Power Quality Improvement in grid connected distribution systems using Artificial Intelligence based Control algorithms

A DISSERTATION

SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS

FOR THE AWARD OF THE DEGREE OF

MASTER OF TECHNOLOGY

IN

CONTROL AND INSTRUMENTATION

SUBMITTED BY:

SHREYA SINHA

(2K19/C&I/19)

UNDER THE SUPERVISION OF:

Ms. Ankita Arora

Assistant Professor

Department of Electrical Engineering

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Shahbad Daulatpur, Main Bawana Road, Delhi-110042

2019-2021

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

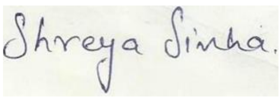
Shahbad Daulatpur, Main Bawana Road, Delhi-110042

CANDIDATES' DECLARATION

I, *Shreya Sinha* (2K19/C&I/19) student of M.Tech., Control and Instrumentation Engineering at Delhi Technological University hereby declare that the dissertation titled "**Power Quality Improvement in grid connected distribution systems using Artificial Intelligence based Control algorithms**" which is submitted by me to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not plagiarized from any source without proper citation. This work has not previously formed the basis for award of any Degree, Diploma, Associateship, Fellowship, or any other similar title or recognition.

Place: Delhi Technological University

Date: 06-07-2021



SHREYA SINHA

2K19/C&I/19

DEPARTMENT OF ELECTRICAL ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi-110042

CERTIFICATE

I, hereby certify that the Dissertation titled "**Power Quality Improvement in grid connected distribution systems using Artificial Intelligence based Control algorithms**" which is submitted by Shreya Sinha (2K19/C&I/19) to the Department of Electrical Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge, this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi Technological University

Date: 06-07-2021

27/7/21

MS. ANKITA ARORA

Supervisor (Assistant Professor)

(Dept. of Electrical Engineering)

ABSTRACT

These days the Power Quality has become the key issue in electrical distribution power systems. The power quality is deteriorating because of the extensive utilization of non-linear loads and power electronic devices like solid-state switching devices which injects the current harmonics in the distribution systems. These harmonics leads to increase in power loss in transmission and distribution network. In this thesis performance analysis of artificial intelligence-based controllers such as Artificial neural network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) for shunt compensation has been studied for power factor improvement, current harmonics reduction and reactive power compensation. These control methodologies are executed in MATLAB Simulink 2018a. Their comparison analysis with the conventional time domain Instantaneous Reactive Power Theory (IRPT) has been analysed on the basis of various critical factors such as Total Harmonic Distortion Factor (THD), peak overshoot, settling time, convergence rate and the settling time of dc side capacitor voltage. The simulation results obtained demonstrates that ANFIS converges faster than ANN and IRPT under steady state and dynamic changing load conditions and has THD of around 1.06% obtained.

Keywords—DSTATCOM, Fundamental current, IRPT, ANN, ANFIS, Total Harmonic Distortion.

ACKNOWLEDGEMENT

The satiation and elation that go with the successful fulfilment of the project would not be complete without mentioning the people who made it plausible.

I would like to take the opportunity to thank and express my deep sense of gratitude to my mentor Ms. Ankita Arora, Assistant Professor, Delhi Technological University. I am enormously obligated to her for her significant direction at all phases of the project, counsel, helpful proposals, positive and steady demeanour and constant consolation, without which it would not have been possible to finish the major project.

I also want to thank our teachers who consistently strive to make our department stand apart among others. Their devotion is a power that rouses us to work more diligently.

At last, I would like to thank our parents, family, college staff, companions and all the individuals who were straightforwardly and by implication engaged with this project work for their help and consolation.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AI	Artificial Intelligence
ANFIS	Adaptive network based fuzzy inference system
ANN	Artificial neural network
APF	Active power filter
DSTATCOM	Distribution static synchronous compensator
FIS	Fuzzy inference system
FL	Fuzzy logic
FLC	Fuzzy logic controller
IRPT	Instantaneous Reactive Power Theory
IGBT	Insulated gate bipolar transistor
IEEE	Institute of electrical and electronic engineering
MSE	Mean square error
RMSE	Root mean square error
PCC	Point of common coupling
PI	Proportional Integral
PWM	Pulse Width Modulation
RMS	Root mean square
SVC	Static VAR Compensator
SAPF	Shunt active power filter
SAPF	Series active power filter
THD	Total harmonic distortion
UPQC	Unified power quality conditioner

VSC	Voltage source converter

LIST OF EQUATIONS

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

Power quality are the prime concern of any power system at the different levels (generation level, transmission level, distribution level and utilization level). The rapid increase in power quality problems is due to the proliferation of power electronic based equipment which include converters, SMPS, computer etc. Due to employment of these power electronic based non-linear load, power quality issues like load unbalancing, poor power factor, voltage regulation arises. A voltage source convertor DSTATCOM provides shunt compensation to intensify the power quality by supplying the required reactive power. Many control algorithms are there that maintains the grid current as sinusoidal even with nonlinear load. The ANN and ANFIS based control algorithms provide more sinusoidal source waveform.

In this thesis, Instantaneous Reactive Power Theory methodology is compared to Artificial Neural Network and Artificial Neural Fuzzy Inference System. ANFIS based control algorithm gives better source current waveform with reduced harmonic distortion as compared to ANN and IRPT. ANFIS learns faster and gives better efficiency when compared to IRPT and ANN. The comparison-based analysis of IRPT, ANN and ANFIS is done and it is illustrated that ANFIS performs better when compared to IRPT and ANN.

CHAPTER 2

LITERATURE SURVEY

2.1. INTRODUCTION

The quality of supply power is the most concerned areas of industrial sector as well as domestic sector and are categorized into current quality problems and voltage quality problems. Some power quality issues are sag, transients, and harmonics. Flexible controllers like DSTATCOM are based on the principle of VSC. The configuration of DSTATCOM consists of IGBT based convertor with a dc link capacitor to store energy on the dc side. The gating pulse to the DSTATCOM are produced by implementing hysteresis carrier less PWM (Pulse width modulation). This hysteresis carrier less PWM technique compares this fundamental component of current with the source current to induce the gating pulse for DSTATCOM. The principle of DSTATCOM involves generation of compensating current which rely on the fundamental component of current obtained from some techniques of extraction. The control algorithm thus employed to generate the fundamental component of current determine the operation of the DSTATCOM.

These custom power devices consisting of DSTATCOM helps to reduce power quality issues like compensating harmonics, power factor improvement, resonance, compensating voltage related problems within IEEE standards and is consolidated at the PCC to boost power quality of the system.

2.2. POWER QUALITY PROBLEMS

Some of the power quality issues are:

2.2.1. VOLTAGE SAG

Voltage Sag is decrease in voltage amplitude between 10% to 90% of nominal RMS voltage for a short period of time.

CAUSES OF VOLTAGE SAG

On the utility side, voltage sag occurs due to natural phenomenon and some human created events like switching operation. Starting of large motor may lead to voltage sag.

Some of the natural phenomenon leading to voltage sag are:

- Wind
- thunderstroke
- Equipment malfunction
- Falling of trees on the power lines

Some other causes are:

- Direct online starting of large motors
- short circuit
- Arcing fault
- Energizing power transformer

EFFECT OF VOLTAGE SAG

- malfunction of process controllers
- malfunction of adjustable speed drives
- reduction in the performance of the motor
- flickering in illumination devices

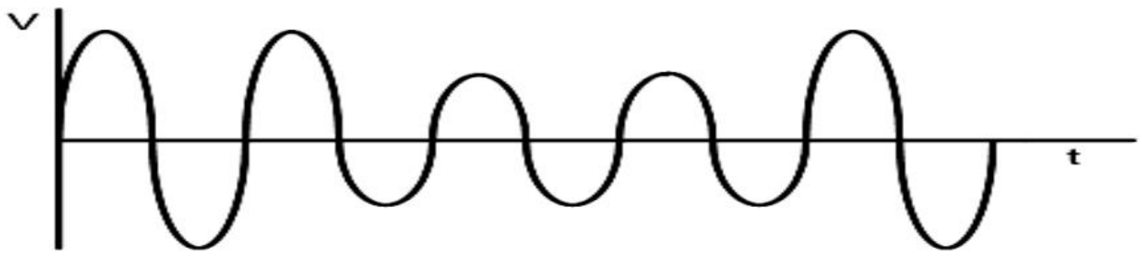


Fig.2.1. Representation of Voltage Sag

2.2.2. VOLTAGE SWELL

Voltage swell is increase in voltage amplitude between 110% to 180% of nominal RMS voltage for the duration of 0.5 minute to 1 minute as described by IEEE 519.

CAUSES OF VOLTAGE SWELL

- DE energization of a very large load

- abrupt interruption of current leading to large voltage

EFFECT OF VOLTAGE SWELL

- hardware failure due to overheating
- breakdown of components

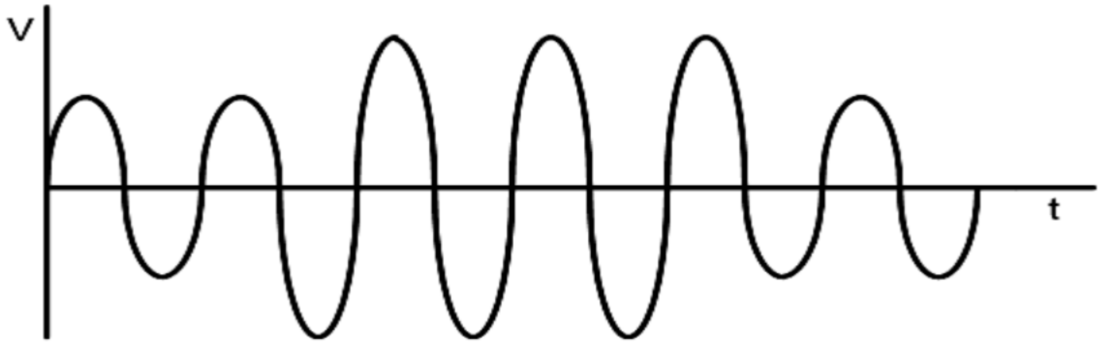


Fig.2.2. Representation of Voltage Swell

2.2.3. INTERRUPTION

It is classified as short duration interruption and long duration interruption.

SHORT DURATION INTERRUPTION:

It is explained as the reduction of load current or supply voltage to less than 1% of the nominal for a duration of less than 1 minute.

