APPLICATION OF SEIG FOR DC MICRO-GRID USING DIFFERENT CONTROL SCHEMES

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CANDIDATE'S DECLARATION

I, (Sahil Bansal), Roll No. 2K16/C&I/16 of M. Tech (Control & Instrumentation), hereby declare that the project Dissertation titled "APPLICATION OF SEIG FOR DC MICRO-GRID USING DIFFERENT CONTROL SCHEMES" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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ABSTRACT

The generation of electricity from wind energy involves the usage of Induction Machines. Induction machines can be operated successfully as induction generators if there is sustained availability of excitation which is possible by connection of capacitor banks. Self-excited induction generators (SEIG) are preferred mostly in isolated areas to generate electrical energy.

This dissertation work proposes the creation of fixed DC grid voltage sourced from SEIG operating under variable speed and load conditions using power electronics interfaces and suitable control schemes. For the designing of the proposed system, first step is to study and analyse the steady-state characteristics of the chosen Induction Generator. The value of capacitor bank is chosen according to the non-linear magnetisation characteristics of the Induction machine. Two different topologies are designed for the achievement of proposed work. One by using Uncontrolled Diode Bridge Rectifier (DBR) and DC-DC converter and the other by using Hysteresis Current Controller and Pulse width Modulated (PWM) Rectifier system. For both the topologies, MATLAB Simulink® models are designed for the implementation of control strategy. Three Different controllers namely PI , ANN and ANFIS are employed in MATLAB® to get the desired results.

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Lastly, I would like to thank all those whose names may not have appeared here but whose contribution has not gone unnoticed. I would like to thank all of them, for their help in various ways.

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NOMENCLATURE

a	Per unit frequency.
b	Per unit speed.
C	Excitation capacitance per phase.
E_1	Air gap voltage per phase at rated frequency.
E_2	Rotor emf per phase referred to stator.
E_a	Air gap voltage per phase = aE1.
f	Rated frequency.
I_1	Stator current per phase.
I_2	Rotor current per phase, referred to stator.
I_b	Base current.
I_L	Load current per phase.
I_m	Magnetising current per phase.
$I_{Lp\ u}$	Per unit load current.
P_{out}	Output power.
R	Load resistance per phase.
R_1	Stator resistance per phase.
R_2	Rotor resistance per phase, referred to stator.
S	Generator slip.
V	Terminal voltage per phase.
V_{pu}	Per unit voltage.
V_{ref}	Reference voltage (= 1.0 per unit).
X_1	Stator reactance per phase.
X_2	Rotor reactance per phase, referred to stator.
X_c	Capacitive reactance due to C at rated frequency.
X_m	Magnetising reactance per phase at rated frequency.

CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

Electricity is one of the most important basic need of every human being living on Earth. According to World Bank, database in 2016 around 97% of urban population has access to electricity but only 77.3% of rural population is accessing this basic need. Even in India 14.5% of population still has no access to electricity. To provide this utility in this growing era is not possible only by using fossil fuels. Also, fuel based resources are very limited, so there is an urgent need for the world to switch to renewable sources of energy which can be used again and again.

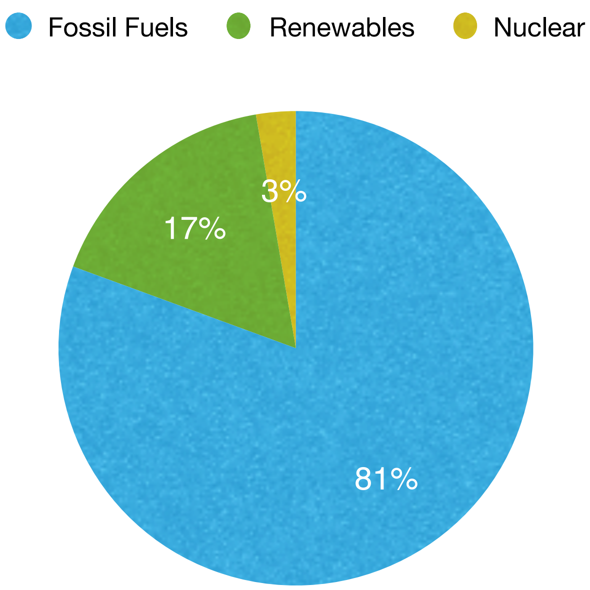


Figure 1.1: Energy Development Chart Of World In 2016

In recent times, distributed generation (DG) based on renewable sources has captivated the industrial sector globally and has become a leading research area. Electricity on a small scale can be produced by distributed generation using wind, solar energy or biomass as a source of energy. Therefore, there is a strong focus on using renewable energy as a safe alternative source of energy, especially because in future it can play a dominant role in the world's energy production and help to tackle the increase of global warming caused by fossil energy. Not only the renewable resources are non-polluting and non-depleting but also they can be installed anywhere accordingly to their availability.

With the increase in distributed generation sources, comes the concept of Micro-Grids which involves the integration of various non-conventional sources to meet the demand loads. A micro-grid is a cluster of DG sources, loads, and interconnected storage devices that can be operated as a flexible single system with the help of power electronic control interfacing. Micro-Grids are installed closer to the consumers. They are mainly used to supply electricity to small towns, industrial areas and universities. They can be operated in stand-alone mode and can also be connected to a grid. Micro-grids can be configured in three types.

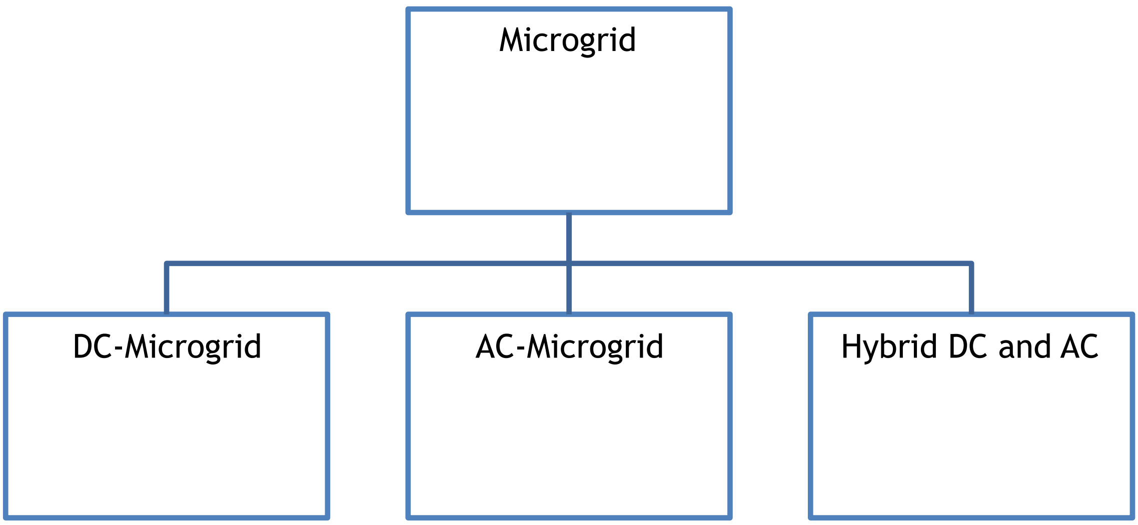


Figure 1.2: Types Of Micro-Grid

The DC micro-grid presents several operational advantages.

- Mostly DG systems employed in the micro-grids are based on DC supply. Connecting storage devices to DC micro-grid only require voltage regulator as they have DC output voltage, compared to AC based micro-grid which needs synchronisation of the system by matching the magnitude and phase of grid voltage and frequency.
- Most loads are conventional electronic loads like TVs, computers, etc that are connected to a DC micro-grid. So there is no for need for multiple conversions stages of the power system.
- The DC micro-grid uses less wiring, this makes it more efficient and reliable.
- In DC micro-grids, the voltage control is concerned only with active power flow, as reactive power flow in DC systems does not exist.

Increasing trend in the number of power generation units and load devices operating with DC current, has led to the thought of believing in DC Micro-grid system as potential drivers of the present world. However, the implementation and standardisation of DC distribution systems faces critical challenges, owing to the market inertia offered by AC systems.

Implementation of micro-grid using power electronics interfaces needs a control system to preserve the energy output and the quality of power and to provide flexibility. Conventional PID controllers are the most vastly used controllers. Recent years have been dominated by Artificial Neural Network Intelligence (ANN) and Fuzzy Logic Controller (FLC). Neural Topology does not need mathematical modelling of the system controlled and on the other hand Fuzzy logic Controller has played a very important role in the design and development of real time applications. The adaptive-network-based fuzzy inference system (ANFIS) combines the strength of both these controllers and results in highly effective controller which is capable of adaptive learning in control of highly non-linear systems.

1.2. ORGANISATION OF REPORT

This dissertation work proposes the creation of fixed DC grid voltage sourced from SEIG operating under variable speed and load conditions using power electronics interfaces and suitable control schemes. Chapters are divided on the following basis.

- Chapter 1 covers the Introduction to the report.
- Chapter 2 covers the Literature Review of the study material that has been referred to during the course of work.
- Chapter 3 introduces the basic concepts and modelling of Induction Generator.
- Chapter 4 covers the system design, implementation and results of DC Micro-grid using Uncontrolled Diode Bridge Rectifier with DC-DC Converter on MATLAB Simulink® using suitable control strategy.
- Chapter 5 covers the system design, implementation and results of DC Micro-grid using PWM based Rectifier system on Simulink® using different control strategies.
- Chapter 6 is the Conclusion and Future Work where all the work done is been concluded and the future scope of this work is presented.

CHAPTER 2

LITERATURE REVIEW

The alarming rate of increase in environmental pollution has become a major concern in daily life of people. Scarcity of conventional resources and their inability to create clean energy has led people to think, create, develop new innovative technologies for generating energy that is clean and non-depleting [1]. Environment friendly energy production includes solar energy along with wind power , hydro power, tidal energy and many more sources. Out of these renewable energy sources, Wind is a clean source of renewable energy that besides being free, produces no air or water pollution. This has sparked attentions of the researchers for renewable energy. For distributed generation from renewable energy sources like wind, Self-Excited Induction Generator (SEIG) has become prime choice. Induction Machines operating at speeds higher than the synchronous speed behave active power generators but requires lagging VARS for its operation. This reactive power demand is met by the use of capacitor banks [2]. Due to adverse geographical conditions, in remote rural areas, the utility of SEIG as standalone machine is very crucial as installation of transmission lines and distribution systems is very cumbersome. In comparison to the most commonly used synchronous generator, Induction generators has advantages owing to its simple and rugged structure, like low cost, absence of DC excitation, less maintenance, etc. The most important disadvantage of using SEIG which restricts its usage is its lack of ability to control the voltage output and frequency under variable load and speed change in stand-alone system. [3].

For the designing of the proposed system, first step was to study and analyse the steady-state characteristics of the chosen Induction Generator. Many researchers have used the conventional circuit of an induction motor, to analyse and estimate the steady-state performance of the stand-alone SEIG. The two most used models of SEIG are the impedance model and the admittance model [4-6]. Both these models fail to effectively represent SEIG during generating operation without the presence of an active source. A new equivalent circuit model [7] is mentioned for the representing induction generator to analyse the steady-state characteristics performance of the stand-alone SEIG. The steady-state characteristics performance of the stand-alone SEIG was analysed with the help of the given equivalent circuit representation. The parameters of the Induction machine used was chosen according to the given induction machine working in Constant voltage and fixed frequency mode making use of Genetic algorithm [8]. The value of capacitor bank was chosen according to the non-linear magnetisation characteristics of the chosen Induction machine. Also the experimental results obtained in the model [9] were verified on MATLAB Simulink® and PSIM®.

In the recent times, much development in the design and operating characteristics of induction generator has taken place to enhance their utility under variable speed and load conditions in stand-alone mode. The generated output voltage and frequency of the SEIG is very sensitive to variations in prime mover speed and loading conditions. To make SEIG useful for loads, apart from frequency insensitive loads, conversion of AC voltage to DC voltage is proposed. DC micro-grid is an attractive option for distributed generation units as they present many advantages like no worries for reactive power and harmonics related problems, comparatively few stages of power conversion, and convenience in connecting energy storage units, like battery and plug-in EV’s, etc. Various control algorithms have been proposed by the researchers to get constant DC output from SEIG [11-21].

Researcher [11] has designed a dual-stage conversion scheme which consists of excitation causing system and a diode based bridge rectifier (DBR). To maintain output voltage of SEIG at a constant value reactive current is supplied with a series connected power converter to a AC powered capacitor. The capacitor works as a reactive power supplier and it also helps in suppressing the current harmonics created by diode rectifier. As the results suggest, this system is limited only to small range of speed for the SEIGs.

Researcher [12] has designed a 4-kW hybrid system based on wind energy for a 3-kW dc load. In this configuration, a three-phase operated diode based bridge rectifier (DBR) and a dc–dc converter have been used for charging of battery, and supplying power to dc load sourcing from wind based SEIG.

Researcher [13] has proposed a scheme with single-stage conversion, in which an electrolytic capacitor is used to support DC bus. This scheme uses a voltage sourced converter (VSC). A ramp reference with a specific slope is chosen for a successful voltage building up process of DC bus. In following paper, field-oriented control method have been used to design voltage and current controllers resulting in improved reliability of voltage during starting process in SEIGs [14].

Researcher [15] have used a current controller and a phase-locked-loop (PLL) circuit for generating pulses to control PWM based voltage source converter. DC loads are being supplied from SEIG. In this scheme, a Digital signal processing based control (closed-loop) is employed for the operation of the converter for making voltages at DC terminals constant. In a subsequent paper, a hybrid excitation unit is used to excite SEIG. Capacitor bank in combination with active power filter (APF) can make the generator able to supply currents for DC loads [16].

Jayaramaiah et al. [17] have presented a scheme for voltage regulation of SEIG. The scheme consists of two PI controllers along with one current controller based on hysteresis. Firstly the researcher makes use of a current controlled VSI, and in the next process the inverter current references have been controlled by controlling instantaneous real power and reactive power [18]. Both processes have employed a battery connected across the DC terminals. Both schemes are used for operating AC loads at constant voltage and fixed frequency.

Kuo et al. [19] has presented a hybrid vector controlled IM model, operating under non-linear and unbalanced loading conditions. CC-VSI is used for the regulation of the voltage. By comparing the actual value of signal and the reference value of current signal within a small fixed band of hysteresis current, the switching patterns are generated. This scheme employs a battery across the DC side terminals of the inverter.

Karthigaivel et al. [20] have developed a scheme for controlling firing angle. Wind driven SEIGs are used to supply battery loads by employing the three-phase semi-converters.

Some researchers have analysed the dc micro-grid system performance with different levels of voltage and appropriate power electronic interfaces based on many important factors like thermal limit, efficiency, voltage drop, safety issues and cost[21]. In consideration of various factors mentioned above, it was concluded for low-power requiring applications like residential systems and telecommunication systems, a voltage system operating at low levels of 24/48 V gives desired results [22].

Researcher [23] has presented a three phase DBR connected to a dc–dc converter to convert the AC output of SEIG into DC voltage of DC micro-grid bus. A method to track the maximum power of WECS for dc micro-grid is also presented.

Researcher [24] has fully described the implementation and configuration of the control scheme to convert the output of SEIG to a controllable DC voltage. The insulated gate bipolar transistors (IGBTs) are used as switches in the circuit of PWM rectifier. The gate pulses are appropriately adjusted by adjusting its number and width. Hysteresis based current controller is used in this scheme.

The conventional PI controllers can replaced by more advanced Artificial Intelligence based controllers Artificial Neural Network (ANN) and Adaptive-network-based fuzzy inference system (ANFIS). The capability of Artificial Neural Network (ANN) is enhanced learning of processes and of Fuzzy Logic Controller (FLC) is to effectively handle the uncertainties [25]. ANFIS combines the strength of both these controllers and results in highly effective controller which is capable of adaptive learning in control of highly non-linear systems. Major difficulty is faced in selection of suitable membership functions, fuzzy rules and universe of discourse as it involves conventional Trial error. The main benefit of using ANFIS approach is the automatic realisation of fuzzy systems using neural network methods. ANFIS is very advantageous in modelling of systems that are highly non-linear[26].

All these literatures were analysed to understand the basic working of Induction machines in generating mode. This helped in designing different control strategies with suitable parameters to be employed between SEIG and DC micro-grid.

CHAPTER 3

BASICS OF INDUCTION GENERATOR

3.1. WORKING OF INDUCTION MACHINE

Induction generator and induction motor are similar to each other both mechanically and electrically. When the shaft is rotated at speeds higher than the synchronous speed Induction machines produce electrical power and behave as induction generators. Induction generators finds their utility in wind turbines and micro hydro-plant installations due to their capability to generate power even at fluctuating speeds. The construction of Induction generator is simpler than other generator types in both mechanical and electrical aspects. Generally there are two methods employed for the excitation of the generator, either electrical grid can provide external reactive supply or externally connected capacitor bank can be used to supply the reactive vars. Rotor currents are induced by the rotating magnetic flux of the stator. Generating or motoring mode of the induction machine is determined by the rotating speed comparison of rotor and flux. If the rotor is ahead of rotating flux, the machine operates in generating mode producing power at synchronous frequency. If the rotor is behind the flux, it acts like a motor. In induction generator's standalone operation, capacitor bank connected to the machine establishes the magnetising flux and in case of grid connected induction generator, magnetising current is drawn from the grid. They are mostly suitable for wind generating stations with speed being a variable factor.

Synchronous generators are used for large scale power generation whereas induction generators are mainly used these days for distributed generation owing to their many advantageous features. Induction generators do not need separate DC excitation source like synchronous generators. Induction generators are extremely useful for generation in remote rural areas as they are relatively easy to set-up, can work in stand-alone mode and are very economical.

3.1.1. Induction Generator : Advantages And Disadvantages

Induction generators are the preferred choice for the distributed generation units owing to its many advantages over other generators. But every advantageous thing possesses some disadvantages which is needed to be overcome to fully exploit its usage.

Advantages of the Induction generator

1. Simple, rugged and robust construction
2. Less maintenance
3. Less costly as compared to other generators.
4. Inherent protection for overloads
5. Absence of DC Excitation

Disadvantages of the Induction generator

1. Requires significant reactive vars for voltage build-up
2. Lagging power factor.
3. Not able to control the voltage output and frequency under variable load and speed change in stand-alone system.

The widespread usage and acceptability of SEIG is mainly dependent on the control scheme adopted to overcome the unacceptable voltage regulation and frequency variation, and its performance in handling dynamic and unbalanced loading conditions. The conventional synchronous generator and the induction generator in parallel operation supplements local power demand rises and also low cost power generation with improved power factor can be obtained.

