1D_{12} + C_3D_{10} + C_5D_8 + C_7D_6 + D_4) + (C_9D_3 + C_8D_5 + C_6D_7 + C_4D_9 + C_2D_{11})$

$K_7 = -(C_3D_{12} + C_5D_{10} + C_7D_8 + D_6) + (C_9D_5 + C_8D_7 + C_6D_9 + C_4D_{11})$

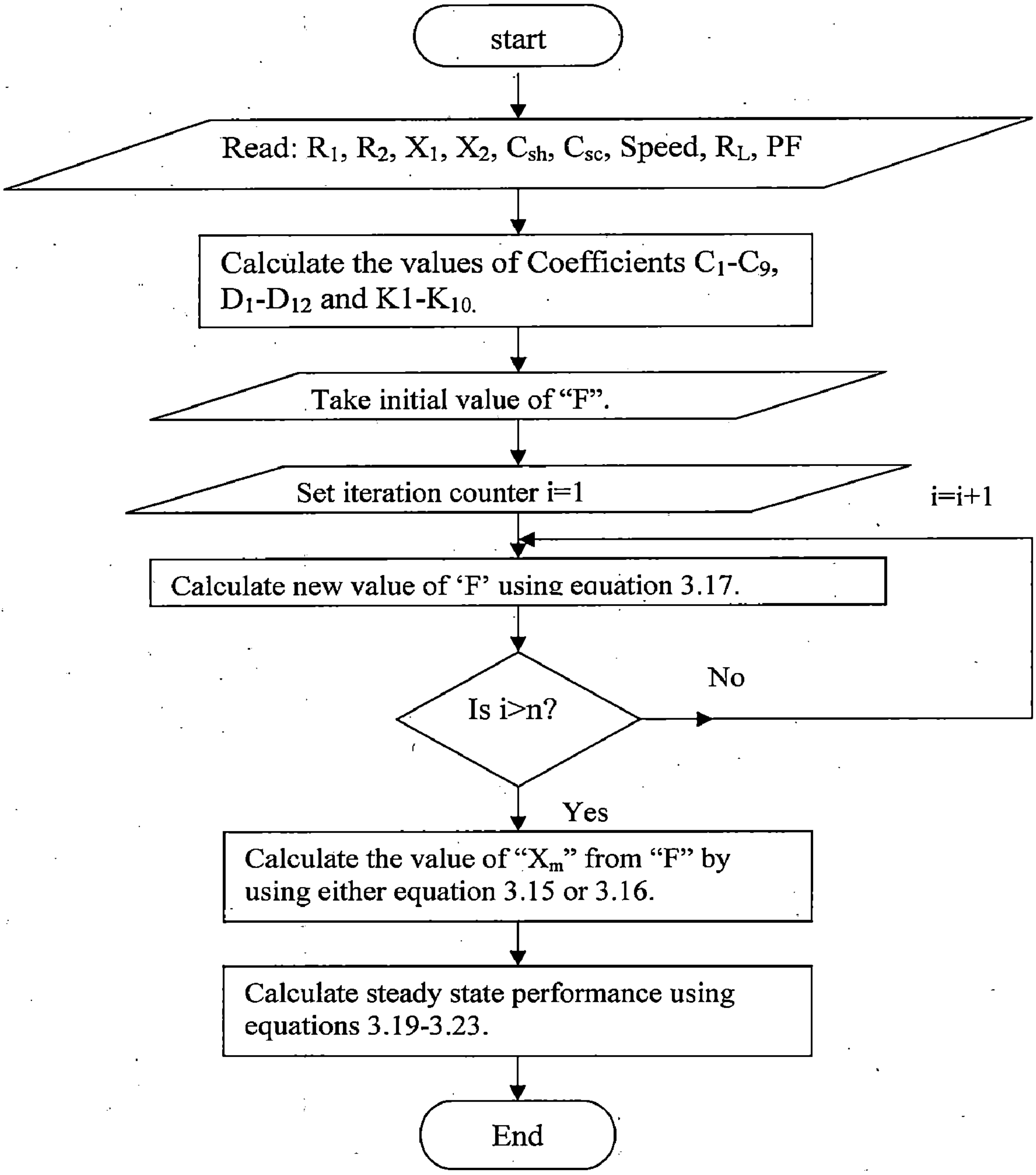
$K_8 = -(C_5D_{12} + C_7D_{10} + D_8) + (C_9D_7 + C_8D_9 + C_6D_{11})$

$K_9 = -(C_7 D_{12} + D_{10}) + (C_9 D_9 + C_8 D_{11})$

$K_{10} = -D_{12} + C_9 D_{11}$

Appendex-2

Flow-chart of iteration method



Appendex-3

Rule Base for fuzzy Model of Series compensated capacitor excited induction generator:

R2	X	Xsh	Xse	Xm	K1	K2	K3	N	p.f.	Pout	VL	Is	IL
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2	1	2	2	2	2	2	2	1	3	7	6	6	7
2	1	2	2	2	2	2	2	1	3	8	7	6	8
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2	1	2	2	2	2	2	2	1	3	10	7	7	9
2	1	2	2	2	2	2	2	1	3	11	9	7	9
2	2	2	2	2	2	2	2	1	3	1	8	3	1
2	2	2	2	2	2	2	2	1	3	2	7	3	2
2	2	2	2	2	2	2	2	1	3	3	5	3	4
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2	2	2	2	2	2	2	2	1	3	11	8	8	11
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