EFFECT OF SHORT DURATION INTERRUPTION

- sensitive equipment failure like PLC
- Unwanted tripping of protective devices
- Data loss and malfunctioning of equipment processing data

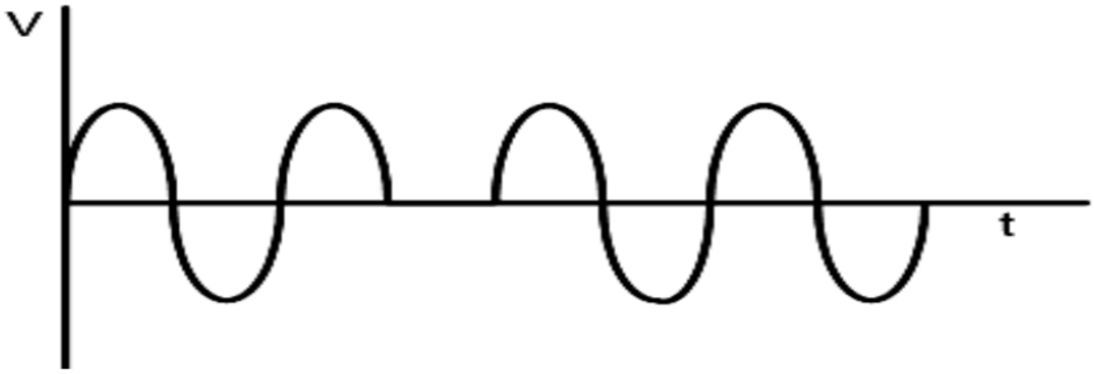


Fig.2.3. Representation of Short Interruption

LONG DURATION INTERRUPTION:

Long duration interruption or sustained interruption is described as the decrease in supply level voltage to zero for a duration of more than 1 minute as described by IEEE 1159.

EFFECT OF LONG DURATION INTERRUPTION:

- utility equipment failure
- shutdown of the customer facility.

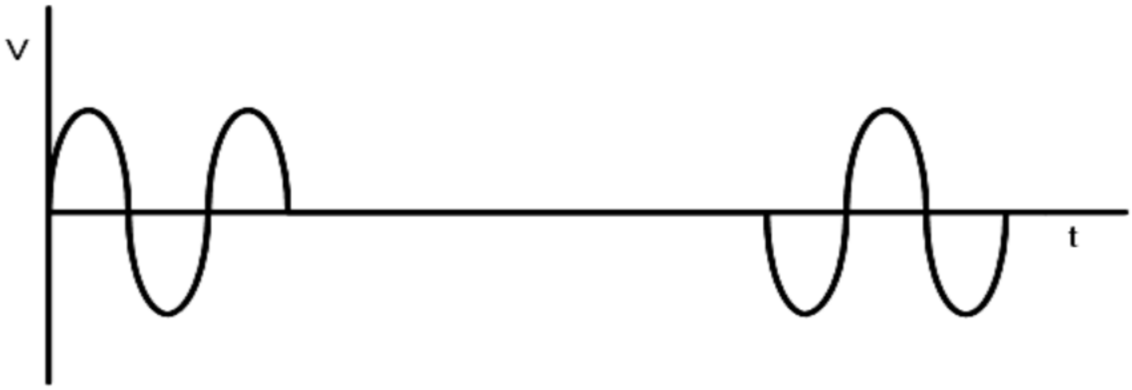


Fig.2.4. Representation of Long interruption

2.2.4. HARMONICS DISTORTION

Harmonics are sinusoidal current and voltages that operates at fundamental frequency or at an integral multiple of fundamental frequency while sinusoidal variations in current or voltage is termed as harmonic distortion. The major cause of introduction of harmonic distortion in the system is the presence of non-linear load or variation in load impedance.

EFFECTS OF HARMONIC DISTORTION

- Conductor losses
- Due to higher order harmonics, the Skin Effect leads to the requirement of oversizing of conductors or may lead to losses
- Overheating of rotors
- Reduction in torque

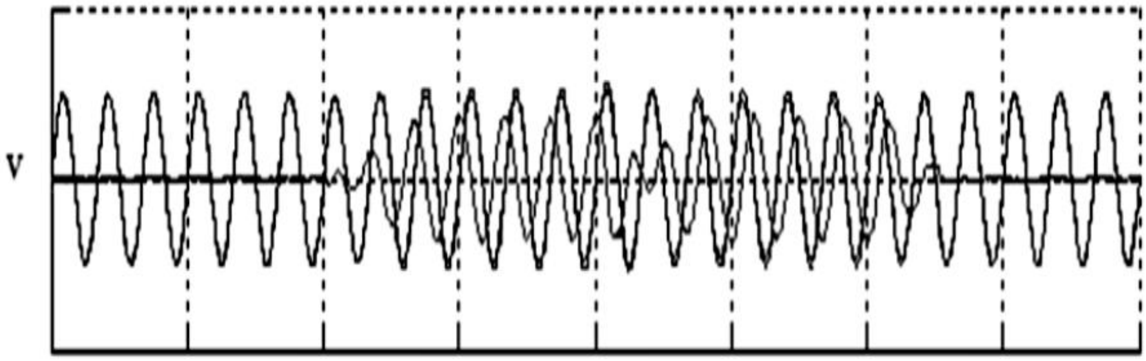


Fig.2.5. Representation of Harmonic Distortion

2.2.5. TRANSIENT

Transients are sudden surges that are introduced in the distribution system or utility. Large voltages are introduced in the system due to these transients leading to very large amount of current for a very short duration of time (microsecond or millisecond).

IMPULSIVE TRANSIENT

Short and unidirectional change in both voltages and current that are caused due to lightening or switching of inductive load is termed as impulsive transient.

Fig.2.6. Representation of impulsive transient

OSCILLATORY TRANSIENT

Small bidirectional change in voltage, current leading to overheating of equipment and failure of insulation material is termed as oscillatory transient.

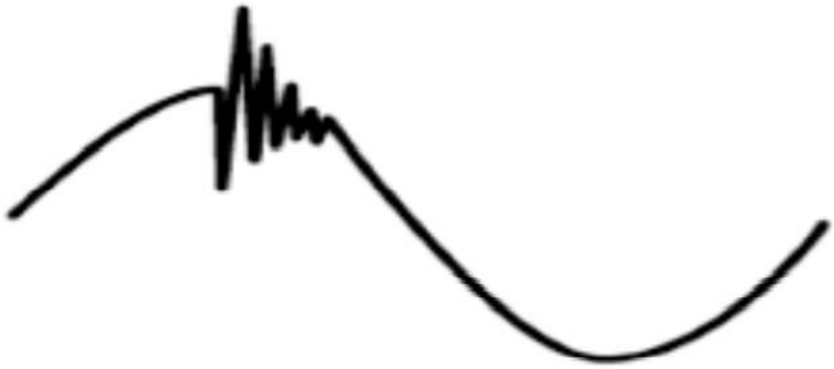


Fig. 2.7. Representation of Oscillatory transient

2.3. CONVENTIONAL DEVICES

Some Conventional devices like SHAPF, SAF and UPQC are:

2.3.1. SHUNT ACTIVE POWER FILTERS

Active Power Filters is based on the principle of compensation of harmonic current/voltage at low or medium voltage levels. The topology of APF comprises VSC and CSC for the generation of compensating signal and are categorized into SAPF, SAF and HAPF based on its connection configuration.

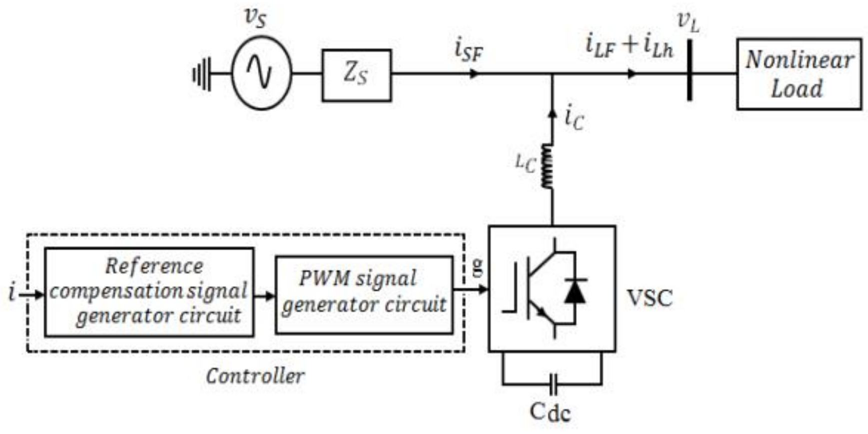


Fig.2.8. Representation of SAPF

The major components of SAPF consists of VSC and the interfacing inductor as shown in Fig.2.8. this dc link capacitor acts as energy storing element and supplies the stored energy as required. The other part of SAPF is the controller unit that extracts the compensating signal, used to generate gate pulse for the IGBT switches of the VSC.

2.3.2. SERIES ACTIVE FILTERS

Series Active filter (SAF) is employed between the source and the load through a coupling transformer as illustrated in Fig.2.9. SAF are employed to regulate voltage and to remove harmonics. It introduces a voltage fundamental component in series with the supply voltage as is based on the principle of elimination of voltage harmonic component on the load side

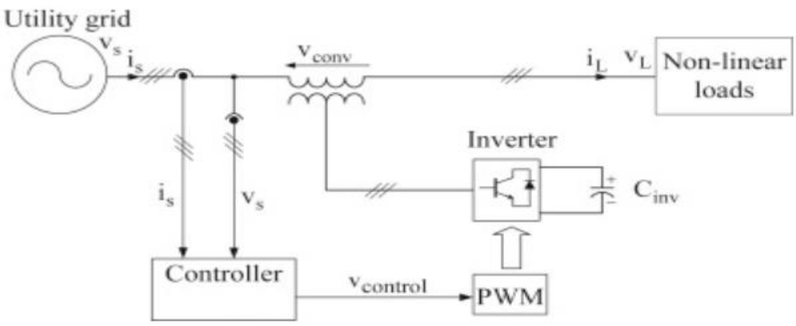


Fig.2.9. Representation of SAF

2.3.3. UNIFIED POWER QUALITY CONDITIONER (UPQC)

UPQC is implemented for the compensation of voltage distortion and voltage imbalance in grid connected distribution system. The topology of UPQC comprises both SAPF and SAF in fig.2.10. It consists of two VSC that are connected back-to-back through a dc link capacitor. Load current harmonics are compensated by employing SAPF in parallel to the transmission line and voltage distortions and unbalance is compensated using SAF in UPQC.