3.1.2. Types Of Induction Generators

Classification of induction generators is done depending on rotor construction and excitation method. According to their type, they find their utility in different areas of interest.

On the basis of rotor construction IG's are classified into:

- Squirrel cage induction generator
- Wound rotor induction generator

3.1.2.1. Squirrel Cage Induction Generator (SCIG)

In SCIG, the rotor winding consists of copper or aluminium bars which are embedded in semi closed slots. These bars are short circuited at both ends by end rings. The rotor bars and rings are designed to take the shape resembling the cage of a squirrel. The bars at the rotor constitutes uniformly distributed rotor slot winding.

3.1.2.2. Wound Rotor Induction Generator (WRIG)

In the WRIG, the stator is similar to that of SCIG but the rotor slots also accommodate winding similar to the stator. The slips are not provided with power but their main purpose is to allow placement of series resistance. This improves the starting characteristics but results in more costly operation due to increased maintenance.

On the basis of excitement process IG's are classified as:

- Grid connected induction generator (GCIG)
- Self-excited induction generator (SEIG)

3.1.2.3. Grid Connected Induction Generator (GCIG)

The induction generator in grid-connected mode (GCIG) when driven above the synchronous speed generates real active power and takes the reactive power from the grid. It is also called autonomous system. The grid voltage and grid frequency governs the voltage and frequency respectively resulting in a simpler operation.

3.1.2.4. Self-Excited Induction Generator (SEIG)

The SEIG takes the reactive power from a capacitor bank connected across the terminals of stator of the induction generator for excitation process. A dual purpose is served by this capacitor bank for SEIG. It not only combats the machine inductance for voltage build-up but also helps in correction of the power factor of the induction generator. The generated output voltage and frequency of the SEIG is very sensitive to variations in prime mover speed and loading conditions. To make SEIG useful for loads, apart from frequency insensitive loads, conversion of AC voltage to DC voltage is proposed.

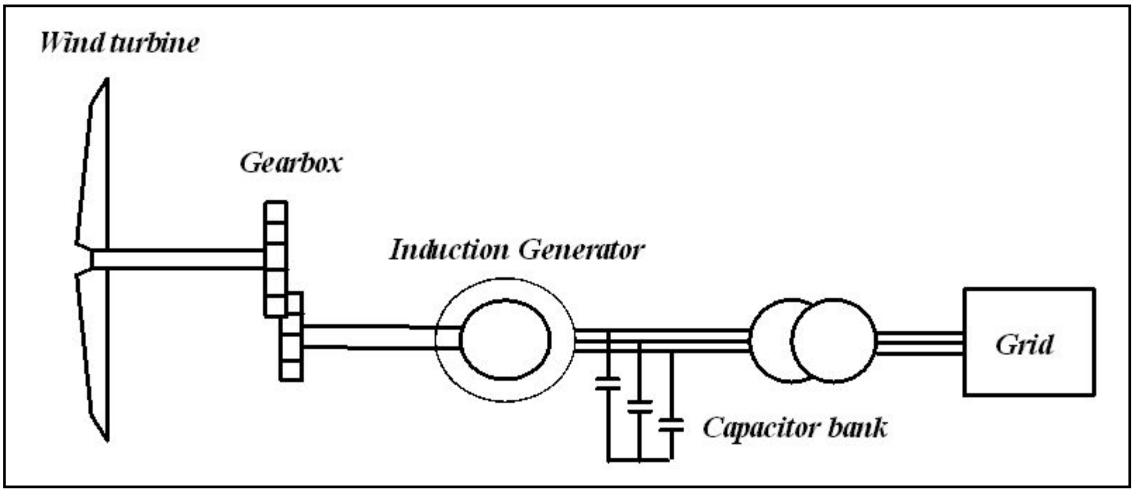


Figure 3.1: Self-Excited Induction Generator

Fig. 3.1 shows a self-excited induction generator connected to the wind turbine using suitable gear box. The capacitor bank is connected to supply reactive power for excitation purposes.

3.2. MODELLING OF SELF EXCITED INDUCTION GENERATOR

To study and analyse the steady-state operation of the self excited induction generator (SEIG), the equivalent circuit of Induction machine, as shown in Fig. 3.2 is represented.

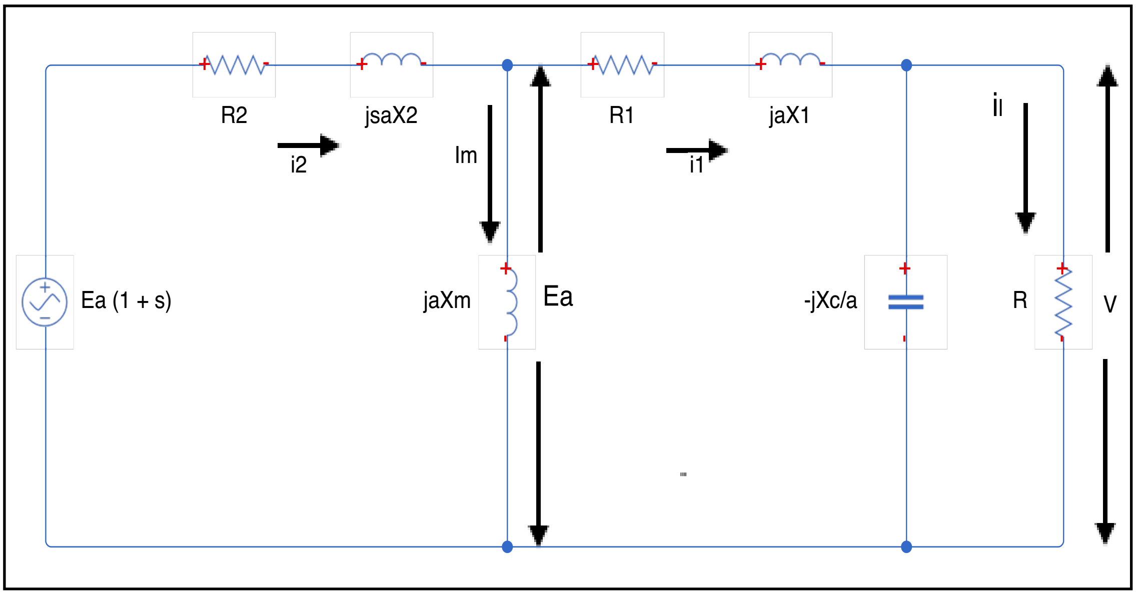


Figure 3.2: Per Phase Equivalent Circuit Representation For Seig

In fig. 3.2, per phase equivalent circuit of SEIG is represented. The source voltage is represented by E_a (1 + s). The rotor and stator side resistances and reactances are shown. The magnetising reactance of SEIG is shown as jaXm. The load is represented as parallel combination of per phase capacitance (used for the excitation and voltage build-up process) and resistive load.

This circuit may be modified to a even more practical and simplified format, as shown by Fig. 3.3, wherein the parallel combination of excitation capacitance and resistive load is transformed to series combination of R_L and X_L and similarly Ea (1 + s) represents the voltage source corresponding to electrical power through rotor transformed from mechanical power. By doing so, analysis of steady state characteristics of SEIG becomes more simpler an effective.

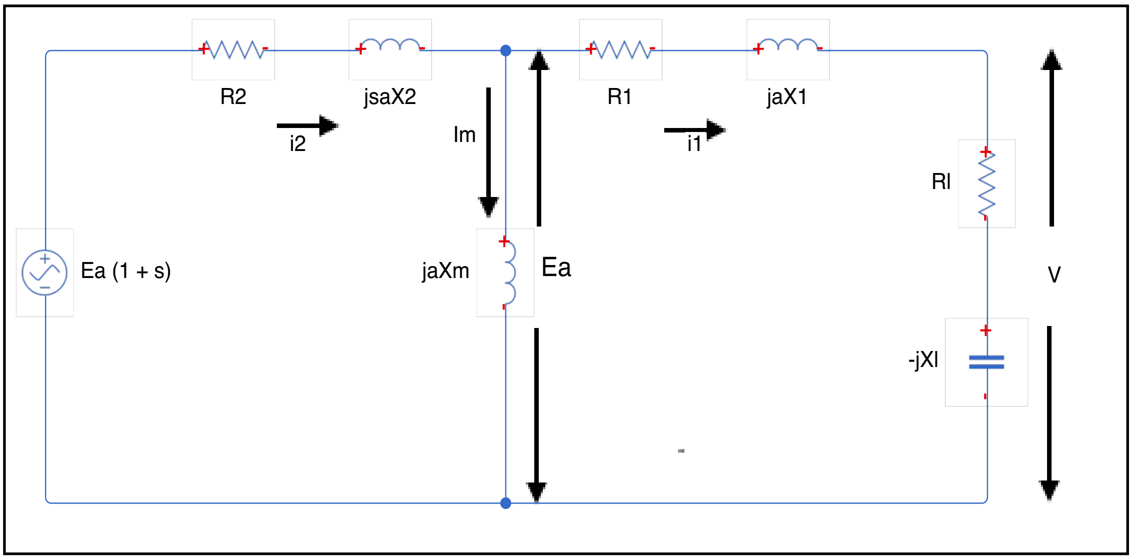


Figure 3.3: Modified Per Phase Equivalent Circuit For Seig

In fig. 3.3, modified per phase equivalent circuit of SEIG is represented. The load side is represented by the series combination of R_L and X_L and source voltage is represented by E_a (1 + s).

By the analysis of the circuit shown in Fig. 3.3 value of R_L and X_L can be calculated using the following equations :

$$R_L = \frac{RX_c^2}{a^2R^2 + X_C^2}$$

$$X_L = \frac{aR^2X_C}{a^2R^2 + X_C^2} \tag{3.1}$$

On further analysing the circuit, following equations were realised.

$$a_2s^2 + a_1s + a_0 = 0 \tag{3.2}$$

Where

$$a_2 = a^2X_2^2R_{1L}$$

$$a_1 = -R_2(R_{1L}^2 + X_{1L}^2)$$

$$a_0 = R_{1L} R_2^2$$

Equation (3.2) being quadratic in nature, on solving provides us two possible values of slips. The lower value of slip result is only relevant for the generating mode. The higher value is relevant for motoring mode.

$$R_{1L} = R_1 + R_L$$

$$X_{1L} = aX_1 - X_L \tag{3.3}$$

$$X_m = \left[\frac{-R_2(R_{1L}^2 + X_{1L}^2)}{sa^2 X_2 R_{1L} + aR_2 X_{1L}} \right] \tag{3.4}$$

The relation between generated frequency and operating speed is shown in equation (3.5).

$$b = a\,(1 + s) \tag{3.5}$$

Where, 'a' represents the value of per unit frequency and 'b' represents the value of per unit speed.

The speed of the prime mover required to generate terminal voltage at a particular frequency value for a given excitation capacitance and load can be evaluated using the Equations (3.2), (3.4), and (3.5), along with the induction machine's magnetisation curve.

Generated voltage of the SEIG can be controlled by proper handling of capacitors used for excitation. The performance of the induction machine can be analysed if the air gap voltage E1 is known at rated frequency, by using the model representing equivalent circuit shown in Figs. 3.2 and 3.3.

Stator Current of SEIG:

$$I_1 = \frac{aE_1}{\sqrt{R_{1L}^2 + X_{1L}^2}} \tag{3.6}$$

Terminal Voltage of SEIG:

$$V = I_1\sqrt{R_L^2 + X_L^2}$$

$$V = \frac{aE_1\sqrt{R_L^2 + X_L^2}}{\sqrt{R_{1L}^2 + X_{1L}^2}} \tag{3.7}$$

Value of Load Current:

$$I_L = \frac{V}{R} \tag{3.8}$$

Output Power obtained:

$$P_{out} = 3I_L^2 R \tag{3.9}$$

3.3. MAGNETISATION CHARACTERISTICS OF SEIG

The details of the induction machine used in this dissertation are mentioned in appendix-1. The variation of air gap voltage with magnetising reactance at rated frequency for the induction machine [9] is as follows:

- $X_m < 169.2$ ⟶ $E_1 = 512.69 - 2.13X_m$
- $179.42 > X_m \geq 169.2$ ⟶ $E_1 = 891.66 - 4.37X_m$
- $184.46 > X_m \geq 179.42$ ⟶ $E_1 = 785.79 - 3.78X_m$
- $X_m \geq 184.46$ ⟶ $E_1 = 0$.

Table 1: Magnetisation Characteristics Of Generator

S No.	X_m	E_1	I_m	L_m
1.	1	510.56	510.56	0.0032
2.	2	508.43	254.22	0.0064
3.	3	506.30	168.77	0.0096
4.	5	502.04	100.41	0.0159
5.	10	491.39	49.14	0.0318
6.	20	470.09	23.51	0.0637
7.	30	448.79	14.96	0.0955
8.	40	427.49	10.68	0.1273
9.	50	406.19	8.12	0.1592
10.	60	384.89	6.42	0.1911
11.	70	363.59	5.20	0.2230
12.	80	342.29	4.28	0.2548
13.	90	320.99	3.57	0.2866
14.	100	299.69	2.99	0.3185
15.	110	278.39	2.53	0.3503
16.	120	257.09	2.14	0.3822
17.	130	235.79	1.81	0.4140
18.	140	214.49	1.53	0.4459
19.	150	193.19	1.29	0.4777
20.	160	171.89	1.07	0.5095
21.	169.2	152.26	0.90	0.5389
22.	175	126.91	0.73	0.5573
23.	179.42	107.58	0.60	0.5714
24.	184	90.27	0.49	0.5860
25.	200	0	0	0.6370

Table 1 shows the magnetisation characteristics of the modelled Induction Generator.

A model is simulated on MATLAB with the specifications above. The results are obtained for different resistive loading conditions. The results are compared to the experimental results [8] and percentage error is calculated.

Table 2: Comparison Of Experimental Results And Matlab Results

S No.	Experimental Results		Matlab Results		Error %
	$I_{lp.u}$	$V_{p.u}$	V	$V_{p.u}$	
1	0.3842	0.9078	198.414	0.9048	0.3305
2	0.3684	0.9210	202.820	0.9248	-0.4126
3	0.3578	0.9526	207.288	0.9452	0.7768
4	0.3421	0.9684	211.240	0.9632	0.5370
5	0.3263	0.9868	215.109	0.9810	0.5878
6	0.2894	1.0131	223.720	1.0200	-0.6811
7	0.2394	1.0578	234.770	1.0700	-1.1533
8	0.1789	1.0921	245.900	1.1210	-2.6463
9	0.1648	1.1000	248.690	1.1340	-3.0910
10	0.1552	1.1052	250.580	1.1426	-3.3840

Table 2 shows the comparison between the experimental results and the results obtained on Matlab.

CHAPTER 4

DC MICRO-GRID USING SEIG : TOPOLOGY 1

4.1. SYSTEM DESCRIPTION : DBR WITH DC-DC CONVERTER

Squirrel-cage Induction machine used in generating mode is provided with mechanical input at its source point. Source input can be obtained by the use of suitable gearbox trains from wind-turbines. Capacitor series bank is connected to the stator of the Induction generator to fulfil reactive var requirement for self-excitation process.

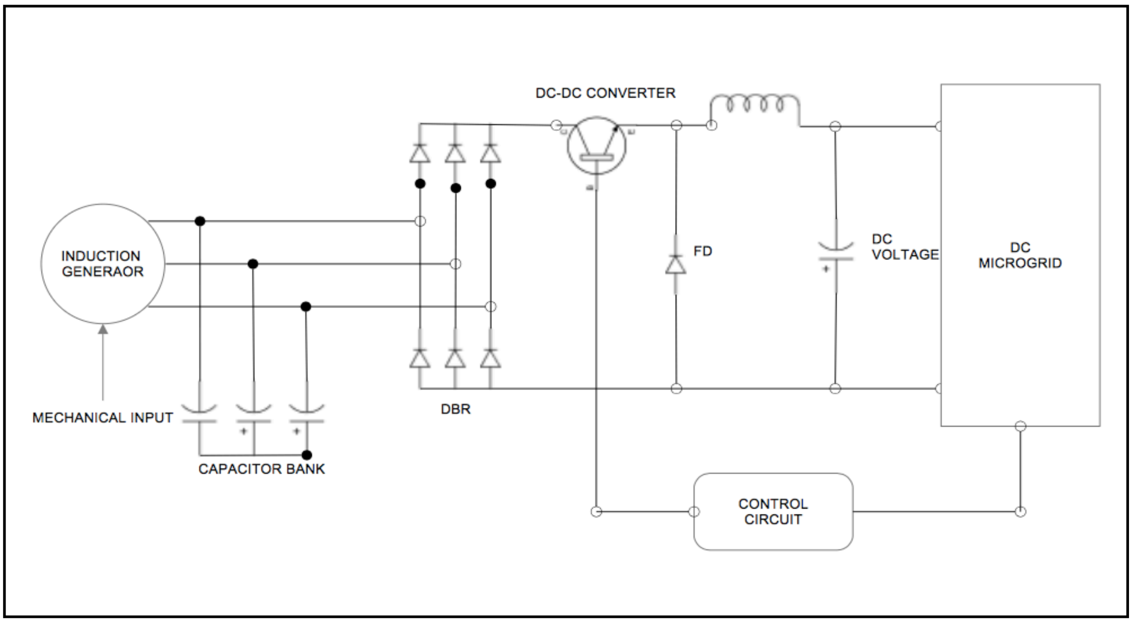


Figure 4.1: Schematic Diagram Of The Proposed Model

An Uncontrolled Diode based Bridge Rectifier (DBR) with DC-DC Converter is used for the rectification of AC voltage output of SEIG to the proposed DC grid voltage as shown in figure 4.1. A L-C filter is used to make the DC output more uniform and free of certain harmonics.

The usage of uncontrolled Diode Bridge rectifier is justified owing to its displacement factor being unity. This relieves capacitor banks of excessive burden of reactive power. As only one switch is to controlled, the circuitry becomes less complicated and easy to implement.