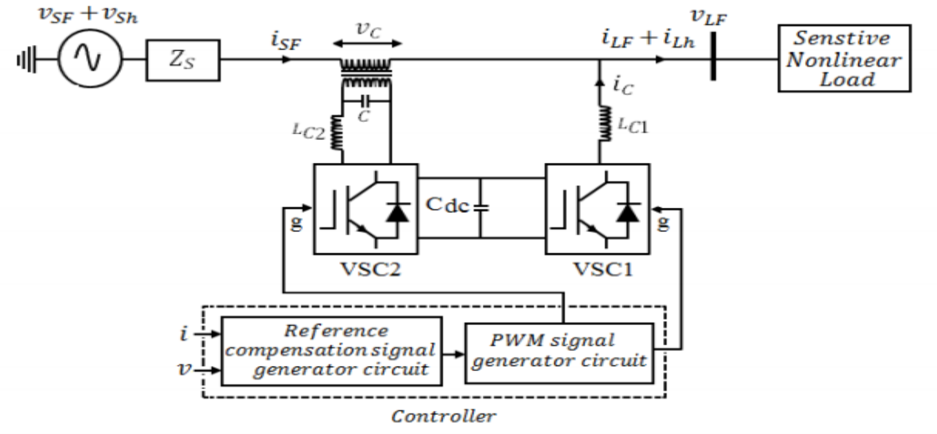


Fig.2.10. Representation of UPQC

CHAPTER 3

SYSTEM CONFIGURATION

The system configuration of Grid connected systems is illustrated in Fig.3.1. DSTATCOM is connected to the distribution system through interfacing inductors. A dc link capacitor is associated at one end of the Distribution Static Compensator. A non-linear load is attached at the load side. DSTATCOM is a static compensator that generates variable capacitive compensation and variable inductive compensation and it consists of an inverter whose DC side is connected with a capacitor. The inverter consists of the switches which contains anti-parallel diodes which charges the capacitor. The mind of the DSTATCOM is a controller block and the inputs of the controller block are the current. Fundamental component of current is generated using the controller. A Hysteresis current controlled PWM is employed to provide the switching signal to the Distribution Static Compensator.

$$source\ current(i_s) + compensating\ current(i_c) = load\ current(i_l)$$

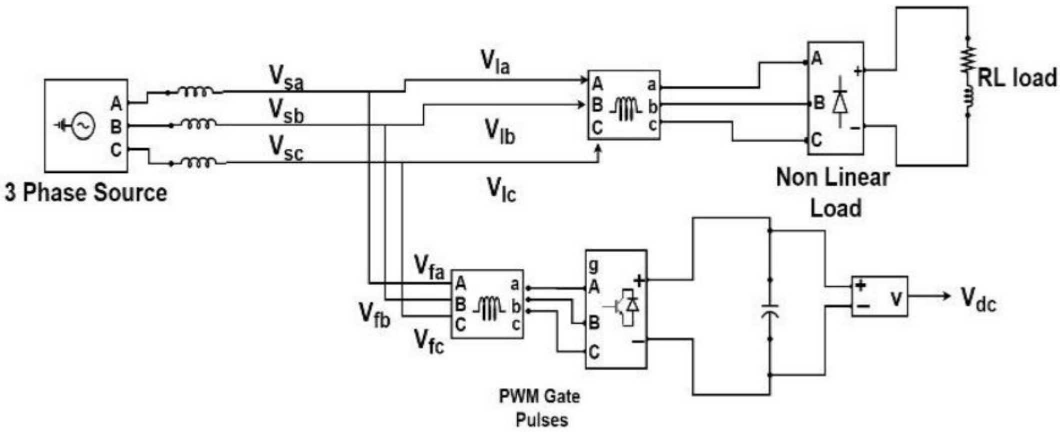


Fig. 3.1. Schematic Representation of DSTATCOM in Grid connected Systems

3.1. About DSTATCOMs (distribution static compensators)

DSTATCOM is a shunt connected voltage source convertor with six IGBT and anti-parallel diodes connected to these IGBTs that deals with the power quality issues like load imbalance, poor power factor, voltage regulation and harmonics.

DSTATCOM is a very new advancement within the field of Power Quality and is very cost-effective methodology for harmonics reduction. Reactive power compensation is done by employing DSTATCOM. DSTATCOM is shunted with dc link capacitor from one side which stores energy and supplies the reactive power when required.

Here, we are employing VSCs rather than CSCs as CSCs incorporates higher losses and is costlier than VSCs.

Basically, we are employing DSTATCOMs here for the elimination of power quality issues related to current in line.

3.2. Principle of Operation of DSATCOMs

The DSTATCOM system consists of VSC, coupling reactors and a controller and the basic principle of DSTATCOM is to generate a controllable ac voltage source.

DSTATCOM is employed to generate and absorb reactive power and it also exchanges real power when connected with an external active dc source.

1) **Reactive Power Exchange:** DSTATCOM generates reactive power when the output voltage of VSC exceeds the system voltage.
   While, DSTATCOM absorbs reactive power when the output voltage of VSC is less than the system voltage.
2) **Real Power Exchange:** DSTATCOM is also used for real power exchange when it is associated with the active dc source. Inverter absorbs real power when VSC output voltage lags behind system voltage, while it supplies real power when output voltage of VSC exceeds the system voltage.

3.3. Control of DSATCOMs

The operation of DSTATCOM is based on control algorithm for its gate pulse. DSTATCOM is employed to provide voltage support, power factor improvement. Whenever loads need the reactive power, DSTATCOM provides reactive power for reactive power compensation. The dc link capacitor in DSTATCOM stores energy and supplies the required reactive power. For the switching of DSTATCOM reference source current is used which has fundamental component of load current.

Steps involved in the employment of the control algorithm:

- Measurement of system current and system voltage
- Calculation of compensating signal
- Generation of gate pulse.

CHAPTER 4

CONTROL ALGORITHMS

For Power quality mitigation, reactive power compensation technique is used as it increases due to employment of non-linear load leading to power loss in the system. DSTATCOM is employed to retain the power factor of source current as unity by supplying the desired reactive power. The dc link capacitor employed in DSTATCOM stores energy and supplies the reactive power as required. DSTATCOM requires gate pulse for its performance and is decided by the reference source current. The reference source current incorporates the fundamental component of load current and different control algorithms are employed to extract it. Some of the control algorithms used here are IRPT, ANN and ANFIS.

4.1. IRPT Algorithm

IRPT algorithm is also called p-q hypothesis. The control algorithm generates pulses utilized for the performance of DSTATCOM. IRPT controller depends upon the conversion of 3-phase quantities to 2-phase quantities and is appropriate to all three-phase system with zero sequence component or without zero sequence component, unbalanced load and balanced load. IRPT algorithm is based on the calculation power.

The terminal voltages are

$$v_a = v_m \sin \omega t$$
$$v_b = v_m \sin(\omega t - 2\pi/3) \quad (4.1)$$
$$v_c = v_m \sin(\omega t - 4\pi/3)$$

The load currents are

$$i_{La} = \sum I_{Lan} \sin\{n(\omega t) - \theta_{an}\}$$
$$i_{Lb} = \sum I_{Lbn} \sin\{n(\omega t - 2\pi/3) - \theta_{bn}\} \quad (4.2)$$

$$i_{Lc} = \sum I_{Lcn} \sin\{n(\omega t - 4\pi/3) - \theta_{cn}\}$$

The three phase quantities are converted to alpha-beta frame by using Clark's transformation.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{Sa} \\ V_{Sb} \\ V_{Sc} \end{bmatrix} \quad (4.3)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (4.4)$$

Here α –β are the orthogonal component and a, b, c are the phase components.

Instantaneous reactive power is

$$q = -v_\beta i_\alpha + v_\alpha i_\beta \quad (4.5)$$

Instantaneous active power is

$$p = v_\alpha i_\alpha + v_\beta i_\beta \quad (4.6)$$

In matrix form

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (4.7)$$

Current in matrix form

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (4.8)$$

Here,

$$\Delta = v_\alpha^2 + v_\beta^2 \quad (4.9)$$

Reference source current in α-β coordinate is

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ 0 \end{bmatrix} \quad (4.10)$$

Where, $\bar{p}$ is the dc part

The 2- phase current is again converted into 3-phase current

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & 1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & 1/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_0^* \\ i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} \tag{4.11}$$

4.1.1. Block diagram of IRPT

IRPT algorithm is employed to produce gate pulse for the DSTATCOM. Clark transformation is implemented here for the conversion of $a-b-c$ to $\alpha-\beta$ reference frame. Three phase load current $i_{la}, i_{lb,} i_{lc}$ and three phase source voltage v_a, v_b, v_c are sensed and Clark transformed thus converting it to $\alpha-\beta$ reference frame. Instantaneous active and reactive power is computed in orthogonal rotating vector $\alpha-\beta\ frame$. Reactive power thus obtained is terminated while Active power is summed with the error signal obtained using PI control and this error signal is produced by implementing dc link capacitor voltage and 200V. Signal is then converted to two phase components and this current signal is then reverse Clark transformed and is converted into three phase quantities. The fundamental component of current thus obtained is fed to the hysteresis current controller and its output is further utilized as the switching signal of DSTATCOM.

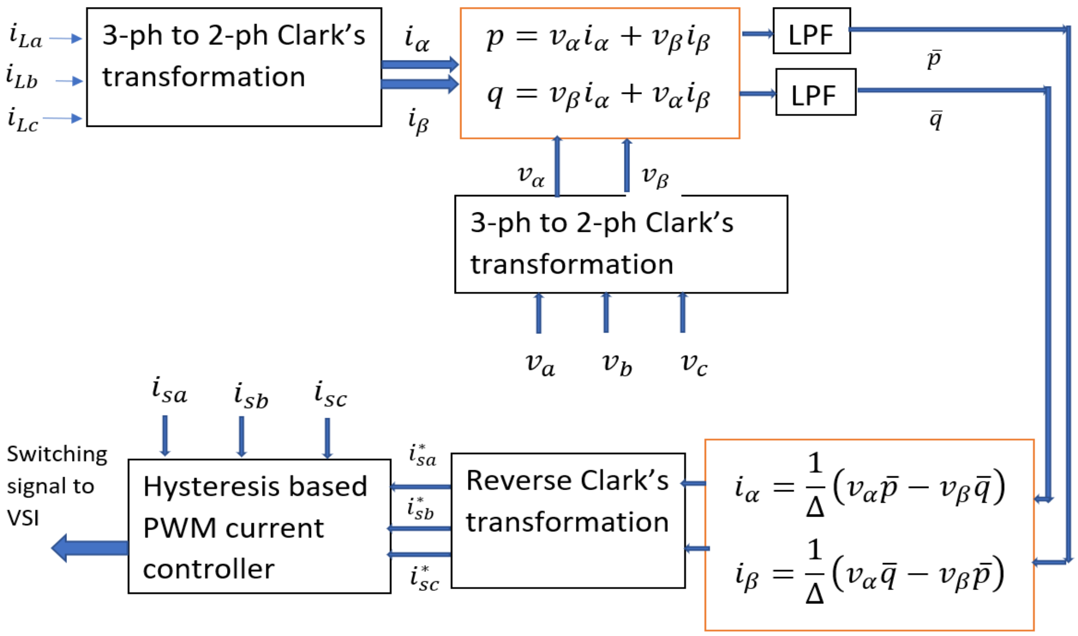


Fig. 4.1. Flow diagram Representation of IRPT

4.1.2. Hysteresis based Current Controller

Hysteresis based current controller is employed to generate gate Pulses for the VSI, it is the most appropriate strategy for current controlled VSI.

Need for HCC against different controllers

1. Fast reaction

2. Good precision is the main characteristic of this controller

3. Fast transient effect with actual for effective implementation

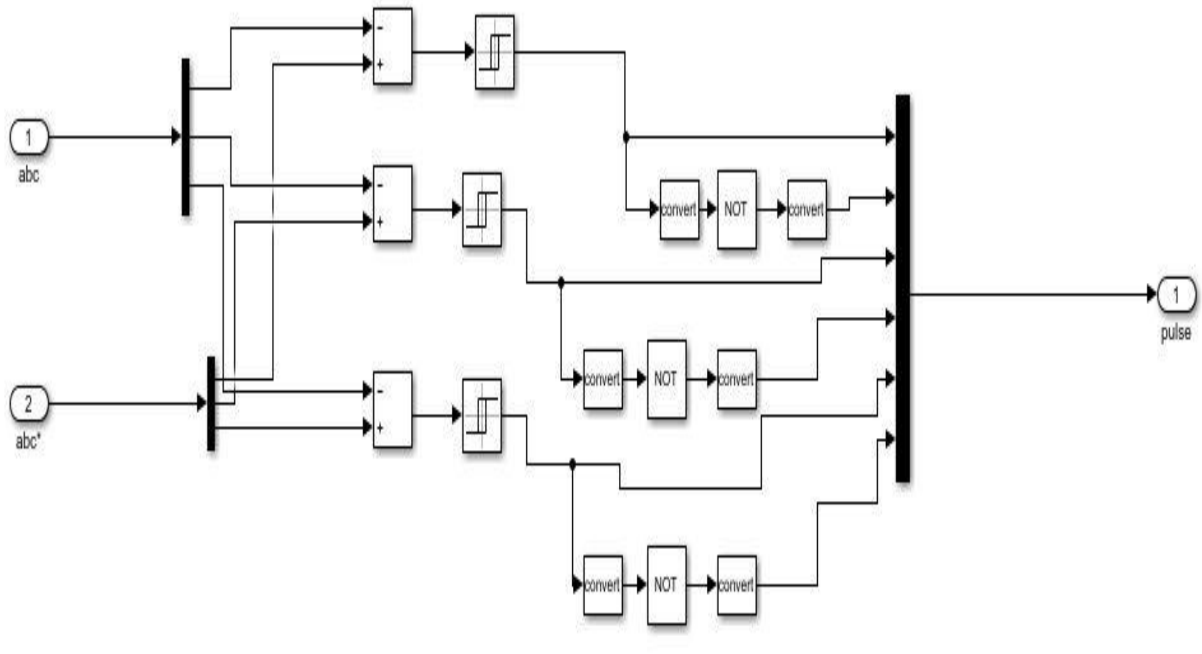


Fig. 4.2. Inside the HCC square

Characteristic of the Hysteresis Current Controller three-stage PWM converters are

• elementary execution

• Intrinsic restricted greatest current

• Exceptional soundness

- Quick transient reaction and great precision
- Inborn vigour to stack parameter varieties
- Reasonable transient and unfaltering state introduction
- Remuneration of impact due to stack parameter changes (reaction and obstruction)
- Top security
- abundantly great elements
- Over burden dismissal
- Utmost cycle task
- Simple to implement

4.2. Artificial Neural Network (ANN)

ANN is a mathematical model or computational model which is based on machine learning algorithm and it functions like the neurons of a human nervous system with cluster of artificial neurons. ANN learns from the past data and gives output based on the predictions, when internal or external data or information move in the network then the group of artificial neurons present in it changes its structure and Unidirectional or Bidirectional weighted signals are organized for the interconnection of ANN. ANNs exhibit a complex relation with input and output where Pattern recognition can be done by the adjustment of the synaptic network in ANN.

Neural Network Algorithm

Learning process begins by separating the data sets into three distinct sets:

- **Training dataset**

  It comprises actual dataset (weights and biases) to train the model. This dataset allows ANN to acknowledge the weights present between nodes and thus it realizes and retains from this data.
- **Validation Dataset**

  It is used to tune the hyperparameters of the model or the performance of the neural network, and this validation dataset results are further used to update higher level hyperparameter.

- **Test Dataset**

  It is employed to obtain the accuracy of the error of neural network and provides an independent measure of network efficacy.

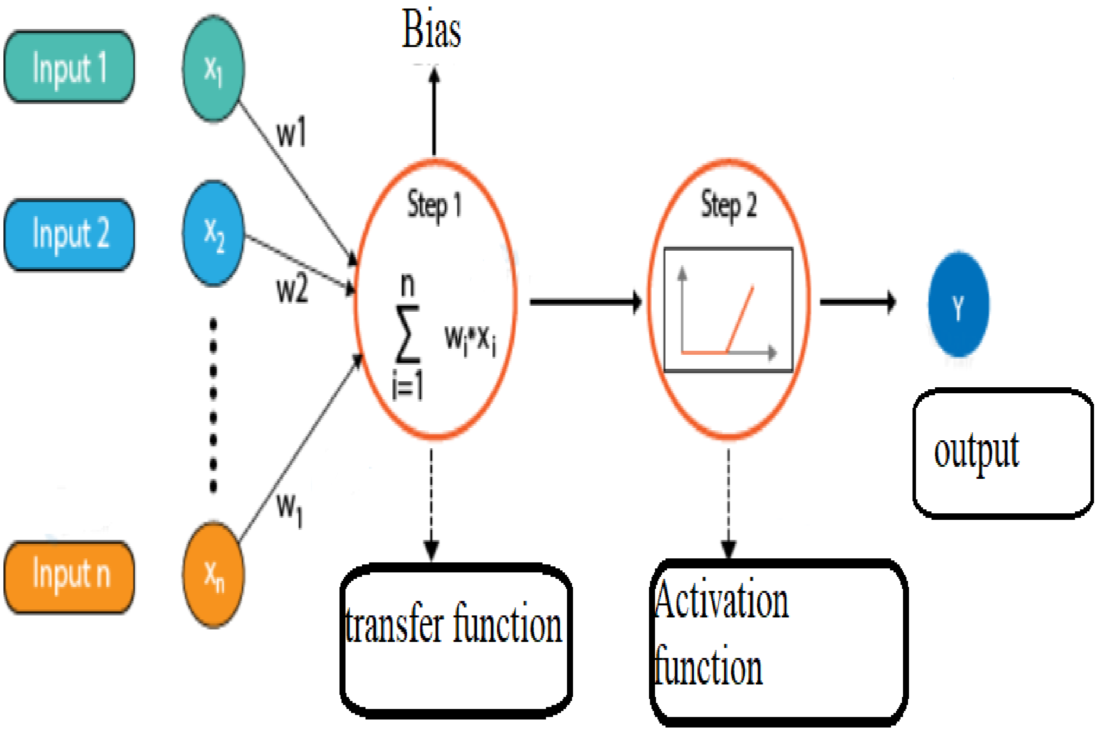


Fig. 4.3. Schematic Diagram of Neural Network

4.2.1. Framework of Neural Network

ANN comprises three layers:

- **Input layer**

  This layer supplies information from outside to the network and passes the information to the hidden layer.

- **Hidden layer**

  It performs computation work; Mathematical calculations are computed in the hidden layer.

- **Output layer**

  Result is obtained from the output layer and it depends on parameters like weights, biases, learning rates etc.

An elementary neural network is depicted as demonstrated in the figure below:

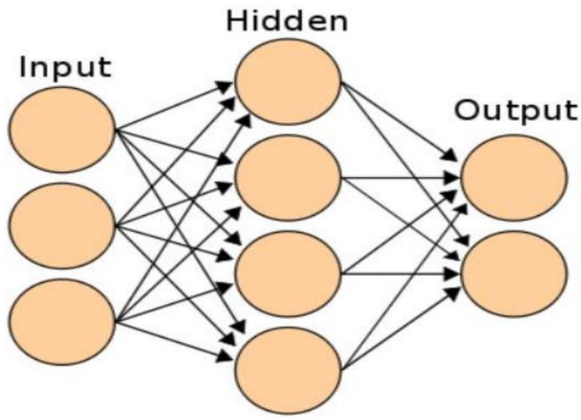


Fig. 4.4. Layers of a basic Neural Network

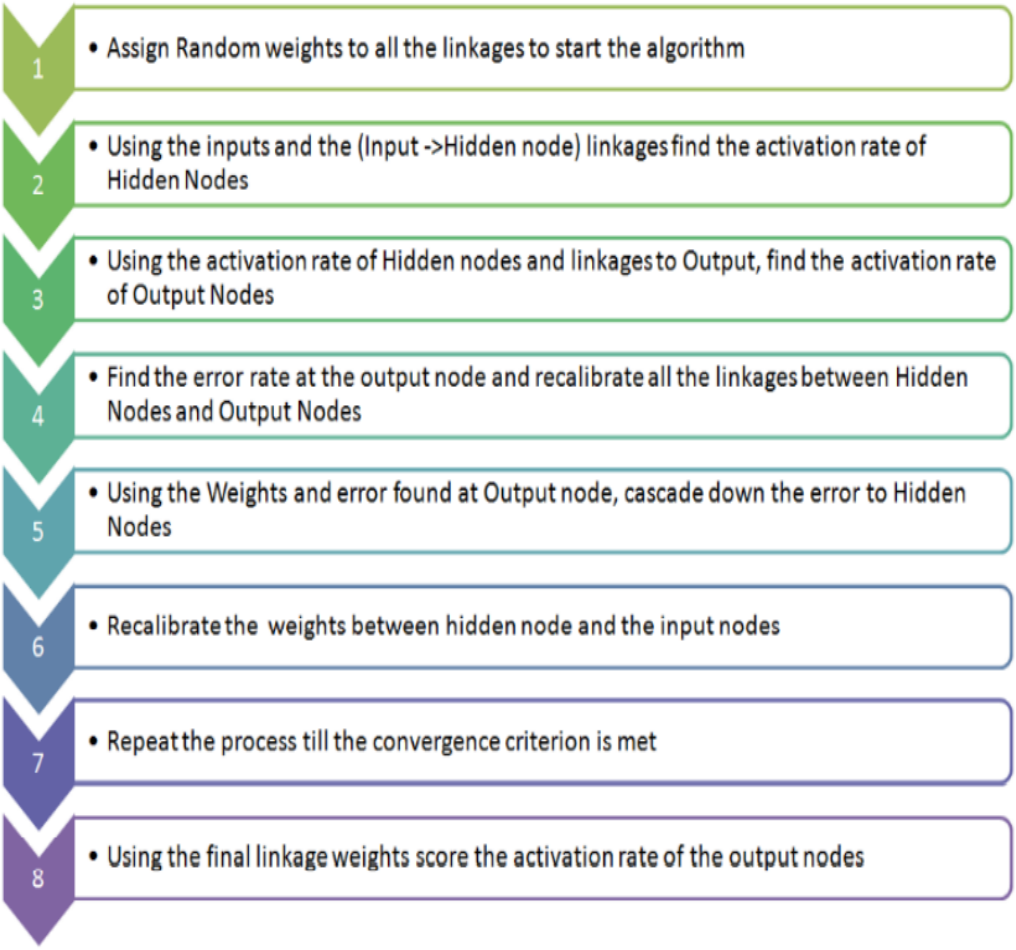


Fig. 4.5. Framework of Neural Network

4.2.2. Back-Propagation Algorithm

Rummelhart and Mclelland developed the backpropagation learning based algorithm and is based on the propagation of total loss back into the neural network, and thus updates the weights by providing the nodes with excessive error rates lower weights or lower error rates higher weights to lessen the loss. The back propagation-based algorithm is one of the most frequently utilized algorithm and is employed for training a multi-layer perceptron in 1986 and it incorporates two steps: the forward pass that refers to the calculation process and is traversing from the first neuron to the last neurons thus determining the output and the backward pass that passes the error back to the network.