4.2. DESIGNING AND SIMULATION

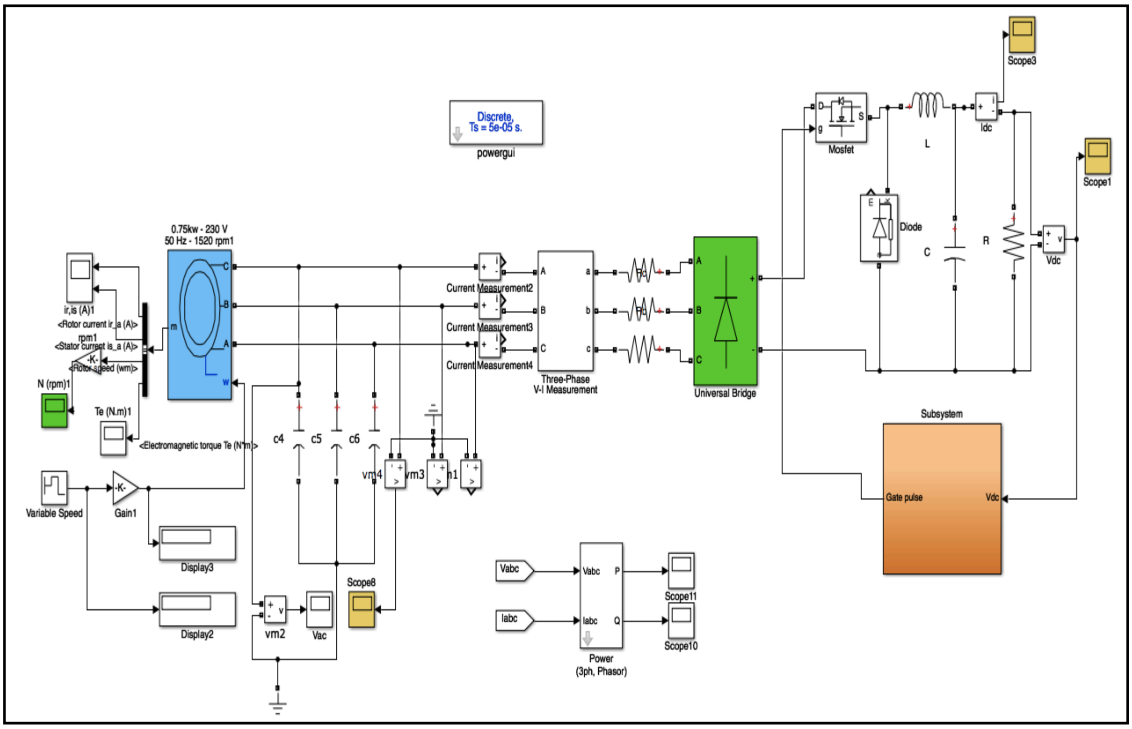


Figure 4.2: Simulink Model Of The Proposed System

Figure 4.2. Shows the Simulink based model designed on MATLAB® of the proposed system.

A control strategy is devised for the generation of constant DC voltage during variable turbine speed and variable load. The system is designed for 48V DC micro-grid applications. A comparator is used between reference value (48V) of DC voltage and measured DC Voltage at the load end, to calculate Error signal. A PI controller with suitable parameters is tuned. A Triangular carrier signal of 2KHz frequency is used for the creation of pulses. The pulse signal is used for the switching of the IGBT employed in DC-DC converter.

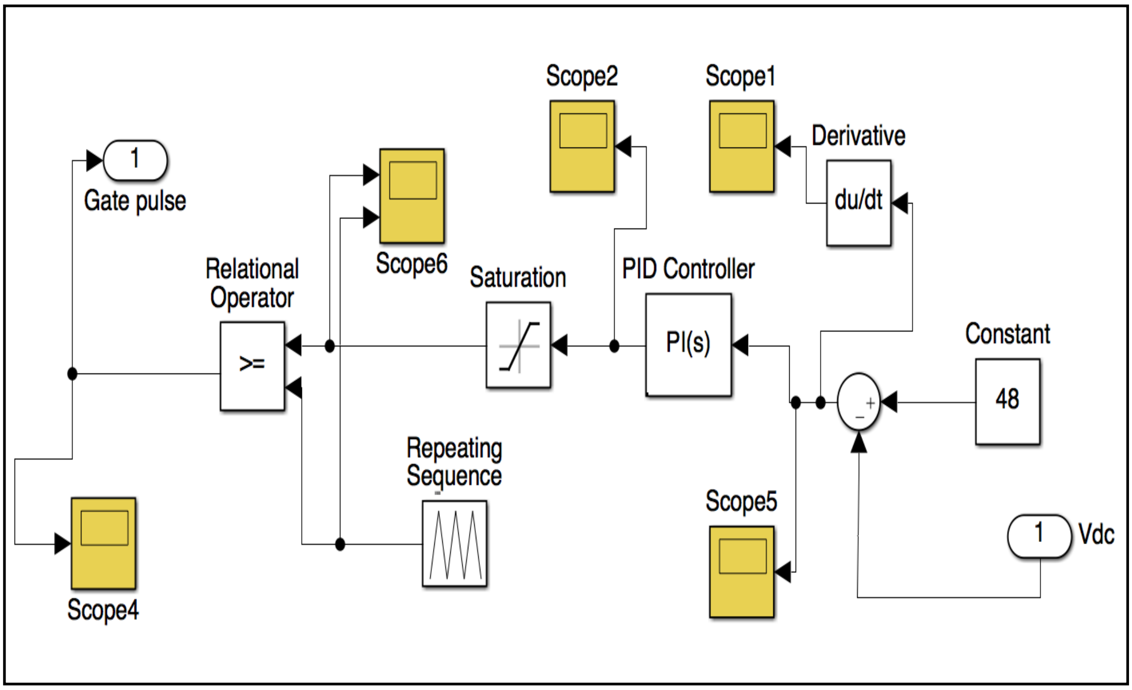


Figure 4.3: Control Model

Figure 4.3. shows the control model designed in simulink making use of the conventional P-I controller.

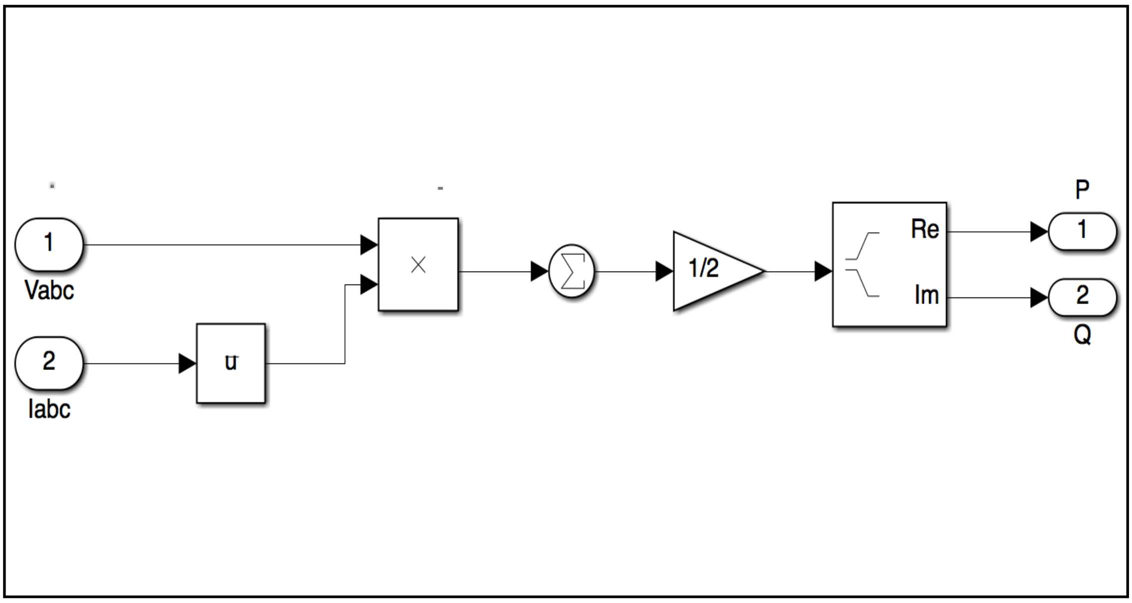


Figure 4.4: P-Q Calculation Block

A block is designed to calculate the value of active and reactive power as shown in figure 4.4.

The values of Active and reactive power are calculated at the generator side using PQ calculation block. PQ calculation block has phase currents and phase voltages as its inputs.

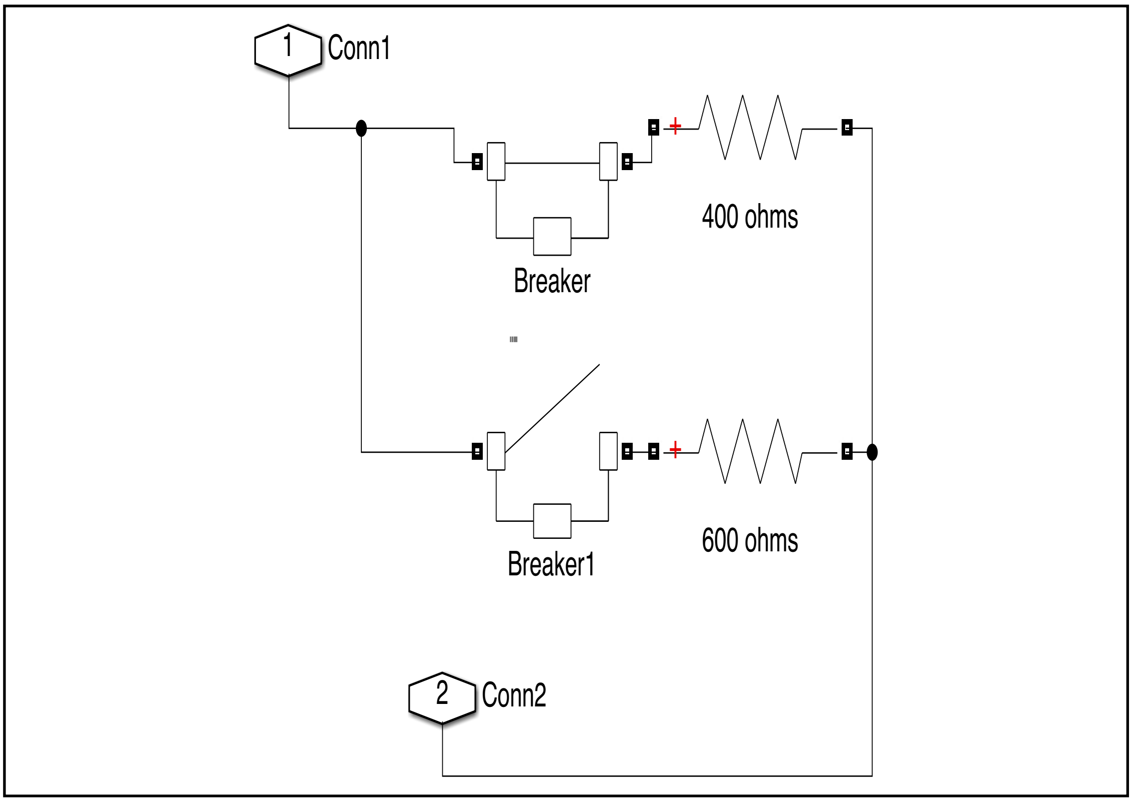


Figure 4.5: Variable Resistance Block

Figure 4.5. shows a variable resistance block designed in Simulink® to switch different values of load at different timings.

The variable resistance block is designed to switch different value of load at different times. It comprises of two time-operated circuit breakers and two resistive loads. The block used in the model gives two values of load.

Load value = 400 Ohms From time t=0 to t=2.5 sec;

Load value = 240 Ohms From time t=2.5sec to t=5 sec;

4.3. SIMULATION RESULTS OBTAINED

4.3.1. With Variable Speed Input

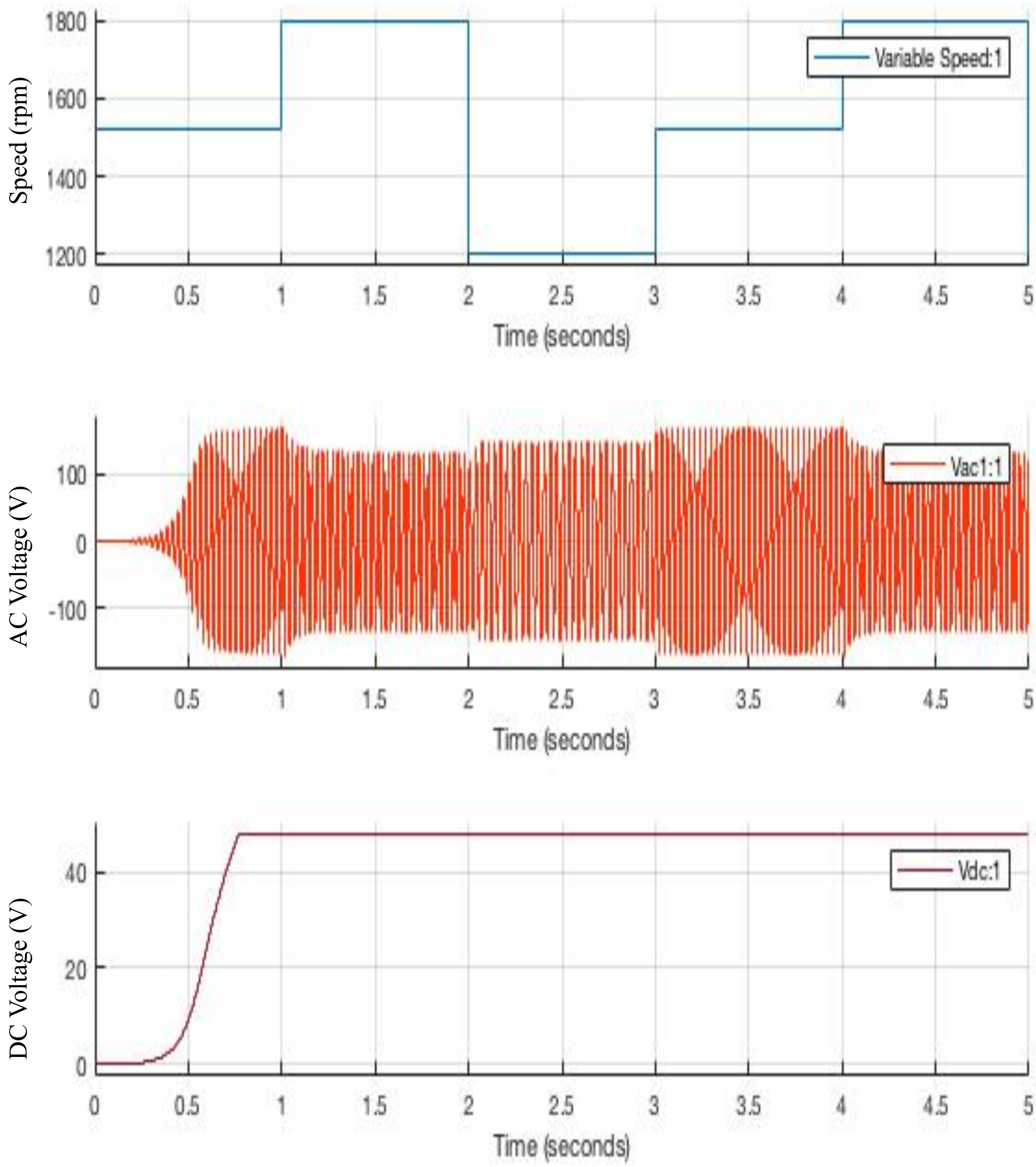


Figure 4.6: Speed Variation Vs Ac Voltage Vs Dc Voltage

Figure 4.6. shows the value of AC and DC voltages generated by induction generator with variable speed as its input. It is seen that the AC voltage generated by the Induction Generator varies with the speed input. But the DC voltage measured at the load end is fixed at 48V with minor deviations in the tolerance range of 0.05.

4.3.2. With Variable Loading Conditions

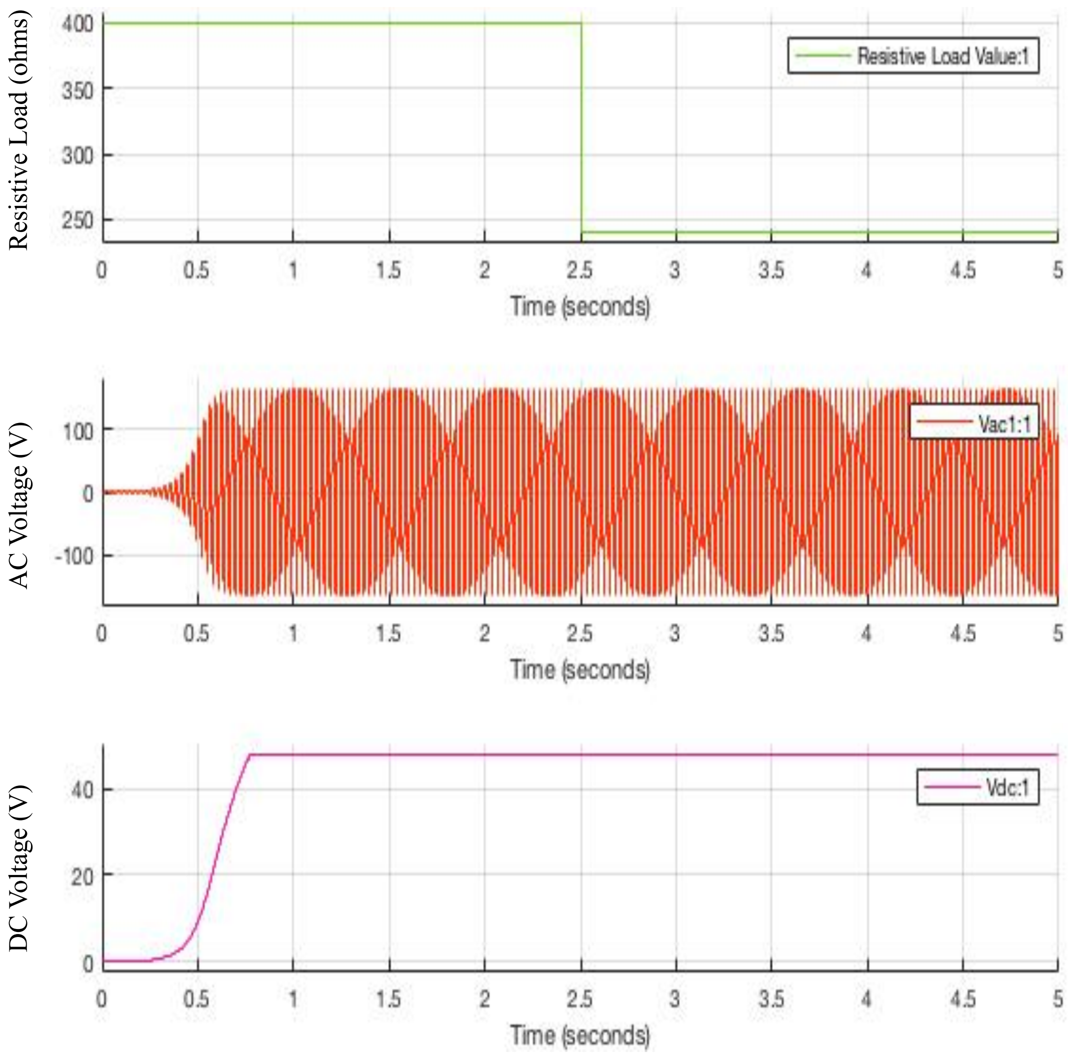


Figure 4.7: Load Variation Vs Ac Voltage Vs Dc Voltage

Figure 4.7 shows the value of AC and DC voltages generated by induction generator with variable load as its input. At time t=2.5 sec, the value of load changes from 400 ohms to 240 ohms.