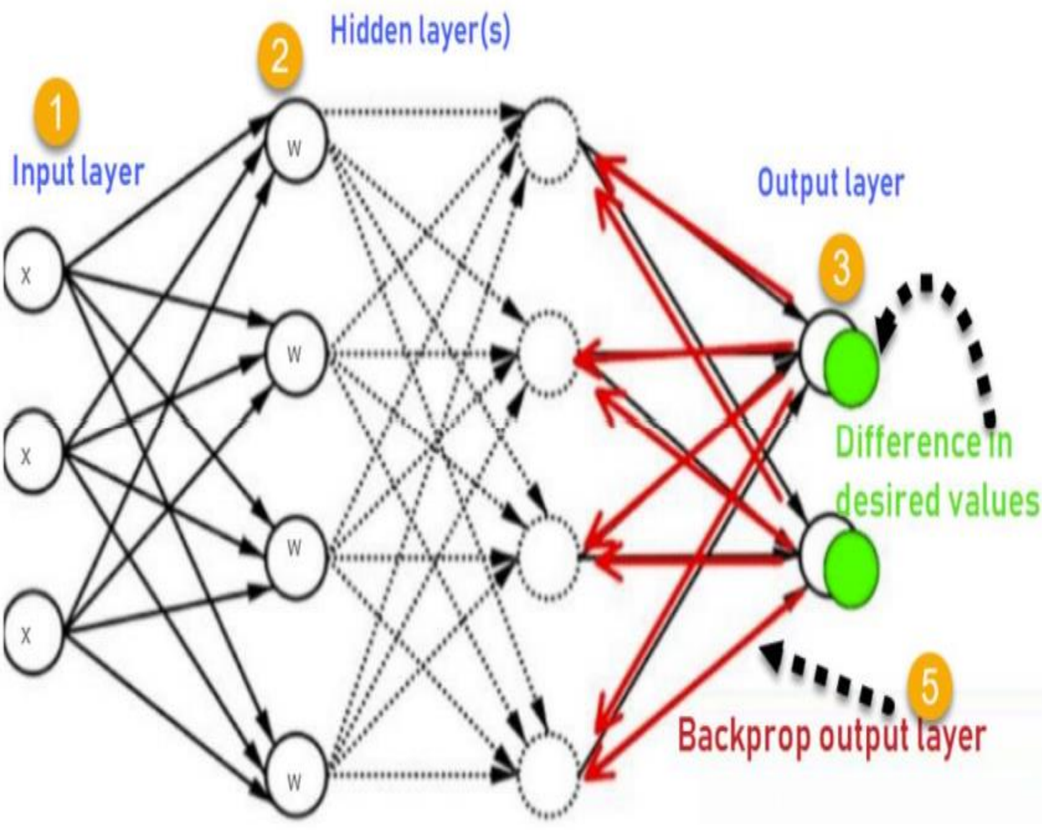


Fig. 4.6. Layers of Back-Propagation Algorithm

4.2.3. Levenberg-Marquardt based Algorithm

Levenberg-Marquardt algorithm is an iterative methodology in which nonlinear function is squared and then it is summed to show the minimum of the function and so it is called as nonlinear least squares minimization. It has evolved into an accepted method for nonlinear least-squares problems. It is an alternative to Gauss-Newton methodology of calculating the function minimum as Levenberg-Marquardt Algorithm is a combo of steepest descent and the Gauss-Newton method. It also works with the gradient vector and Jacobian matrix.

4.2.4. Advantages of Artificial Neural Networks (ANN)

1. **Information Storage-** ANN has the ability to store the information on the whole network.
2. **Performance with insufficient knowledge**- Once ANN is trained, although information is not sufficient, data can provide output while missing information may cause loss in performance.
3. **Fault tolerant**- ANN is a good fault tolerant as the corruption of few cells does not affects the output generation.
4. **Memory Distribution**- ANN is required to teach based on the desired output and thus enabling it to learn accordingly. Selected instances determine the progress of the network.
5. **Gradual Corruption**-A network may degrade after some time but it degrades slowly.

4.2.5. Applications of Artificial Neural Networks (ANN)

1. **Image Compression-** ANN compresses large amount of data at once. For this large amount of data is collected and then is processed at the same time.
2. **Handwriting Recognition-** ANN uses bitmap pattern of letter or digit as input and produces the required output and for its application user trains ANN with the handwritten patterns. Optical character recognition and validation of signature are the two of its application.
3. **Stock Exchange Prediction-** large business companies use ANN to predict stock exchange with the use of current trends, political situation etc.
4. **Telecommunication-** customer payment, network monitoring, intelligent searching speech recognition etc are some of the examples.
5. **Fraud Detection-** ANN uses real time fraud analysis, data mining detects fraud and finds the spot pattern and thus helps in finding fraud transactions.

4.2.6. Artificial Neural Network (ANN) trained with data obtained using IRPT Methodology

Here Levenberg- Marquardt Algorithm rule is implemented to train ANN. Firstly in this algorithm, squaring of nonlinear function is done and then the obtained result is added to show the function minimum and thus it is known as nonlinear least squares minimization. The representation of neural network is illustrated in Fig. 4.7.

ANN comprises three layers first one is the input layer with three input neurons, second one is the hidden layer with 10 hidden neurons and third one is the output layer with a single output neuron. ANN learns through the hidden layer. The hidden layer is a bit arbitrary where 10 hidden neurons are used for better functioning of the system.

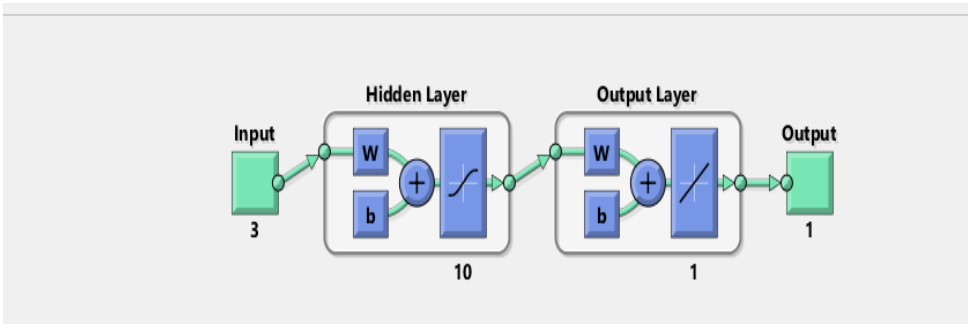


Fig. 4.7. Neural Network Configuration

Levenberg Marquardt algorithm-based methodology is used here to train the neural network. 3-phase load current is used as input for the ANN block as illustrated in Fig. 4.8.

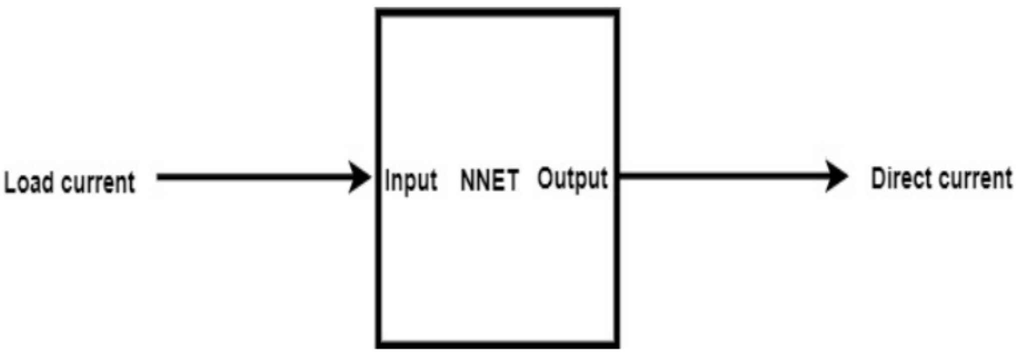


Fig. 4.8. Simulation model of ANN controller

ANN is trained using three phase load current and fundamental components of current and it gives the best result on the basis of prediction. Mean Square Error is utilized here to calculate the error and it specifies the deviation of predicted value from the correct value.

$$E_{mse} = \sum_{K=1}^{N} \frac{1}{2} \left[i_{fin} - i_{oin} \right]^2 \qquad (4.12)$$

Here, i_{fin} denotes calculated fundamental component of current i_{oin} denotes the expected fundamental component of current and N denotes the number of samples required.

IRPT controller is used to get the data. 200001 data is used and 70% data are used in training, 15% data in testing and 15% data are used for validation.

MSE (Mean Square Error) obtained is $8.25712e^{-1}$. Error histogram of ANN is illustrated in Fig. 4.9, Regression in Fig. 4.10, Performance in Fig. 4.11.

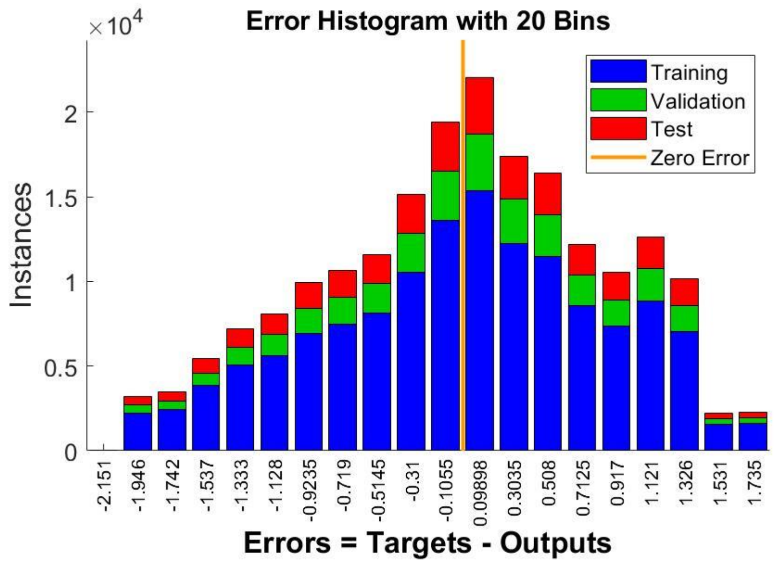


Fig. 4.9. Error histogram of ANN

Table. 4.1. Part of data used in training ANFIS

Load Current			Direct Current
Phase A	Phase B	Phase C	
8.77679	-8.77713	0.000343	10.05246
9.480425	-9.48053	0.00011	10.93797
8.776547	-0.00034	-8.77621	10.05448
9.188109	-0.00022	-9.18789	10.57448
0.000276	9.008077	-9.00835	10.3471
-19.376	-0.00105	19.37702	20.59276
-19.3591	-0.00108	19.36014	20.49166
0.000222	-17.7466	17.74636	20.42235
0.001032	-19.3882	19.38712	20.67995
17.61172	-17.6115	-0.0002	20.27898

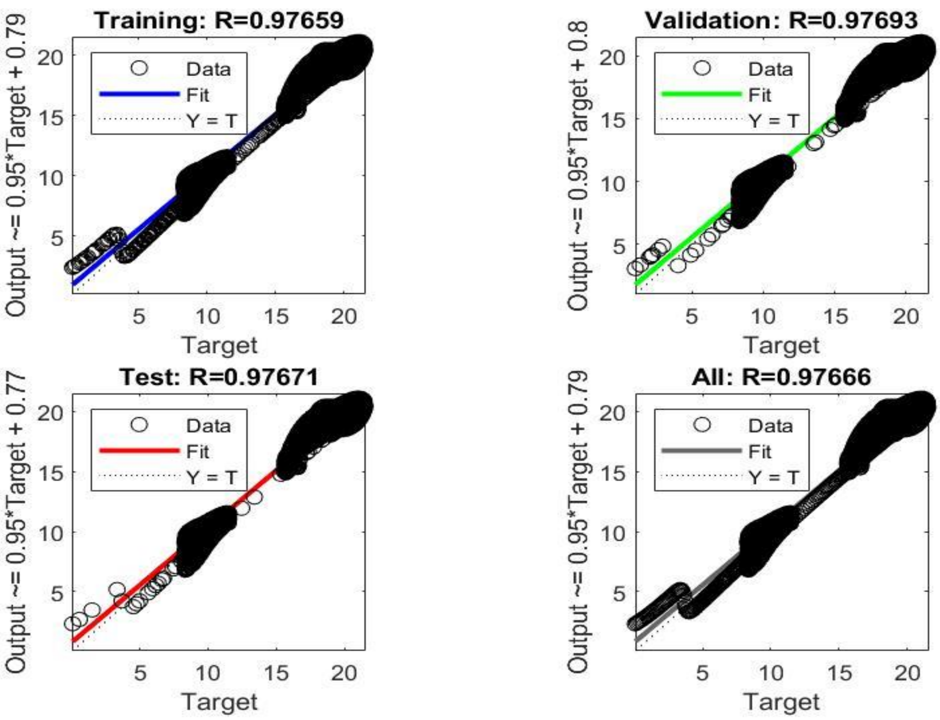


Fig.4.10. Regression

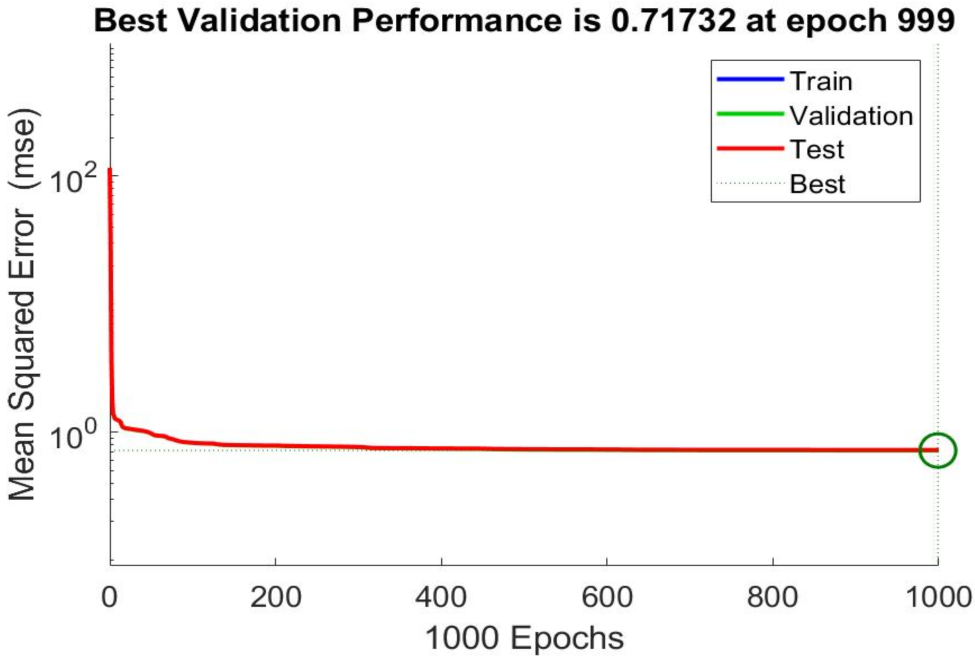


Fig.4.11. Performance

4.3. Adaptive Neuro Fuzzy Inference System (ANFIS)

Jang had introduced the Adaptive Neuro Fuzzy Inference system (ANFIS) methodology in 1993. ANFIS is a data learning-based methodology that incorporates both neural and fuzzy logic and is trained with an appropriate training data.

Adaptive Neuro-Fuzzy Inference System are primarily a family of adaptive neural network that are working as good as fuzzy inference system and incorporate non-linear and adaptive, non-time invariant problem-solving features of ANN.

ANFIS is trained with a suitable training data and it uses hybrid learning, combining the least square and the gradient descent method as training learning rules. The Flow chart of ANFIS is depicted in Fig. 4.12.

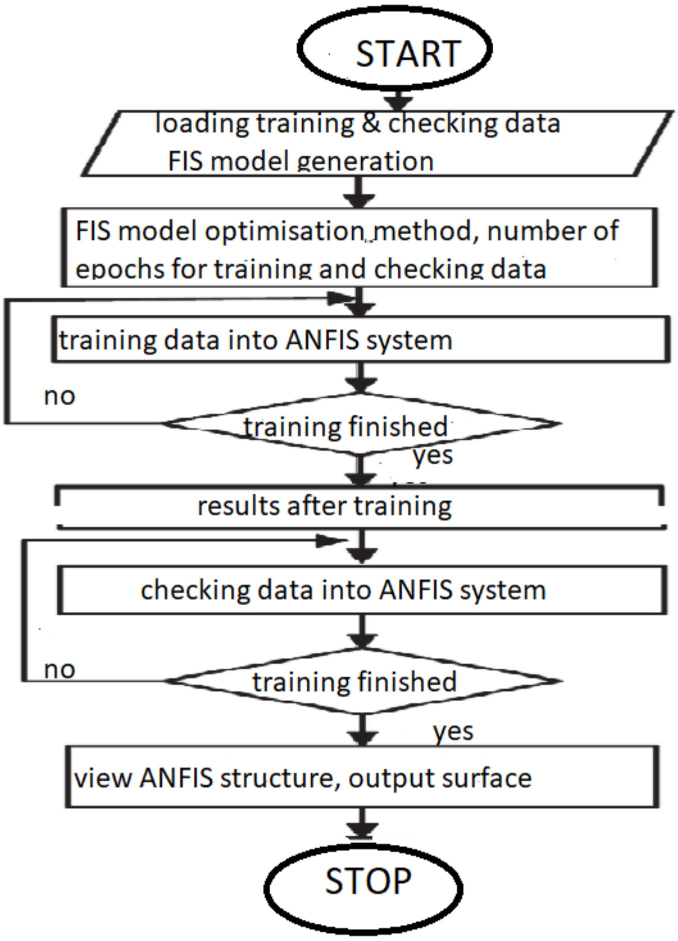


Fig. 4.12. Flow chart of ANFIS

4.3.1. Advantages of ANFIS

ANFIS incorporates the advantages of both ANN and fuzzy and can predict any function to any specific accuracy. ANFIS has the capability of adaption and rapid learning capacity and it estimates with a good accuracy when sufficient layers of hidden neuron and appropriate number of fuzzy rules are available. Back propagation algorithm as well as Gradient descent algorithm are implemented for the parameters of the fuzzy set membership function. ANFIS has following features which provides a wider area for its implementation.

- It provides Quick and accurate learning thus making ANFIS more reliable.
- Human expertise is not required as it gives output based on prediction
- Incorporation of both knowledge (linguistic as well as numeric knowledge) is easy and hence it gives better problem solving.
- Easy implementation

- It has robust generalization capabilities.

4.3.2. Applications of ANFIS

ANFIS controller is broadly employed for controlling nonlinear system. ANFIS performs better when compared to some conventional controller and is utilized as a Temperature water bath controller. Airplanes employs ANFIS based techniques and these days research is going on several ANFIS based technology like Intelligent plans (which can fly by themselves).

4.3.3. Adaptive Neuro Fuzzy Inference System (ANFIS) trained with data obtained using IRPT Methodology

The benefit of using ANFIS based control algorithm over ANN is its ability to learn as ANFIS has better ability to retain and it gives smaller convergence error for the same complex network when compared to ANN. ANFIS has slower convergence rate but it has a better capability to reduce the error.

ANFIS incorporates five layers (input node, rule node, average node, following node and output node) where layer1 is the adaptive node layer and three phase load current is fed into adaptive node layer as input. Adaptive node layer provides fuzzy membership grade of the input as output to the rule node layer (second layer). Layer 2 (rule node layer) produces firing strength for rules. The AND operator is employed and its output is utilized in the input node layer. Layer3 (average node layer) interpolates the calculated firing strength. Layer4 (consequent node layer) takes normalized value as input and provides defuzzified value as output and Layer5 provides the desired output direct current.

For training the ANFIS structure 10 epochs are used and grid partition method is employed here for the generation of FIS structure, triangular membership function is attributed at each input. Fig. 4.14. illustrates Optimized membership function for input1, Fig. 4.15. illustrates Optimized membership function for input2 and Fig. 4.16. illustrates Optimized membership function for input3.

For training 200001 data are used. Fig. 4.13. shows the structure of ANFIS with 78 nodes, 27 linear parameter and 27 nonlinear parameters. For training 27 fuzzy rules are used and training MSE obtained as 0.607807.