The response of PI controller is found to be fast and accurate. The DC voltage measured at the load end is fixed at 48V with minor deviations in the tolerance range of 0.05.

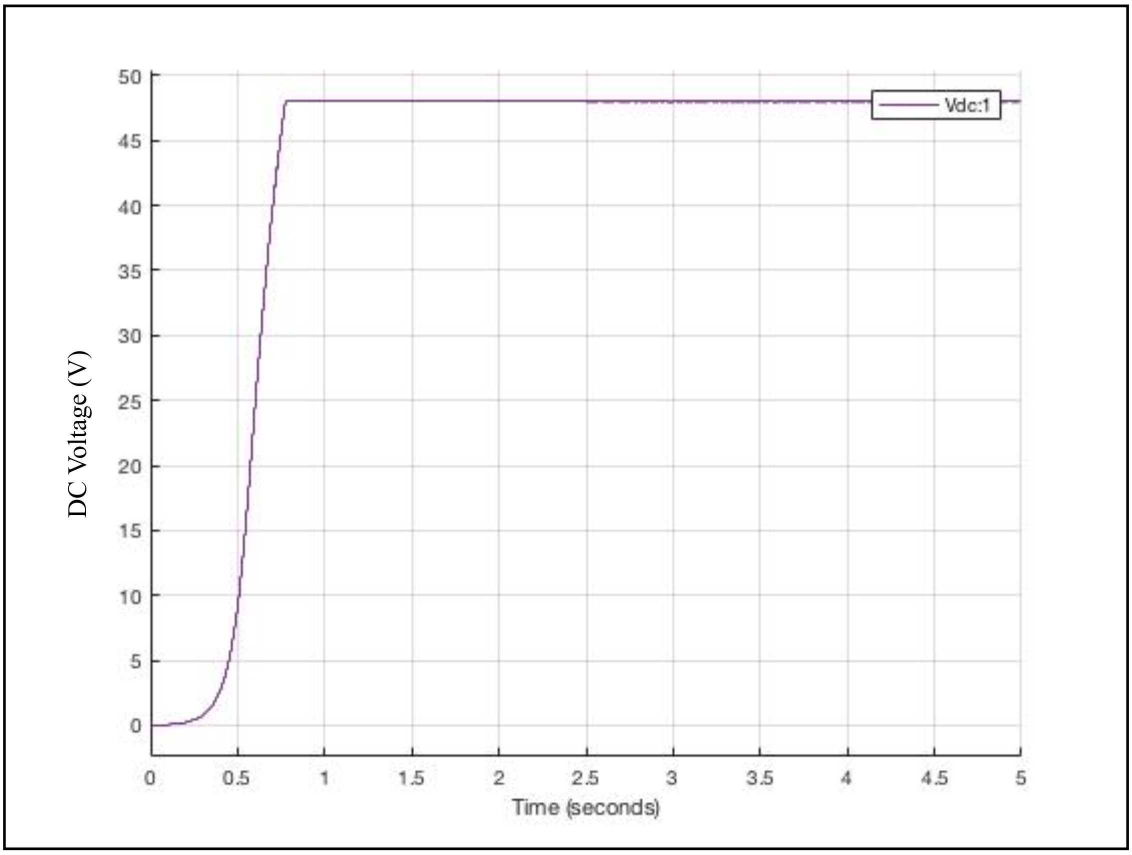


Figure 4.8: Generated Dc Voltage Vs Time

The figure 4.8. shows that the response of system is better for higher resistive values. The voltage build-up of Self Excited Induction Generator used fails for resistive load values less than 200 ohms as the burden on capacitor banks is increased.

CHAPTER 5

DC MICRO-GRID USING SEIG : TOPOLOGY 2

5.1. SYSTEM DESCRIPTION : PWM BASED RECTIFIER SYSTEM

A control strategy is devised for the generation of constant DC voltage during variable turbine speed. The output voltage of the SEIG shows variation in amplitude and frequency because of fluctuations in wind. This voltage is converted to a controllable DC voltage. The insulated gate bipolar transistors (IGBTs) are used as switches in the circuit of PWM rectifier. The gate pulses are appropriately adjusted by adjusting its number and width.

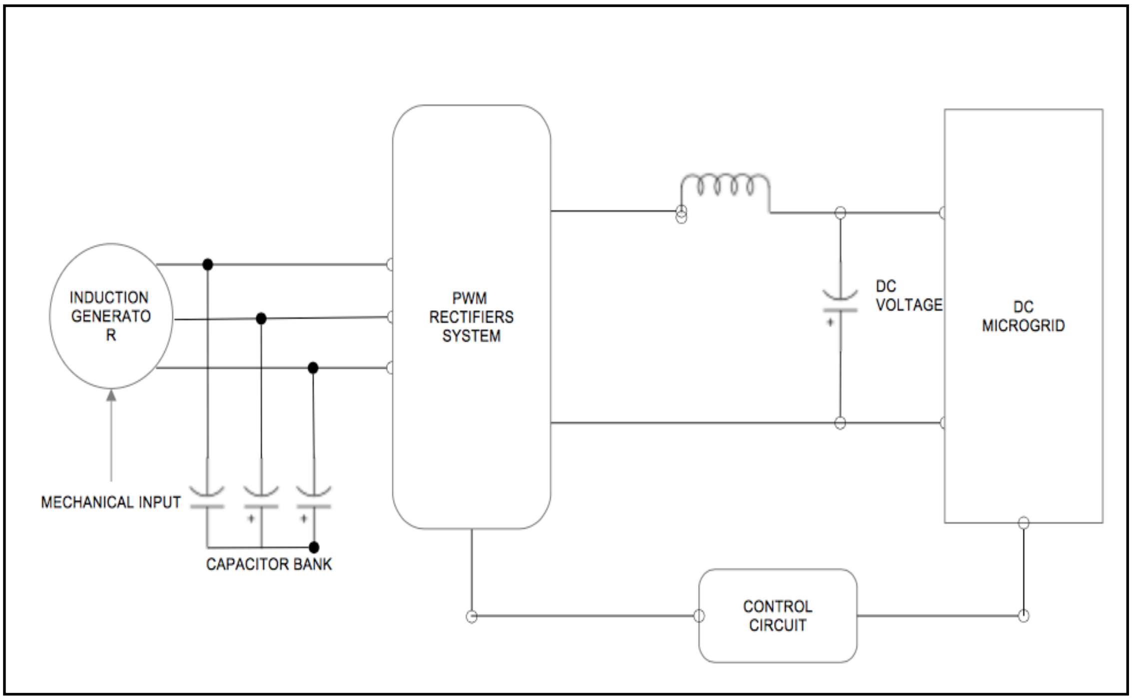


Figure 5.1: Schematic Diagram Of The Proposed System

Three different control strategies have been designed and implemented to suitably control the DC micro-grid voltage. Artificial intelligence (A.I.) control strategies are being taken help of. The results of these different control strategies are compared and analysed.

5.1.1. Using P-I Controller

Suitable voltage and current sensors are used to sense the generator voltages, output DC voltage and input AC currents. These electrical quantities sensed are then fed to the controller.

The proposed controller's overall schematic consists of two control loops. The output DC voltage (V_{dc}) at the terminals of PWM based rectifier is sensed using voltage sensor. This measured voltage considered as feedback voltage for the first loop and reference voltage (desired output voltage, 48 V of the PWM rectifier) are compared using comparator to calculate error signal. The output error signal is given to the second loop. The second loop of the system comprises of a PI controller, which is tuned with suitable parameters. After which adder is used whose output is a voltage equivalent for the reference current (peak magnitude). This reference current is devoid of sinusoidal shaping. Generator voltage and reference current zero crossings are not in synchronisation. Therefore, to attain power factor at the output as unity based alone on this current reference is not possible. Hence, the stator voltage signal is multiplied to the output of the adder to obtain the sinusoidal reference current to the second control loop, controlling current of the PWM rectifier. Being a three phase system, three multipliers are used, for generating the reference currents for the three phases. Therefore, current references (I^*_{abc}) and the input side currents (I_{abc}) from the PWM rectifier are given as input to current regulator.

Hysteresis based current mode controller is used. The band used is 0.01. This type of controller outputs two values i.e. fully on or fully off. The hysteresis based current mode controller generates pulses to perform the switching operation of the three-phase PWM rectifier. Switching operation can be achieved like, if a line current rise above the set point, the controller turns off the IGBT switch and if the current value falls below the set point, the corresponding IGBT switch goes ON. Thus, the inner loop is responsible for sinusoidal rectifier input current to remain in-phase with the generator voltage, whereas the outer control loop fixes the DC voltage constant at the desired set point.

5.1.2. Using Adaptive Network Based Fuzzy Inference System Controllers

ANFIS is an architecture and learning algorithm which was introduced by Jang in the year 1993. It combines the functions of fuzzy logic with neural networks for inferencing. The ANFIS system performs mapping of input data with its associated parameters using input membership functions (MFs), and then accordingly through output membership functions (MFs) to generate outputs. For calculation of initial membership function and rules for the fuzzy inference system, human expertise knowledge about the system is used. Refinement of the fuzzy if-then rules and membership functions to demonstrate the input-output behaviour of a system involving complexity is done using ANFIS.

Fuzzy logic toolbox in MATLAB R2016A has been used for designing and testing of the ANFIS controllers. Sugeno-type fuzzy systems can be created, trained, and tested using the ANFIS Editor Graphical user interface in MATLAB.

Type the command "*anfisedit*" at the MATLAB command window to start the GUI.

The ANFIS Editor GUI window as shown in figure 5.2. performs the following tasks:

i. Loading the Data
ii. Generating FIS Structure
iii. Training the FIS
iv. Testing the trained FIS

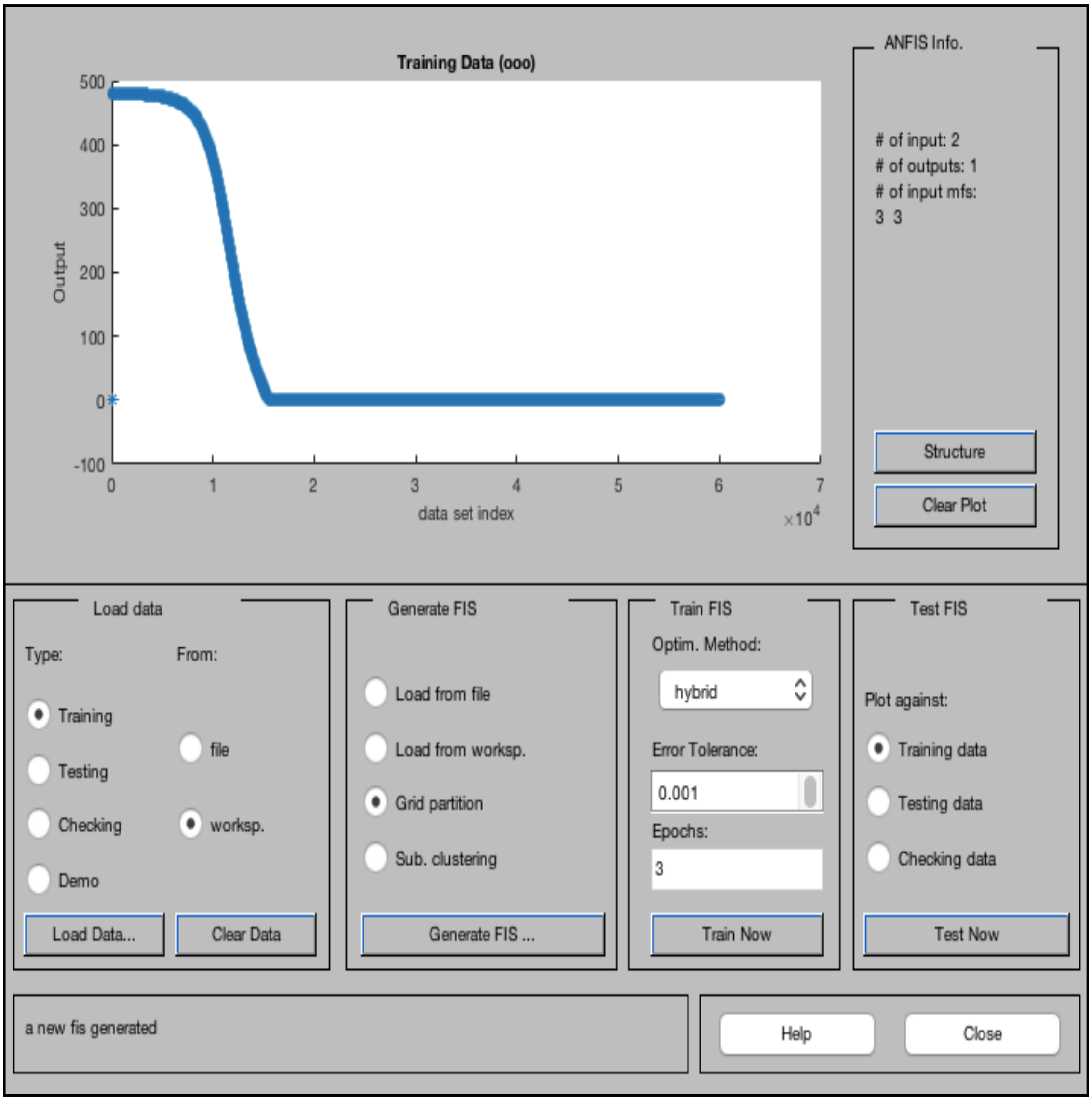
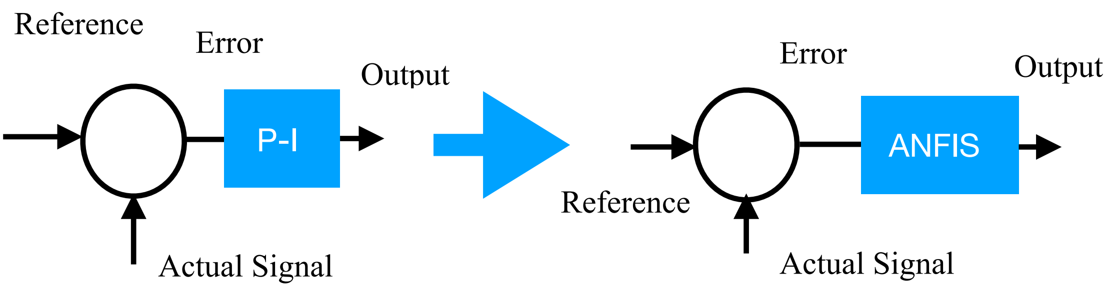


Figure 5.2 : Neuro-Fuzzy Designer

Crucial steps in the design of ANFIS controller are as follows.

- Conventional PI controller is replaced by ANFIS Controller.



- The data required for testing and training the ANFIS is generated by designing and testing suitable PI controllers. The controllers are designed under different operating conditions by using Hysteresis current mode control technique for operation at different input speed conditions. The values of Error, Change in Error and Output of PI controller is required for the training of ANFIS controller which are obtained with the help of MATLAB Script mentioned in Appendix 3.

- By loading the data from workspace, by using grid partitioning method the ANFIS structure gets generated. For input, the triangular type and for output, constant type membership functions are used in this project, respectively.

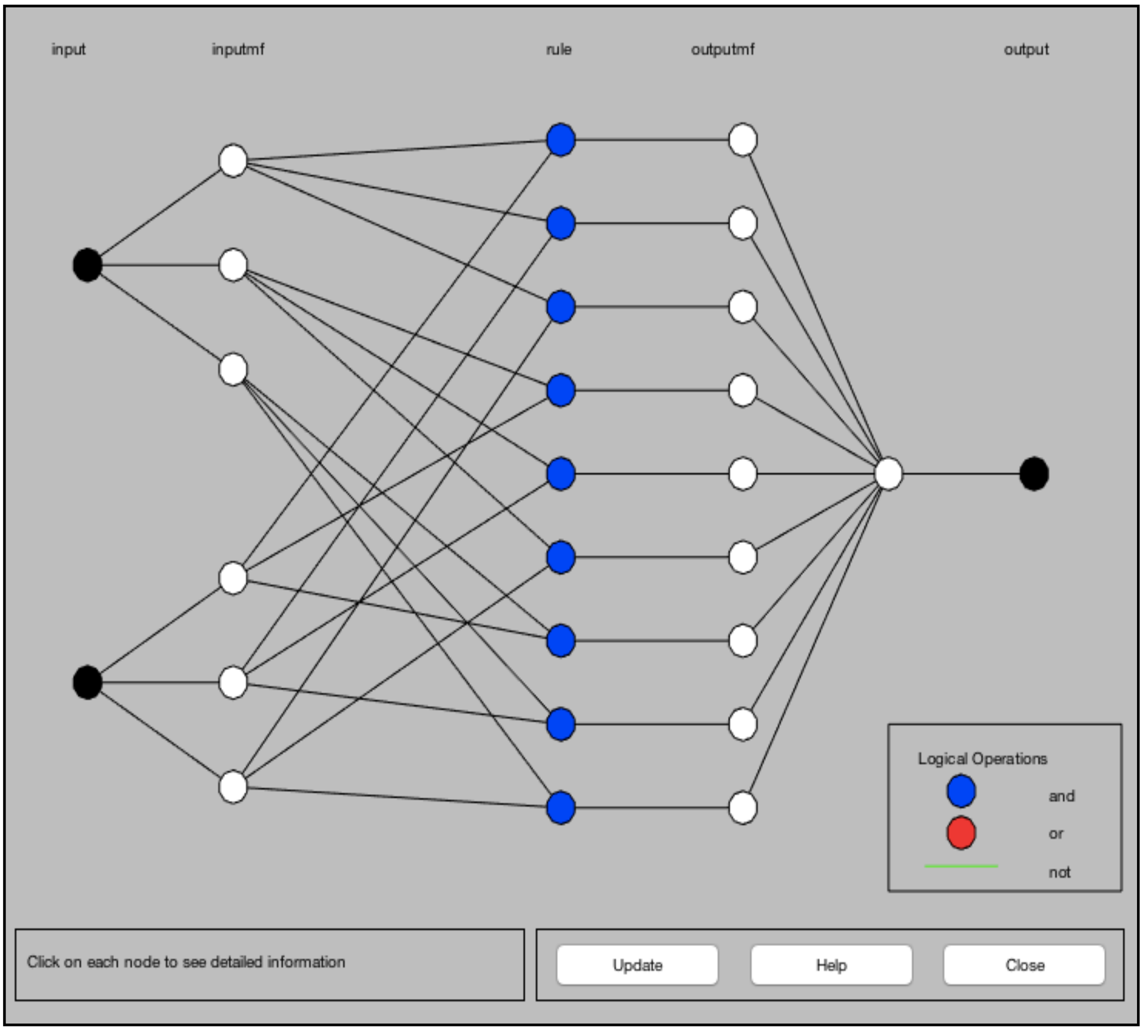


Figure 5.3: Model Structure

Figure 5.3 shows, a ANFIS Model structure obtained for the Sugeno-type ANFIS. This network structure consists of five network layers interconnected to each other using sets of units.

- Layer 1 consist of input variables error and change in error.
- Layer 2 weighs each membership function.
- Layer 3 matches the fuzzy rules pre-conditionally.
- Layer 4 outputs the results from the inference of rules.
- Layer 5 sums up all the outputs from previous layer and De-fuzzifies the fuzzy results into a single crisp value.

- After generating the ANFIS structure, training with hybrid optimum method with tolerance of error at 0.001 p.u. for maximum 3 epochs is performed.

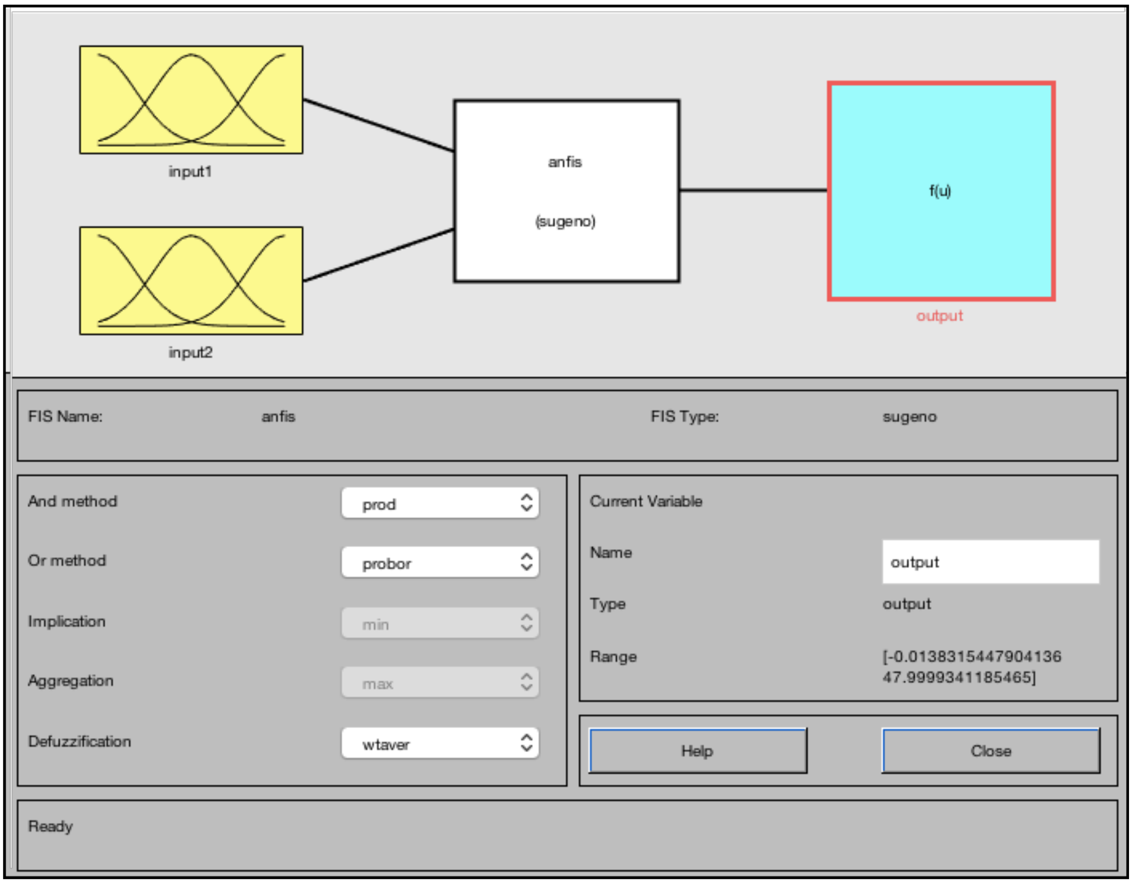


Figure 5.4: Fuzzy Logic Designer

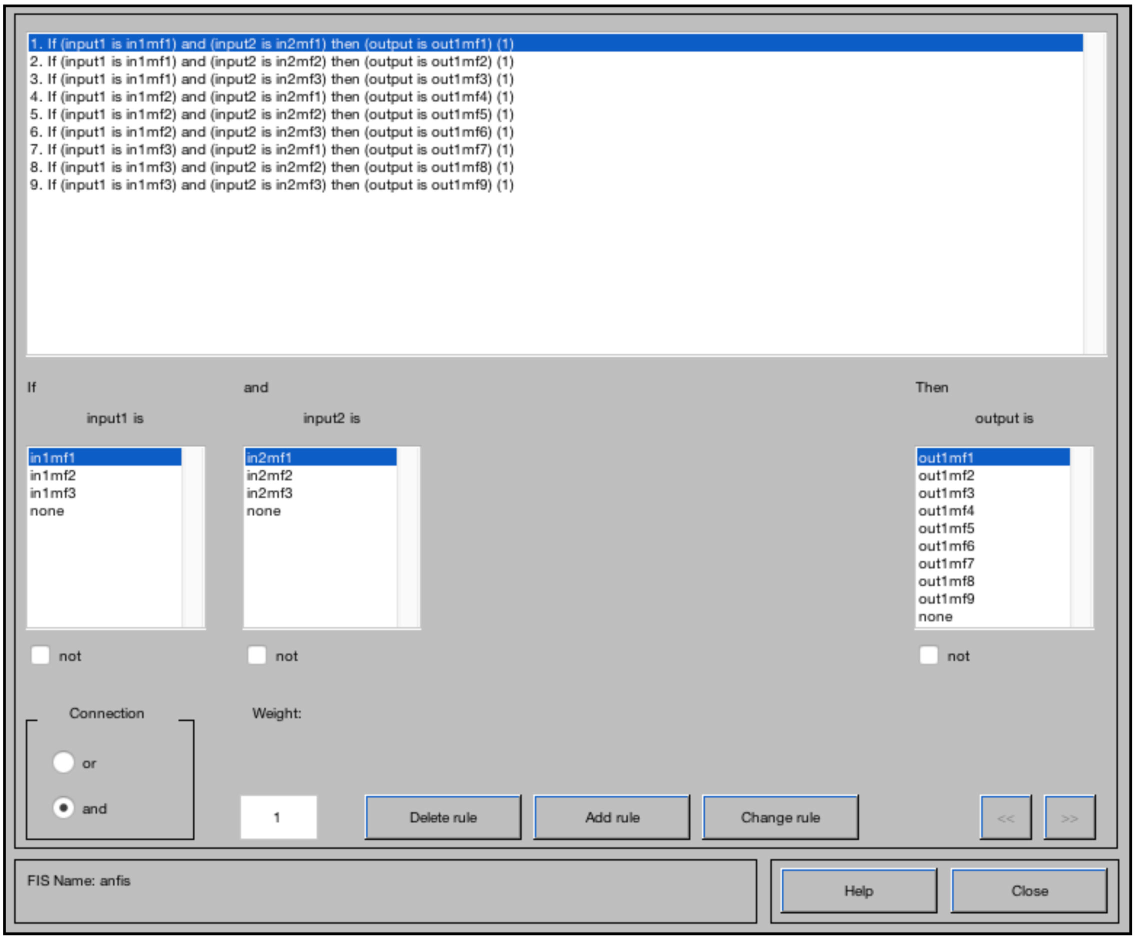


Figure 5.5: Fuzzy Rule-Editor

The fuzzy rules dealing with the membership functions so generated as shown in figure 5.5. are as follows:

1. If (input1 is in1mf1) and (input2 is in2mf1) then (output is out1mf1) (1)
2. If (input1 is in1mf1) and (input2 is in2mf2) then (output is out1mf2) (1)
3. If (input1 is in1mf1) and (input2 is in2mf3) then (output is out1mf3) (1)
4. If (input1 is in1mf2) and (input2 is in2mf1) then (output is out1mf4) (1)
5. If (input1 is in1mf2) and (input2 is in2mf2) then (output is out1mf5) (1)
6. If (input1 is in1mf2) and (input2 is in2mf3) then (output is out1mf6) (1)
7. If (input1 is in1mf3) and (input2 is in2mf1) then (output is out1mf7) (1)
8. If (input1 is in1mf3) and (input2 is in2mf2) then (output is out1mf8) (1)
9. If (input1 is in1mf3) and (input2 is in2mf3) then (output is out1mf9) (1)

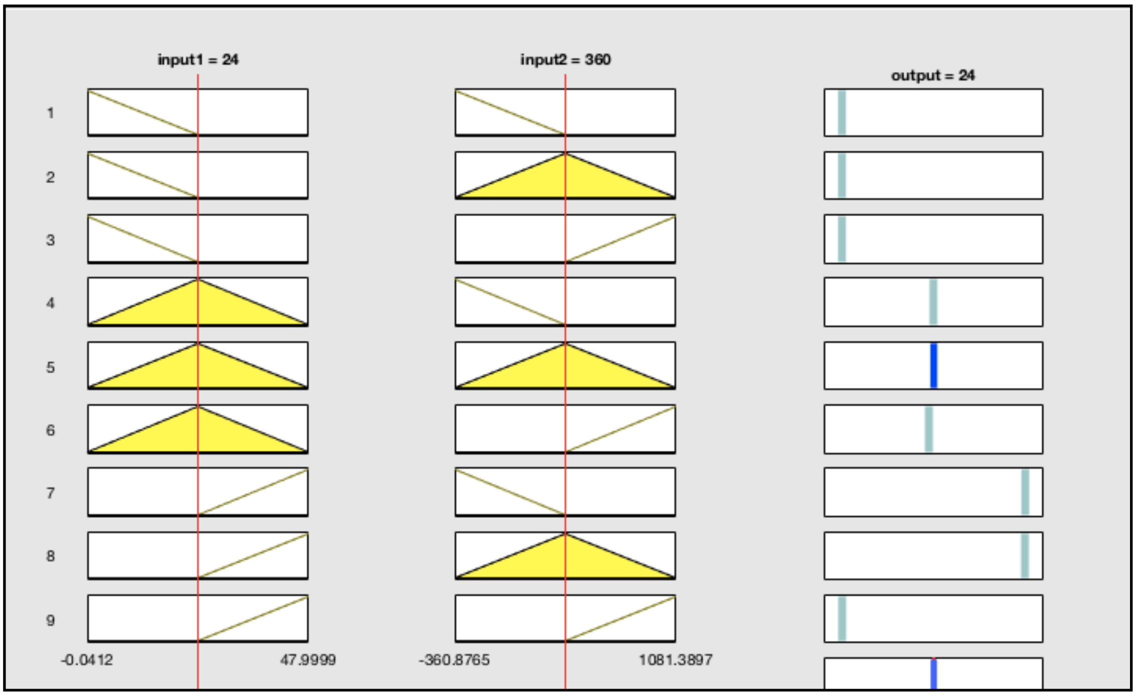


Figure 5.6: Fuzzy Rule-Viewer

Figure 5.6 shows the Rule Viewer which displays membership function rules for the trained data.

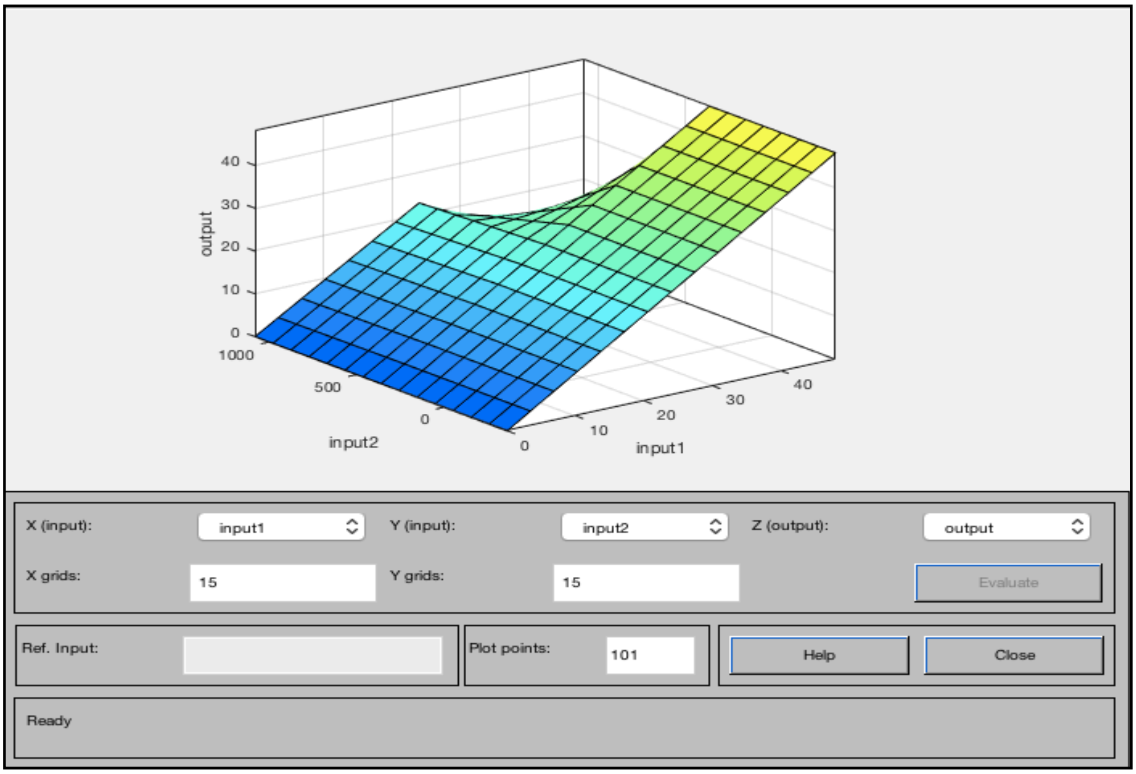


Figure 5.7: Fuzzy Surface-Viewer

Figure 5.7 shows the Surface Viewer which displays membership function rules for the trained data.

Rule Viewer and Rule Editor provides us the tools to display and edit all of the MF's accordingly dealing with the fuzzy inference system. The numbers of rows represent the total number of rules. Each column displays the MF set for a specific input. Each MF in the set is concerned with a specific rule and maps the input variable values to input values of the rule. The plots in the output column show how the rules are related to output variable.

Table 5.1: Design Specifications For ANFIS Based Controller

Number of input(s)	2
Number of output(s)	1
Number of Rules	9
Number of nodes	35
Type of Membership Function	Trimf
Number of training data pairs	60001
Number of Epoch	3
Error	0.001577

5.1.3. Using Artificial Neural Network (Ann) Controllers

Artificial Neural Networks (ANN) is a computational information processing model based on the structures and functions of biological nervous systems. It is similar to artificial human nervous system for receiving, processing, and transmitting information.

The ANN is configured specifically for applications like data classification or pattern recognition. Artificial Neural Networks (ANN) have specular advantages over conventional controllers, like adaptive learning, pattern recognition, real time operation, self-organisation and many more. ANN have produced amazing results in the field of electrical engineering especially in the controller design circuits of Power system and Power electronics.

It is composed of a vast network of processing elements that are inter-connected to form a structure. These processing elements are similar to neurons in the nervous system. Neurons provide single output for multiple inputs. Learning process is inspired by human learning process i.e. learning by example. The information data flows from the input layer to hidden layer and then to the output layer. Based on the output and activation function, the weights of hidden layer are modified so as to obtain better output results.

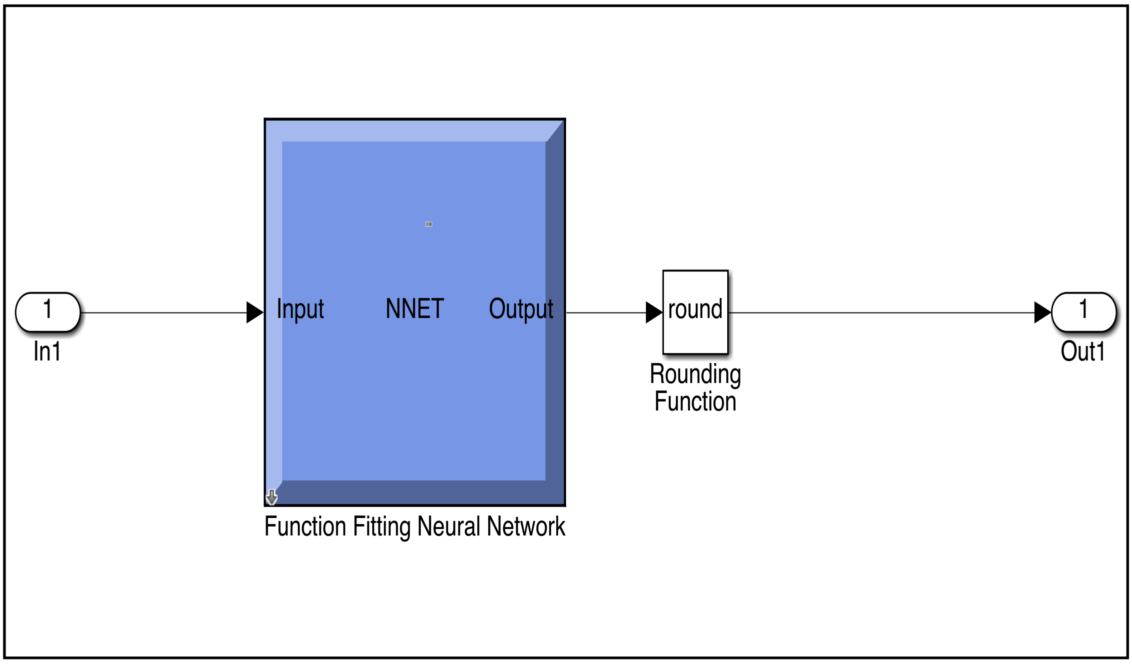


Figure 5.8: Neural Network Controller

Figure 5.8. shows the Neural Network fitting Function block used in the Simulink model. The rounding function connected to the fitting function block helps to refine the results.