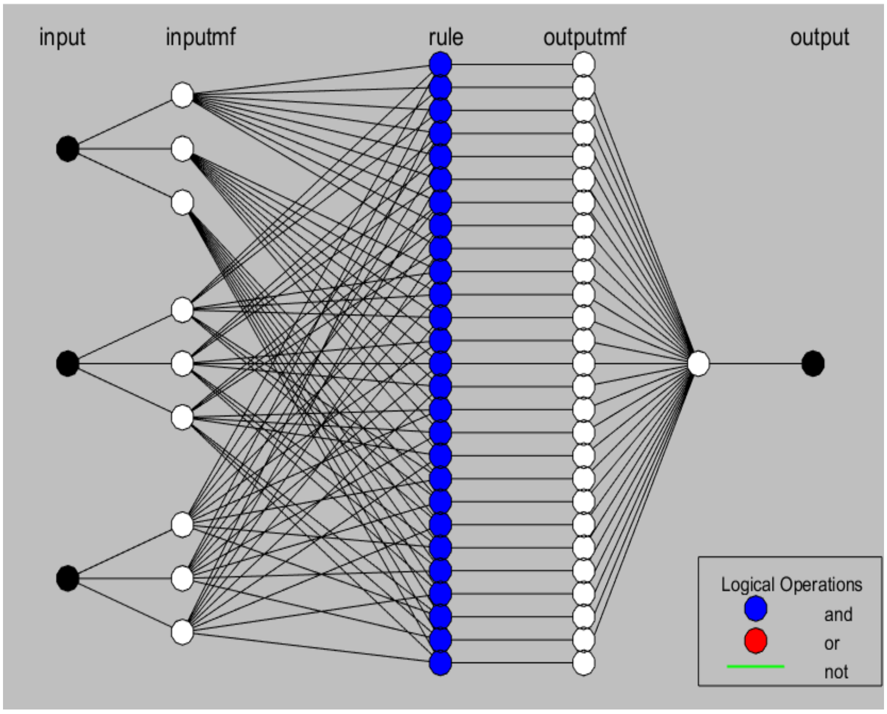


Fig. 4.13. Structure of ANFIS

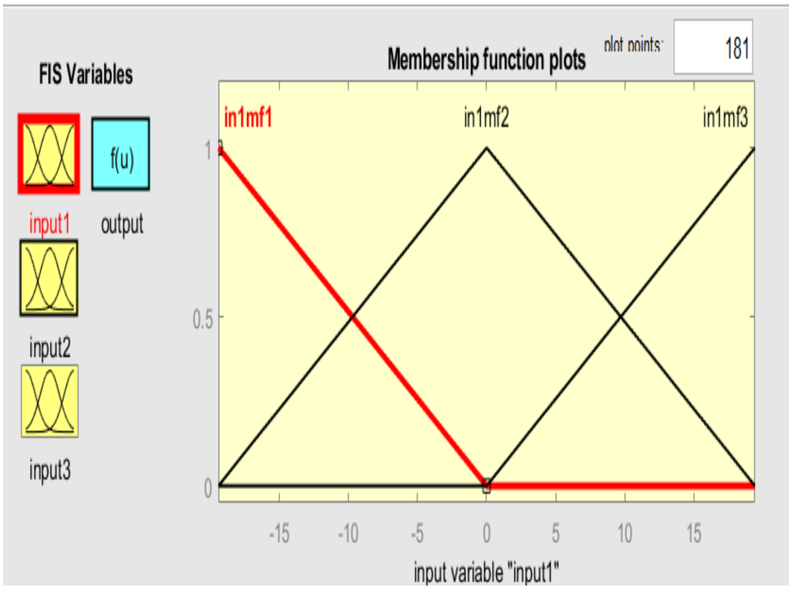


Fig. 4.14. Optimized membership function for input1

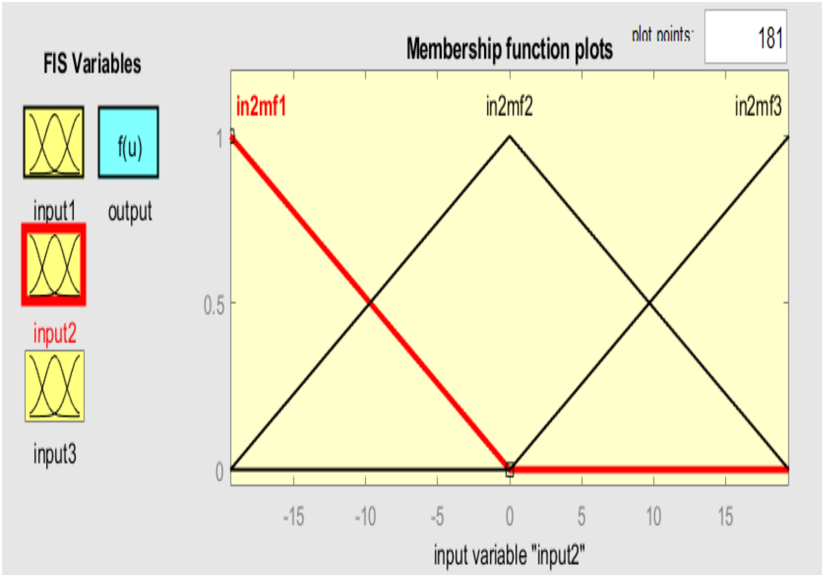


Fig. 4.15. Optimized membership function for input2

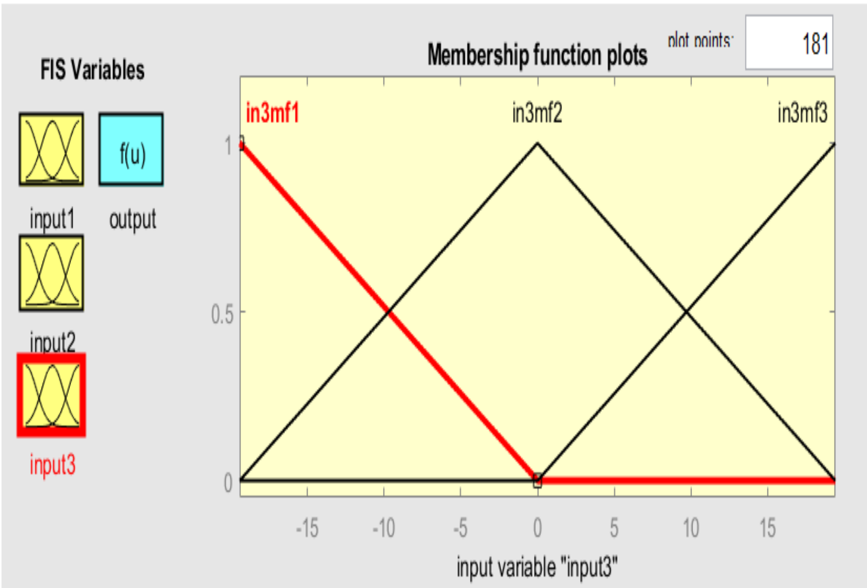


Fig. 4.16. Optimized membership function for input3

Fig. 4.17. Training error for 10 epoch

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1. MATLAB SETUP OF DSTATCOM ARRANGEMENT

MATLAB Simulink model comprises of a DSTATCOM with source (3-phase source), non-linear load, and control block. Non-linear load is connected and is implemented with a series resistance and inductor connected at the output terminal of the universal bridge. DSTATCOM is connected to the distribution system through interfacing inductors. A dc link capacitor is associated at one end of the Distribution Static Compensator. A Hysteresis current controlled PWM is employed to provide the switching signal to the Distribution Static Compensator. The above-mentioned control algorithm (IRPT, ANN and ANFIS) methodology are employed. The modelling is done with the MATLAB Simulink and sim power system and the simulation is executed with ode23s solver in discrete mode. The maximum step size of 5e-06 is used. Fig. 5.1 shows the Simulink MATLAB models employed.

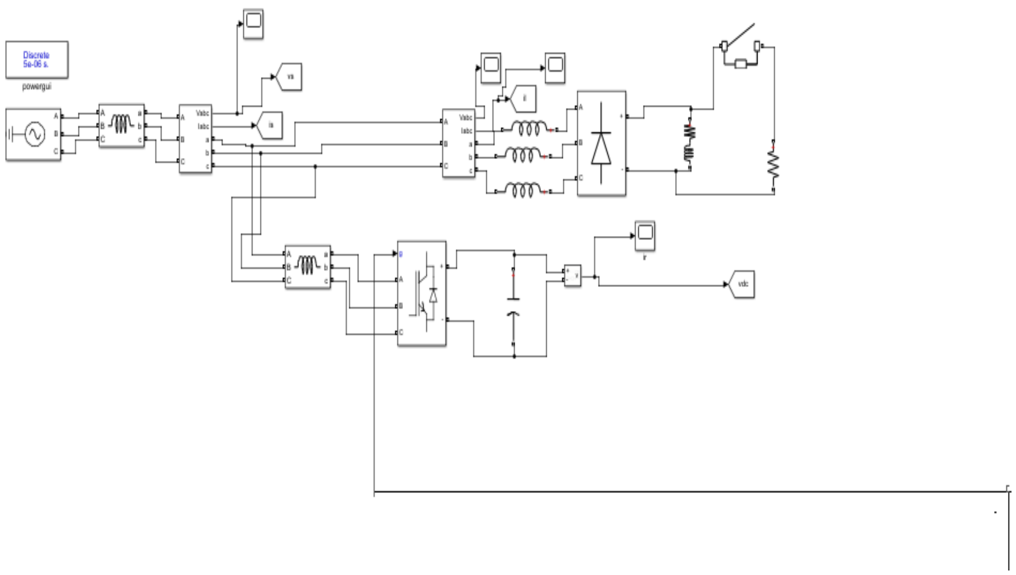


Fig. 5.1. SIMULINK Model

The above circuit consists of a distribution system circuit with a 3-phase non-linear load connected at the output terminal of the universal bridge with a R-L load. These load extracts lagging power factor current and and thus provides reactive power burden in the system. The presence of these non-linear load in the circuit produces harmonics in the circuit and this leads to unbalanced current. This unbalanced and excessive current leads to short circuits and faults in the distribution system. DSTATCOM is employed for the reduction of reactive power loss. The working of the DSTATCOM depends upon the gate pulse and the controller provides this switching signal (gate pulse). The controller gives the real fundamental component of current as output and this along with the source current is fed into the hysteresis current controller. The output of the hysteresis current controller is used as switching signal for the DSTATCOM. The simulation results and comparison performance analysis of the IRPT, ANN and ANFIS controllers are illustrated below

5.2. RESULTS AND DISCUSSIONS

The performance of the DSTATCOM with two intelligent controllers i.e. ANN and ANFIS based control algorithm can be analysed by observing the waveforms obtained. The enhanced power quality is thus determined with the use of DSTATCOM.

The waveform obtained in open loop conditions i.e .without employing any control algorithm is depicted below in Fig.5.2. The target is to make the source current waveform sinusoidal by employing efficient control algorithms.