Neural Network Toolbox in Simulink® is used to implement this Artificial Intelligence based soft computing technique. Neural Networks can be started in MATLAB Simulink® by using command “nnstart” in the command window. A multi-layer perceptron neural network is selected. The value of error signal obtained by the PI controller is used as input data and the output of PI controller is used as target data to train the neural network.

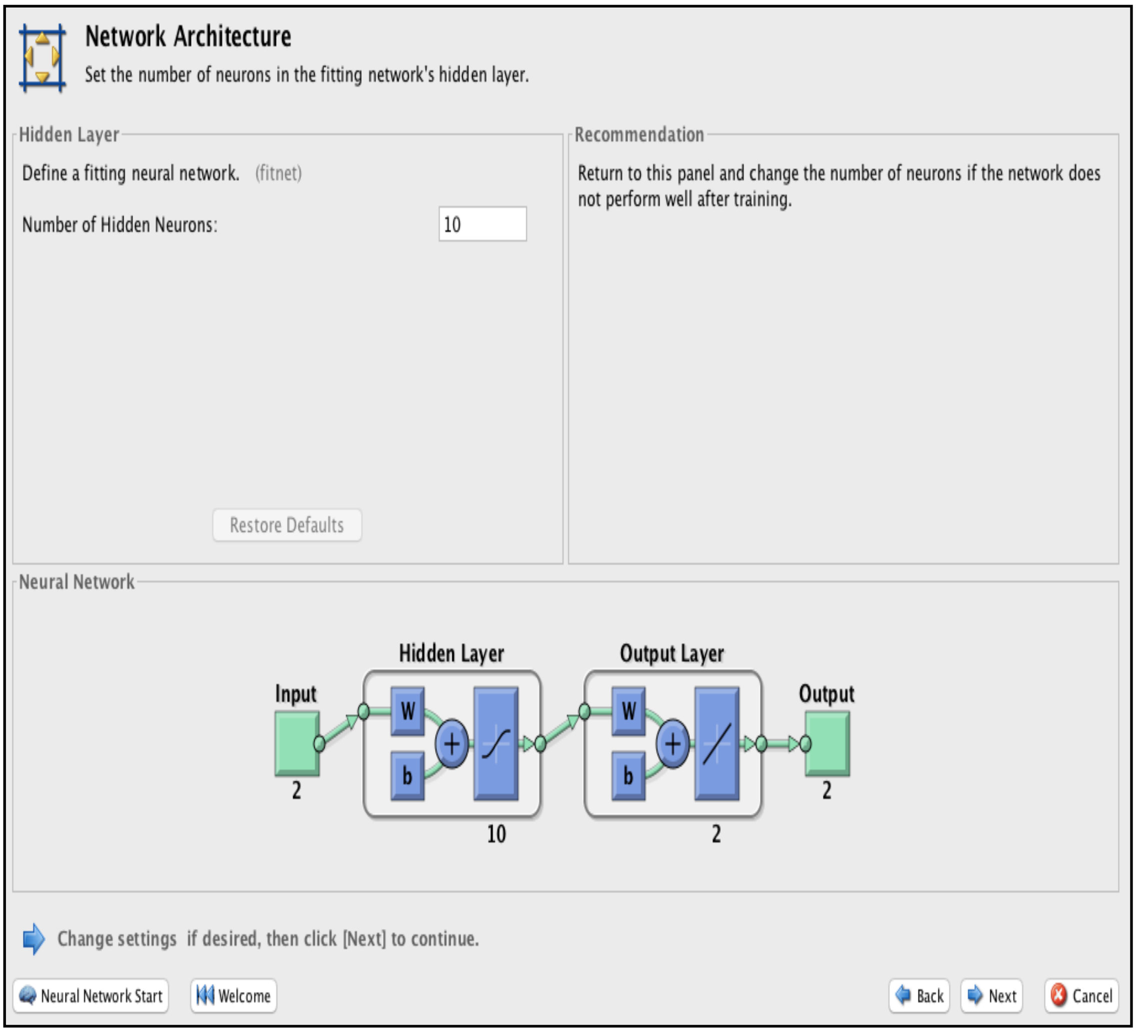


Figure 5.9: Neural Network Architecture

The figure 5.9. shows the ANN architecture which is composed of two inputs, two outputs and ten hidden layers. The number of hidden neurons used in the process are ten.

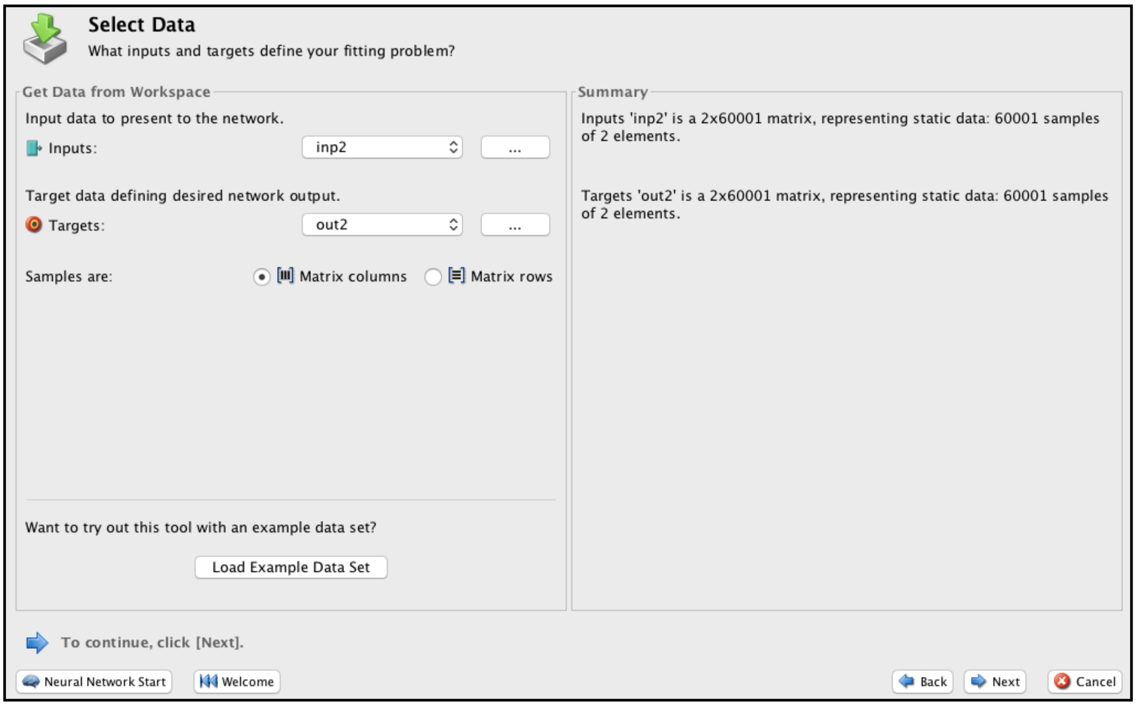


Figure 5.10: Input And Target Data Selection

The figure 5.10. shows the dialog box for selecting input and target data.

Figure 5.11: Limit Setting For Curve Fitting

Figure 5.11. shows the dialog box used for setting the limit for curve fitting.

The validation data should be close to the desired output so as to obtain better accuracy also over-training should be avoided for faster responses.

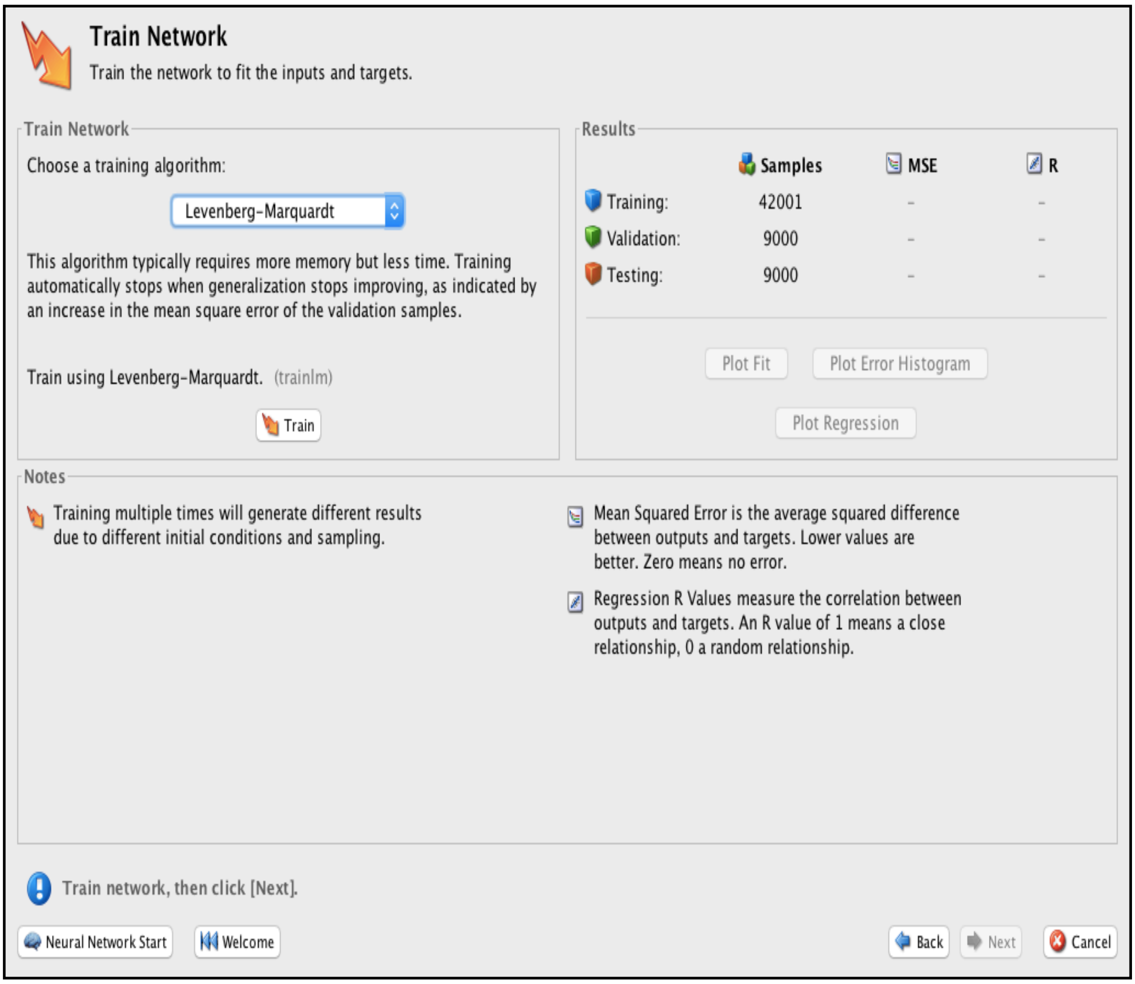


Figure 5.12: Training Settings Of Neural Network

The figure 5.12. shows the dialog box for training settings of neural network. It provides us the option to select the training algorithm. Training by Levenberg-Marquardt training algorithm is chosen as this algorithm typically requires less time but more memory. Training of the network stops automatically when generalisation stops improving, as shown by an increment in the error (mean- square) of the validation samples.

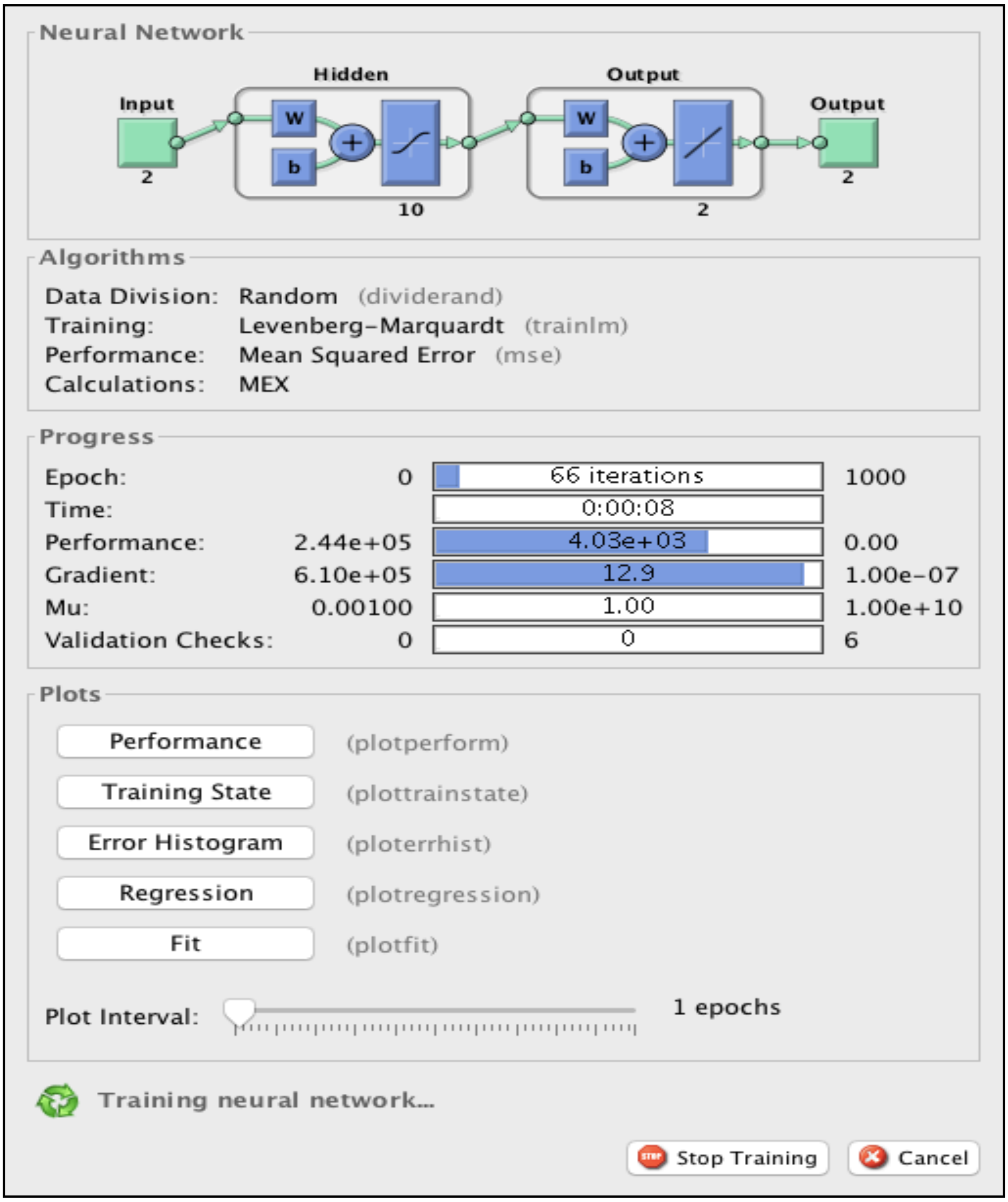


Figure 5.13: Neural Network Training Tool

The figure 5.13. shows the neural network training tool in MATLAB R2016a®.

The neural network training tool in MATLAB Simulink ® helps in the simplified implementation of the training algorithm.

5.2. DESIGNING AND SIMULATION

A Simulink model is simulated for the implementation and configuration of the control scheme to convert the output of SEIG to a controllable DC voltage. The insulated gate bipolar transistors (IGBTs) are used as switches in the circuit of PWM rectifier. The gate pulses are appropriately adjusted by adjusting its number and width. Hysteresis based current controller is used in this scheme. Three different controllers are used for this control scheme.

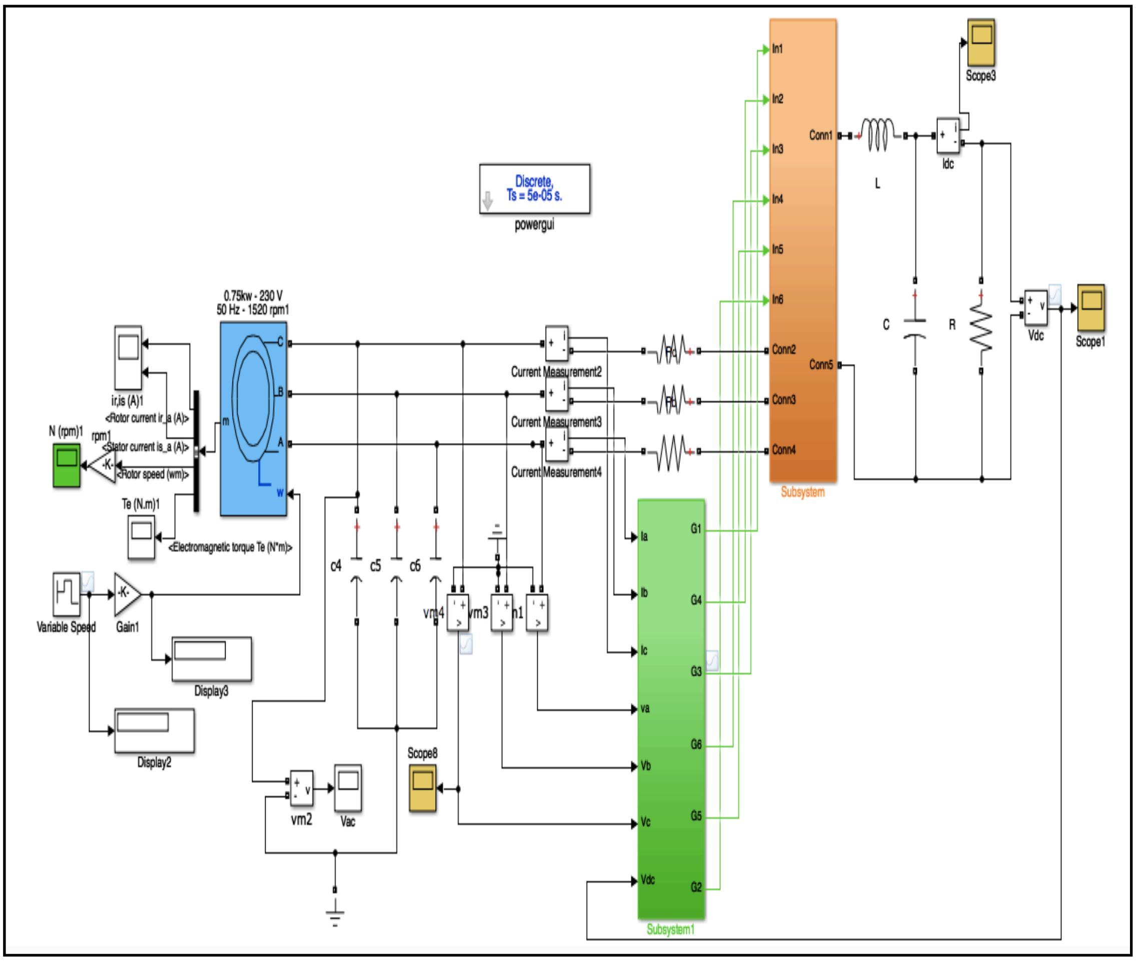


Figure 5.14: Simulink Model Of The Proposed System

Figure 5.14 shows the model simulated of PWM Rectifier based DC Micro-grid using SEIG on MATLAB R2016a.

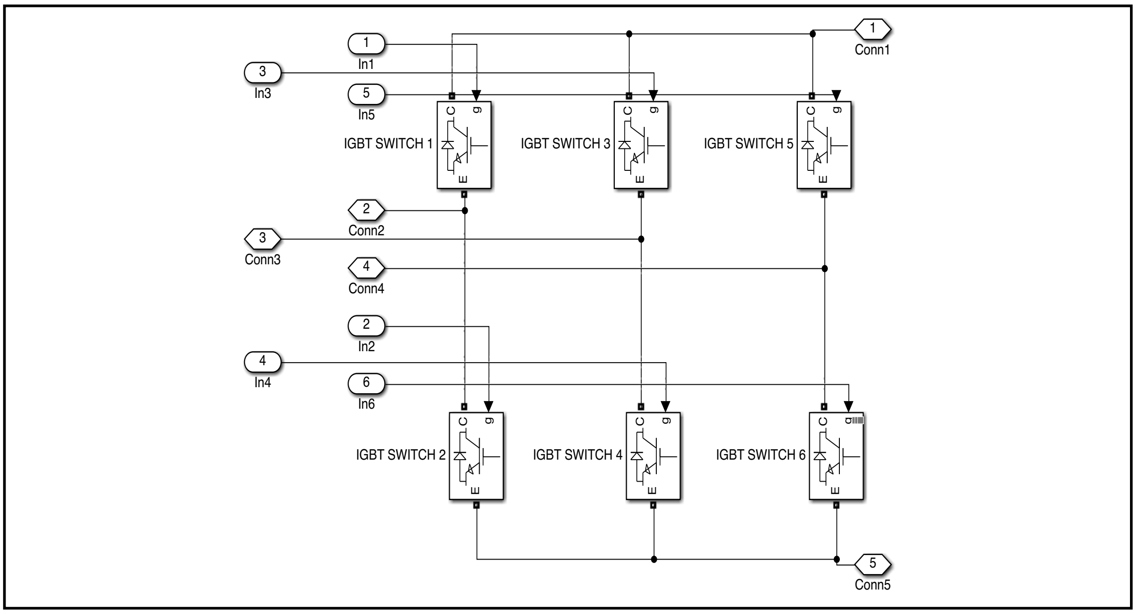


Figure 5.15: Pwm Rectifier

Figure 5.15. shows the model of rectifier operated by IGBT switches and deriving its gate pulses from the current regulator.

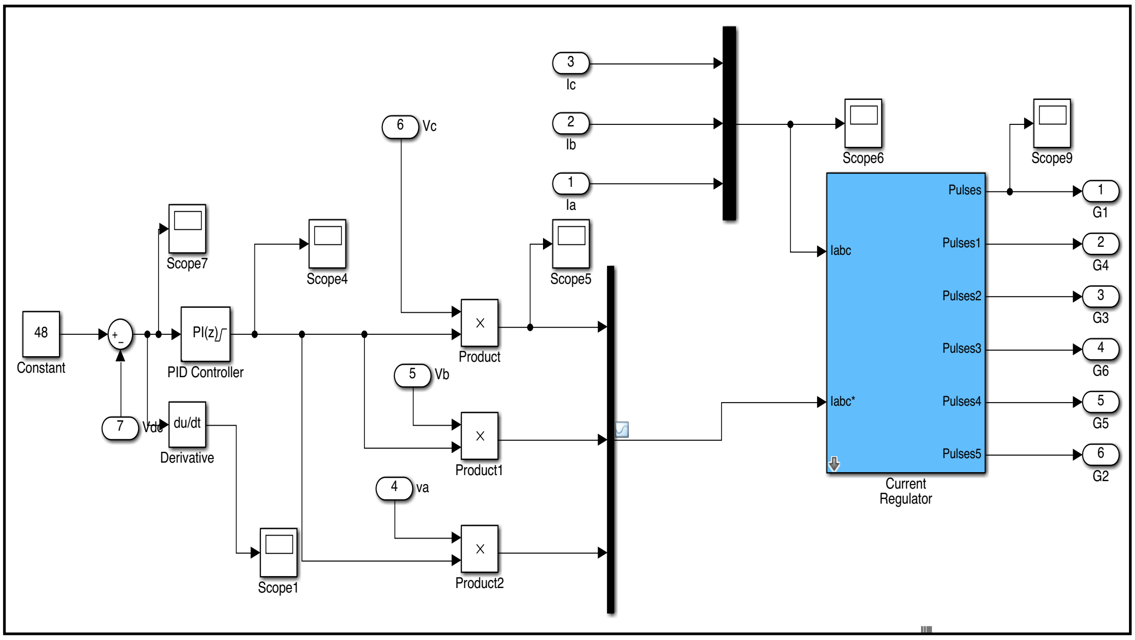


Figure 5.16: Control Model Using Pi Controller

Figure 5.16. shows the control subsystem block created using P-I controller and current regulator.

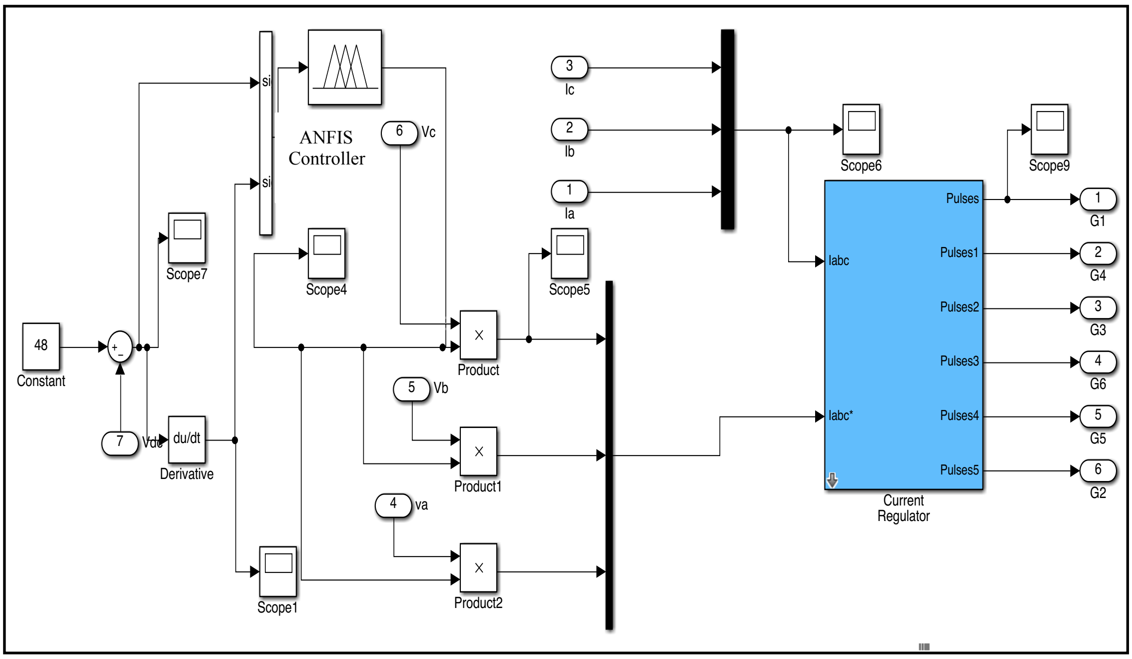


Figure 5.17: Control Model Using ANFIS Controller

Figure 5.17. shows the control subsystem block created using ANFIS controller and current regulator.

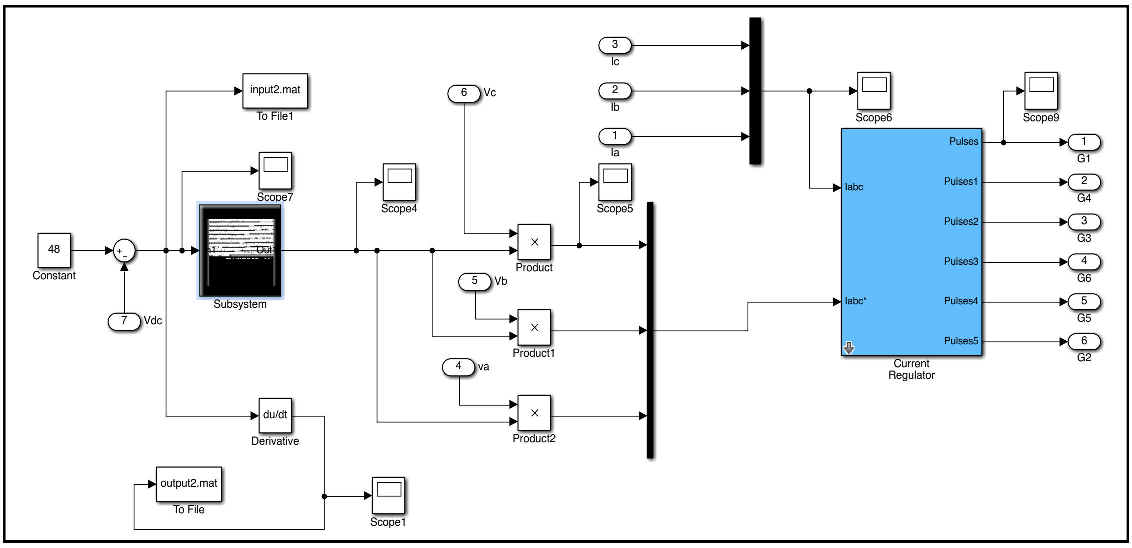


Figure 5.18: Control Model Using ANN Controller

Figure 5.18. shows the control subsystem block created using ANN controller and current regulator.

5.3. SIMULATION RESULTS OBTAINED

Stand-alone Self-Excited Induction Generator with a star-connected capacitor bank is connected to Pulse Width Modulation based Rectifier system to obtain constant DC voltage of 48V at the load terminal. Simulations using three different controllers were simulated and compared for variable speed input and variable loads.

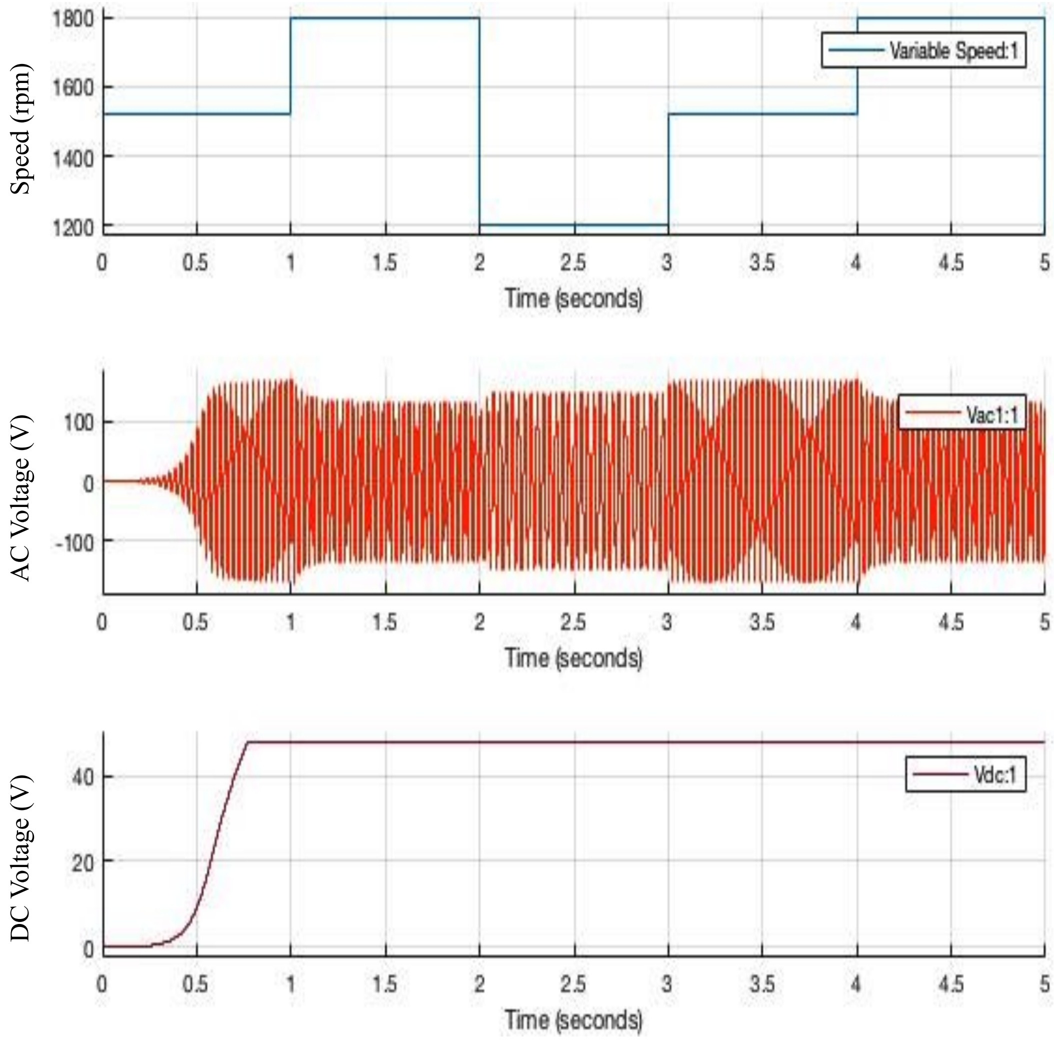


Figure 5.19: Speed Variation Vs Ac Voltage Vs Dc Voltage

Figure 5.19. shows the value of AC and DC voltages generated by induction generator with variable speed as its input. It is observed that the DC voltage remains constant during the operation, thus implying successful control strategy.

5.3.1. Comparison Of Results Obtained Using P-I And ANFIS Controllers

The DC voltage obtained by using a PI controller and ANFIS based controller is compared. The results obtained are very similar and the the tolerance limit is very low.

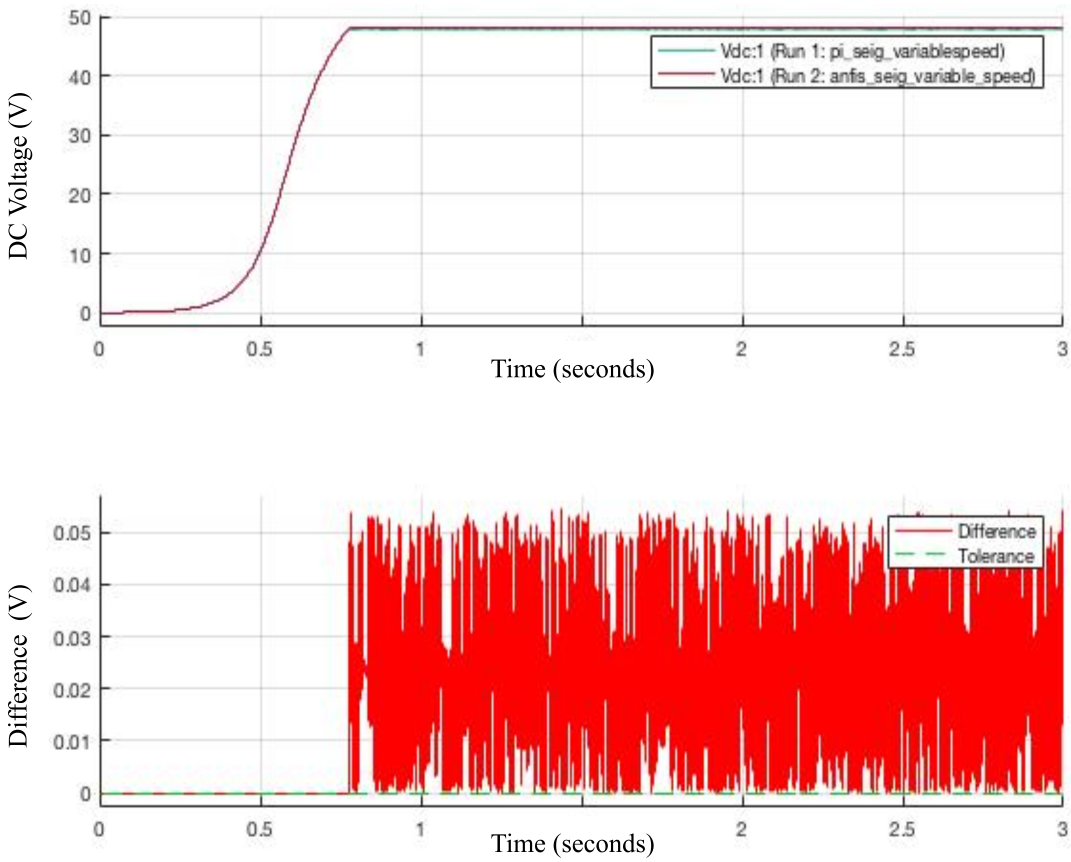


Figure 5.20: Comparison Of PI Controller And ANFIS Based Controller

Figure 5.20 shows the comparison of simulation results using P-I controller and ANFIS controllers. The results are obtained for variable speed input. The results shown by P-I controller and ANFIS controller are almost similar. The enlarged view of results is provided in Figure 5.21. with difference between them. Difference can be seen in graph sin the range of 0.05. It shows us that the ANFIS controller trained using data of P-I controller is effective and can be used in future for further variations.

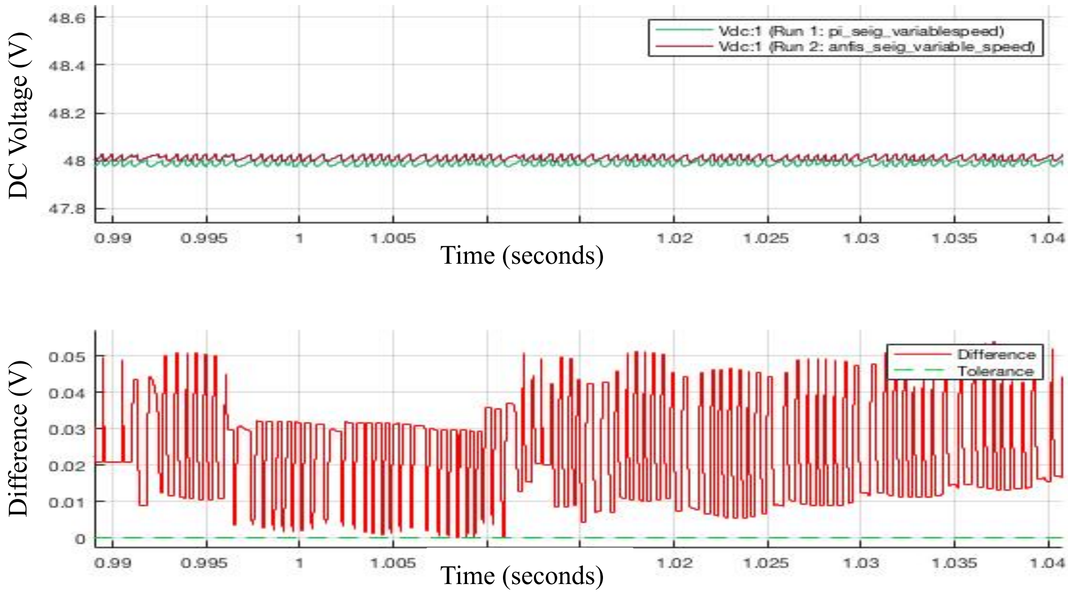


Figure 5.21: Enlarged View Results Using PI Controller And ANFIS Controller

5.3.2. Comparison Of Results Obtained Using P-I And ANN Controllers

The DC voltage obtained by using a PI controller and ANN based controller is compared. The results obtained are somewhat different and the the tolerance limit is relatively high.

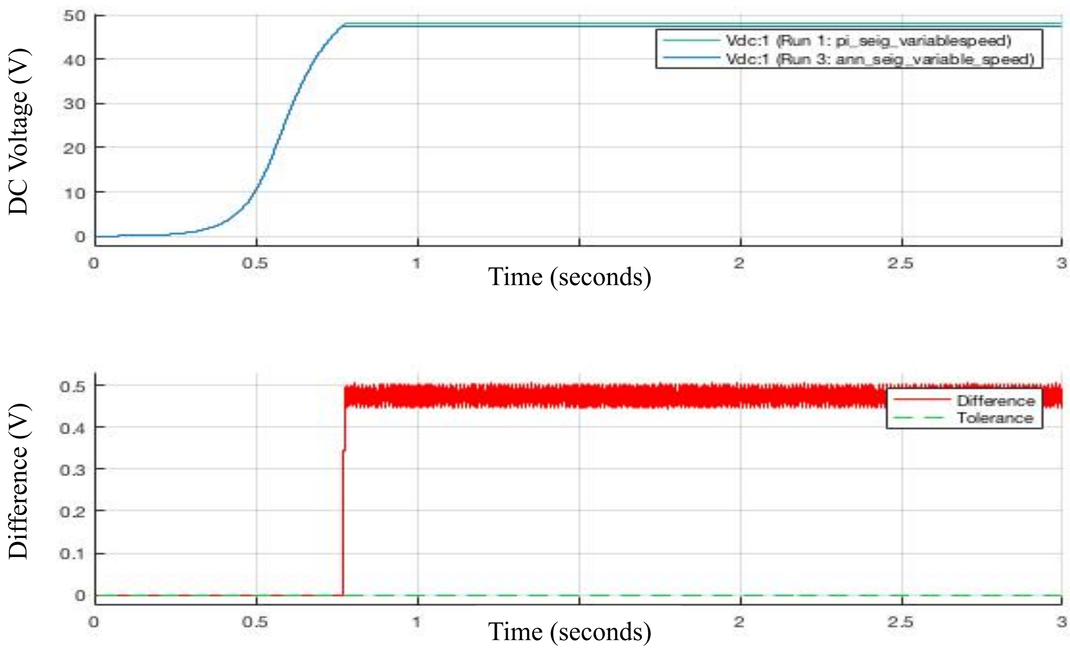


Figure 5.22: Comparison Of PI Controller And ANN Based Controller

Figure 5.22 shows the comparison of simulation results using P-I controller and ANN controllers. The results are obtained for variable speed input. The results shown by P-I controller and ANN controller are almost similar. The enlarged view of results is provided in Figure 5.23. with difference between them. Difference can be seen in graph sin the range of 0.5. It shows us that the ANN controller trained using data of P-I controller is not very effective and some changes are required to be made for it to be used in future for further variations.

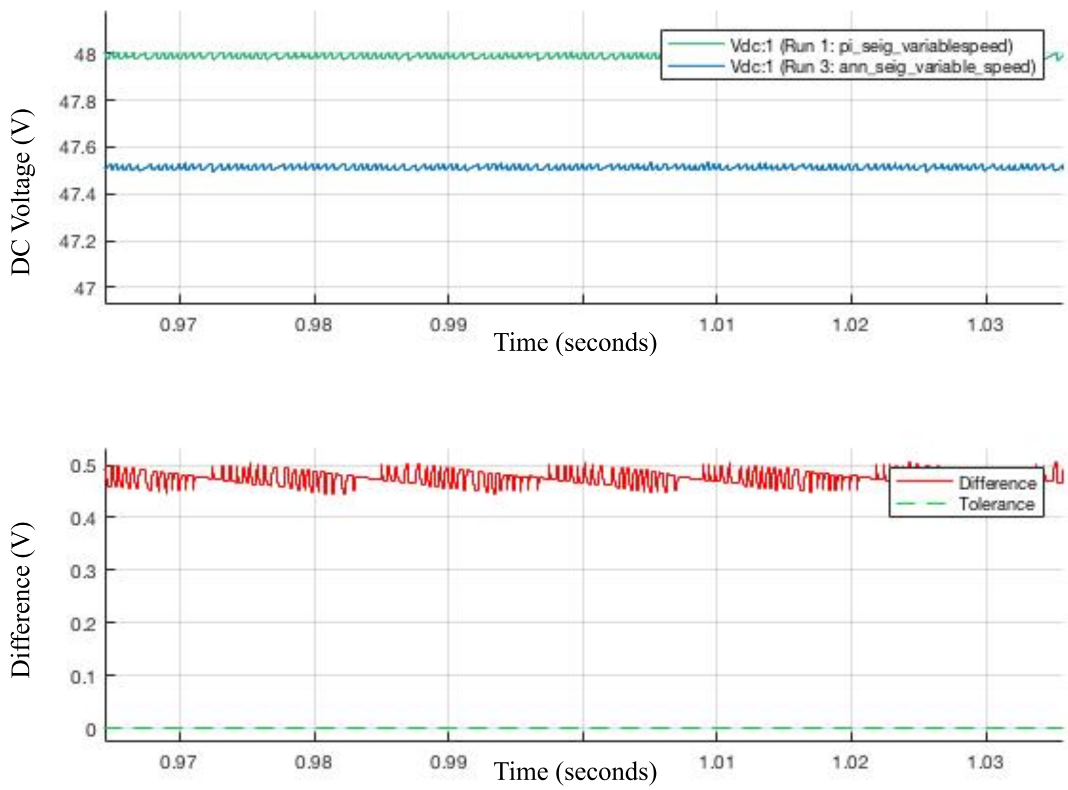


Figure 5.23: Enlarged View Results Using P-I Controller And ANN Controller

5.3.3. Comparison Of Results Obtained Using ANFIS And ANN Controllers

The DC voltage obtained by using a ANFIS controller and ANN based controller is compared. The results obtained are somewhat different and the the tolerance limit is low.

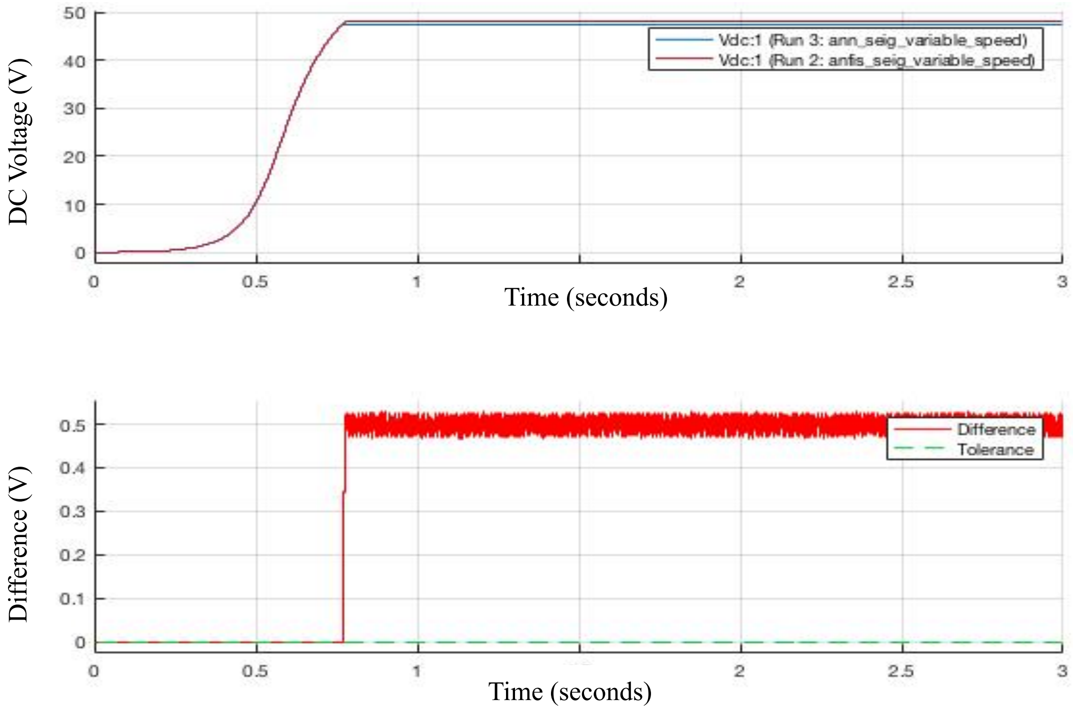


Figure 5.24: Comparison Of Anfis Controller And Ann Based Controller

Figure 5.24 shows the comparison of simulation results using ANFIS controller and ANN controllers. The enlarged view of results is provided in Figure 5.25. with difference between them.

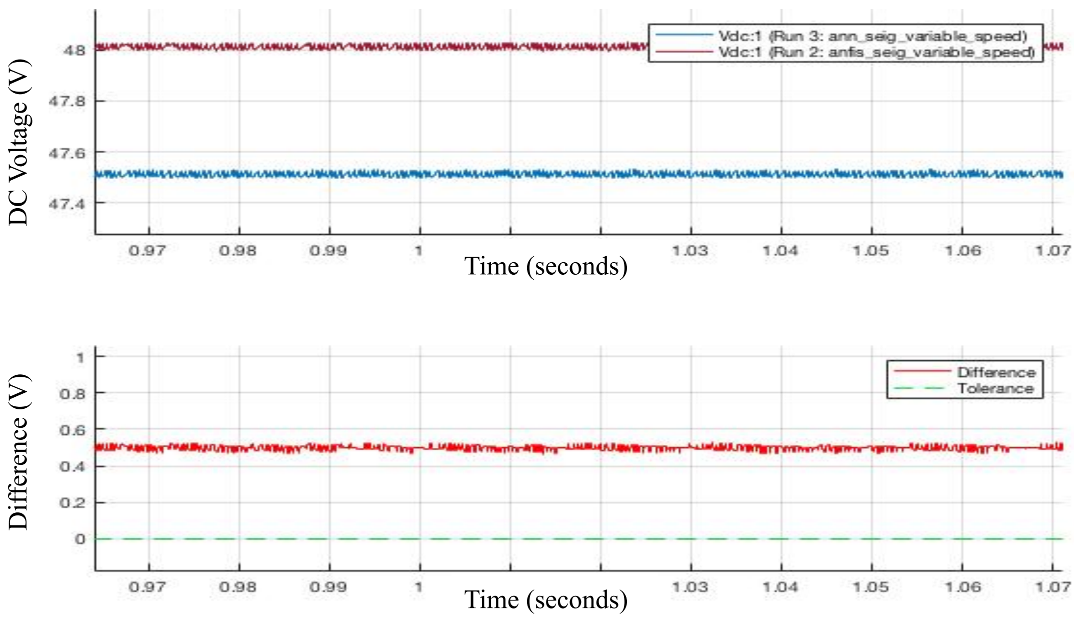


Figure 5.25: Enlarged View Results Using Anfis Controller And Ann Controller

CHAPTER 6

CONCLUSION AND FUTURE SCOPE

6.1. CONCLUSION

Due to depleting conventional energy resources, urgency and scope of renewable resources is discussed. The operation of induction machine working as a self-excited induction generator in isolated mode is explored through simulation. In comparison to the most commonly used synchronous generator, Induction generators has advantages owing to its simple and rugged structure, like low cost, absence of DC excitation, less maintenance, etc.

Firstly, the steady-state characteristics of the chosen Induction Generator is studied and analysed. The value of capacitor bank is chosen according to the non-linear magnetisation characteristics of the Induction machine. The most important disadvantage of using SEIG which restricts its usage is its failure to control the voltage output and frequency under variable load and speed change in stand-alone system. This major drawback of SEIG is compensated by conversion of AC power to DC power by usage of power electronics interfaces and proper control strategies. Two different topologies are designed for the achievement of proposed work. In chapter 4, the topology using Uncontrolled Diode Bridge Rectifier (DBR) and DC-DC converter is discussed. MATLAB Simulink® model is simulated for variable speed and variable loading conditions. The results of the model using PI controller is analysed. In chapter 5 the other topology using Hysteresis Current Controller and Pulse width Modulated (PWM) Rectifier system is discussed. MATLAB Simulink® model is simulated for variable speed conditions. Three Different controllers namely PI , ANN and ANFIS are employed to get the desired results. Implementation of these control strategies in

MATLAB® is illustrated in detail. Artificial Intelligence based controllers are trained by using the data of PI controllers. The results from these three controllers are compared for variable speed operation.

6.2 FUTURE SCOPE

The study and analysis presented in this dissertation provide a good foundation for further research in the area of isolated induction generators. Some of the ideas recommended for future work are:

- In the present work only resistive loads are considered hence, study can be extended variable inductive loads.
- Other control strategies like Space vector pulse width modulation (SVPWM) technique can be implemented to refine the results.
- Other renewable resources like PV array and fuel cell can be integrated to the DC micro-grid in future.
- Further Hardware implementation can be done to verify experimental results using DSPACE and suitable circuitry.

It is hoped that micro-grids may be able to make a very major contribution to the distributed resources based power generation. Distributed resources are small and can be installed anywhere. To extract maximum utility, DC micro-grids are considered. DC micro-grids can combine the power of many resources. If the sun is out, Solar based PV array generates power; if it is windy, the wind turbine will generate the power; if it is neither or if more power is required, the fuel cell, Oil based diesel generators, or main supply can be used. This way a more reliable and efficient power system can be created.

APPENDICES

Appendix-1 Specifications of Induction Machine

Table A1.1: Parameters Of Induction Machine

S.NO	PARAMETER	VALUE
1	Power Rating	750 W/1 HP
2	Number of Phases	3
3	Voltage	380 V
4	Current	1.9 A
5	Frequency	50 Hz
6	R_1	9.5 Ω
7	R_2	8.04 Ω
8	X_1	8.84 Ω
9	X_2	8.84 Ω
10	Base Speed	1500 r/min
11	Base impedance	115.4 Ω
12	Number of Poles	4

Air Gap Voltage: The variation of air gap voltage with magnetising reactance at rated frequency for the induction machine is as given:

- $X_m < 169.2 \longrightarrow E_1 = 512.69 - 2.13X_m$
- $179.42 > X_m \geq 169.2 \longrightarrow E_1 = 891.66 - 4.37X_m$
- $184.46 > X_m \geq 179.42 \longrightarrow E_1 = 785.79 - 3.78X_m$
- $X_m \geq 184.46 \longrightarrow E_1 = 0.$

Appendix-2 Matlab Function for Non-Linear Characteristics of Induction Generator

```
OK = [];
OK1 = [];
for X=184.46:-2:24.46
   if X < 169.2
      E= 512.69-2.13*X
   elseif X >= 169.2 && X < 179.42
      E= 891.66-4.37*X
   elseif X >= 179.42 && X < 184.46
      E= 785.79-3.78*X
   else
      E=0
   end
   I = E/X
   OK=[I 1.732*E]
   OK1=[OK1;OK]
end
```

Appendix-3 Matlab Function for Training data of ANFIS controller

```
ok=[];
ok1=[];
for k=1:1:60001

   ok=[error change_in_error u_output];
   ok1=[ok(:,2) ok(:,4) ok(:,6)];

   end
```

Appendix-4 M-File for ANFIS Network

[System]

Name='anfis'

Type='sugeno'

Version=2.0

NumInputs=2

NumOutputs=1

NumRules=9

AndMethod='prod'

OrMethod='probor'

ImpMethod='prod'

AggMethod='sum'

DefuzzMethod='wtaver'

[Input1]re

Name='input1'

Range=[-0.00711267822883599 47.9999654849299]

NumMFs=3

MF1='in1mf1':'trimf',[-24.0106517598082 -0.00711267822883599 23.9964264033505]

MF2='in1mf2':'trimf',[-0.00711267822883599 23.9964264033505 47.9999654849299]

MF3='in1mf3':'trimf',[23.9964264033505 47.9999654849299 72.0035045665093]

[Input2]

Name='input2'

Range=[-205.712456223802 500.685340407786]

NumMFs=3

MF1='in2mf1':'trimf',[-558.911354539595 -205.712456223802 147.486442091992]

MF2='in2mf2':'trimf',[-205.712456223802 147.486442091992 500.685340407786]

MF3='in2mf3':'trimf',[147.486442091992 500.685340407786 853.88423872358]

[Output1]

Name='output'

Range=[-0.0434810797598769 479.999654849299]

NumMFs=9

MF1='out1mf1':'constant',[-0.0435612380770561]

MF2='out1mf2':'constant',[-0.0434562771377569]

MF3='out1mf3':'constant',[0.00577206101201282]

MF4='out1mf4':'constant',[239.986055763624]

MF5='out1mf5':'constant',[240.019295905842]

MF6='out1mf6':'constant',[196.813909014473]

MF7='out1mf7':'constant',[480.033942578196]

MF8='out1mf8':'constant',[479.988218175622]

MF9='out1mf9':'constant',[0]

[Rules]

1 1, 1 (1) : 1

1 2, 2 (1) : 1

1 3, 3 (1) : 1

2 1, 4 (1) : 1

2 2, 5 (1) : 1

2 3, 6 (1) : 1

3 1, 7 (1) : 1

3 2, 8 (1) : 1

3 3, 9 (1) : 1

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