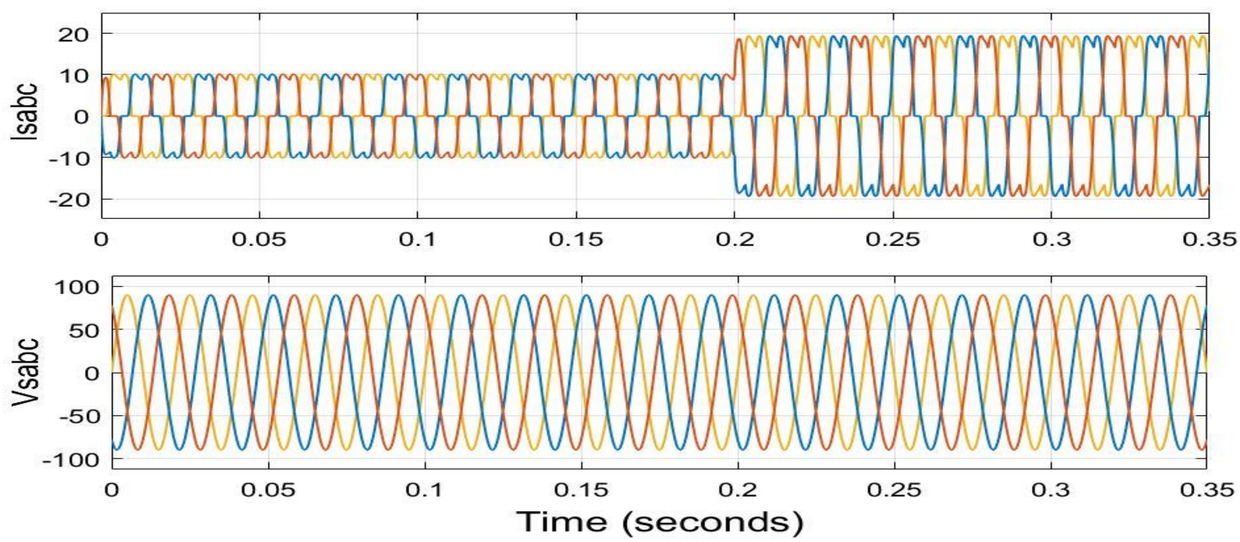


Fig. 5.2. Waveforms obtained before using any control algorithm

5.2.1. Results obtained using IRPT based controller

IRPT control algorithm is implemented to produce the switching signal for the performance of the DSTATCOM. Clark transformation is employed here for the conversion of $a - b - c$ to $\alpha - \beta$ reference frame. 3-phase source voltage and 3-phase load current is sensed and fed to the IRPT controller. Instantaneous active and reactive power is computed in orthogonal rotating vector $\alpha - \beta\ frame$. Reactive power thus obtained is terminated while Active power is summed with the error signal obtained using PI control and this error signal is generated by using dc link capacitor voltage and 200V. Signal is then converted to two phase components of current signal. The current signal is then reverse Clark transformed and is converted into three phase quantities. The generated reference current is fed to the hysteresis base pulse width modulated signal generator and its output is used as a switching signal for the DSTATCOM. The THD for source current and source voltage is determined through FFT Analysis of the power GUI block.

The Simulink model of the IRPT control algorithm is depicted in Fig. 5.3. Nonlinear load is simulated with diode rectifier shunted with resistance (R=15Ω) and inductance of (L = 3mH). The waveforms of source current (i_{sabc}), source voltage(V_{sabc}), load current (i_{labc}) and dc side capacitor voltage (V_{dc}) are illustrated in Fig. 5.7. The Steady state operation of nonlinear load is observed till 0.2 secs. It is analysed that from t=0 sec to t=0.2 sec, the load current of 10A is obtained. The non-linear load is further increased at t=0.2 sec with grid current increasing to 20A to meet the load demand. It is observed that the sinusoidal current is obtained with THD of 2.03% thus fulfilling IEEE 519 standards. It is analysed that dc link capacitor voltage settles with in t=0.03 secs when load is increased to 20 A at t=0.2 secs.

Fig. 5.7. illustrates the result of source current, source voltage, load current and dc link capacitor voltage. Fig. 5.4. depicts the THD of load current is 21.01%. Fig. 5.6. shows THD of source voltage is 0.10%, Fig. 5.5. illustrates THD of source current is 2.03%.

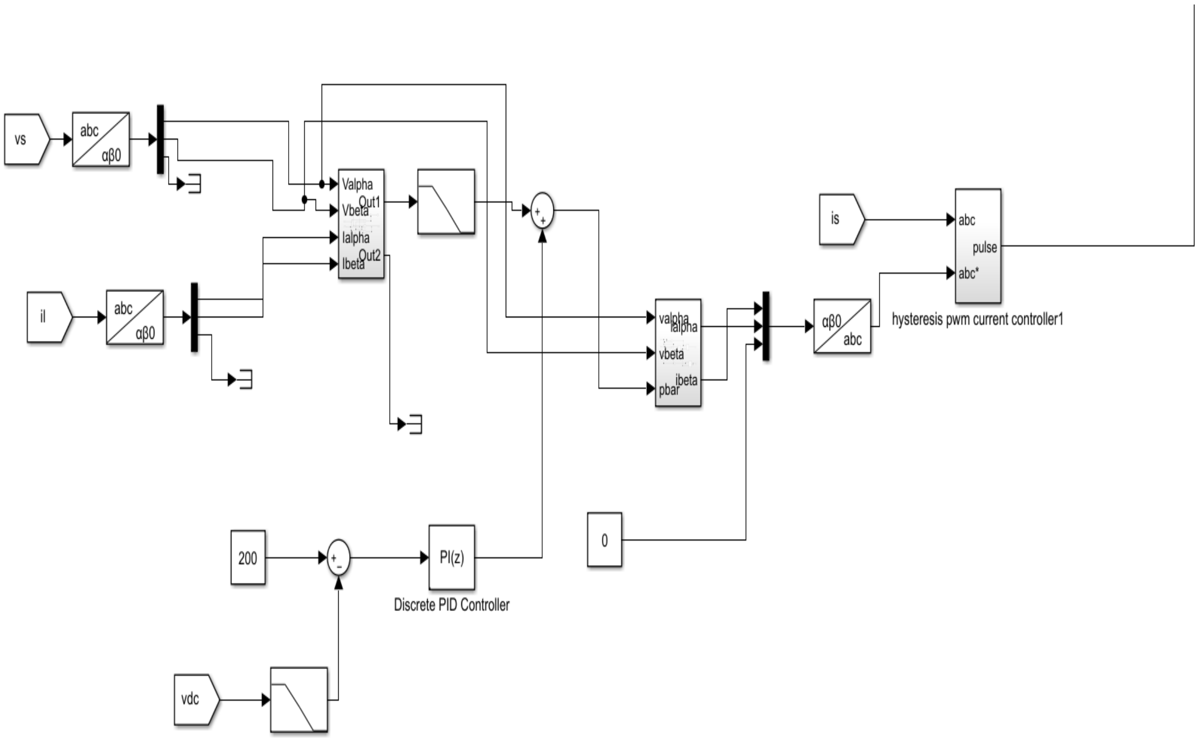


Fig. 5.3. Simulink model for IRPT control algorithm

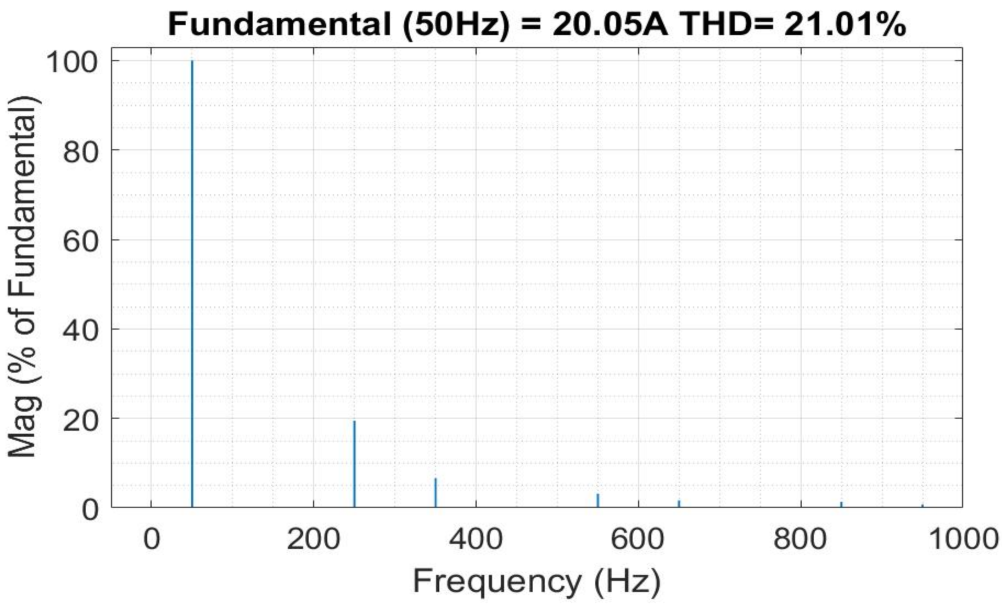


Fig. 5.4. THD of load current using IRPT

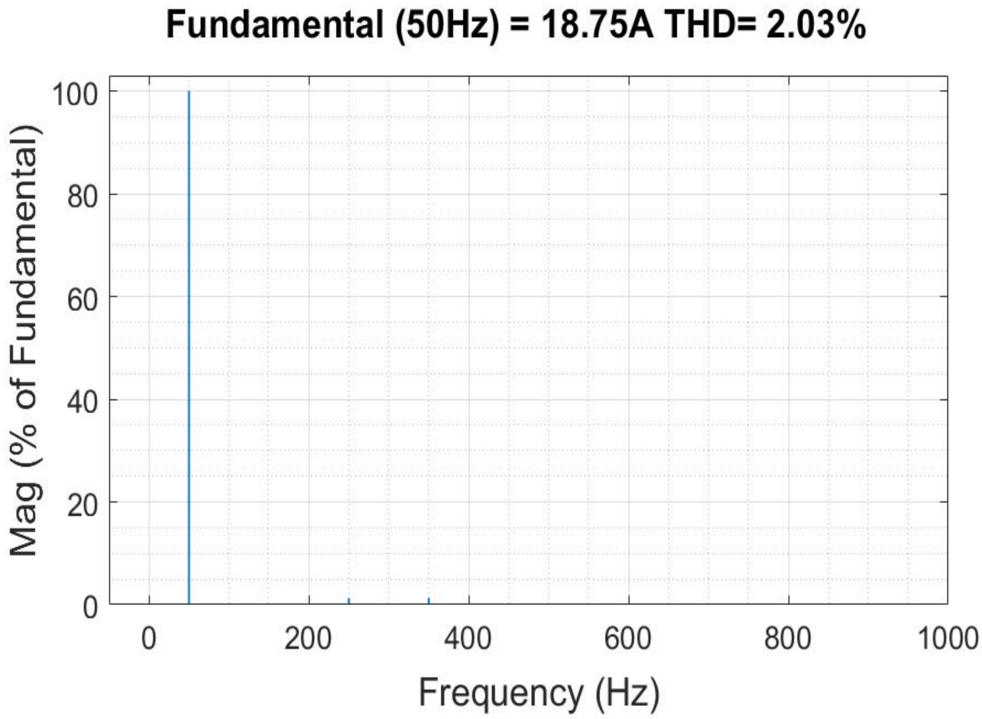


Fig. 5.5. THD of source current using IRPT

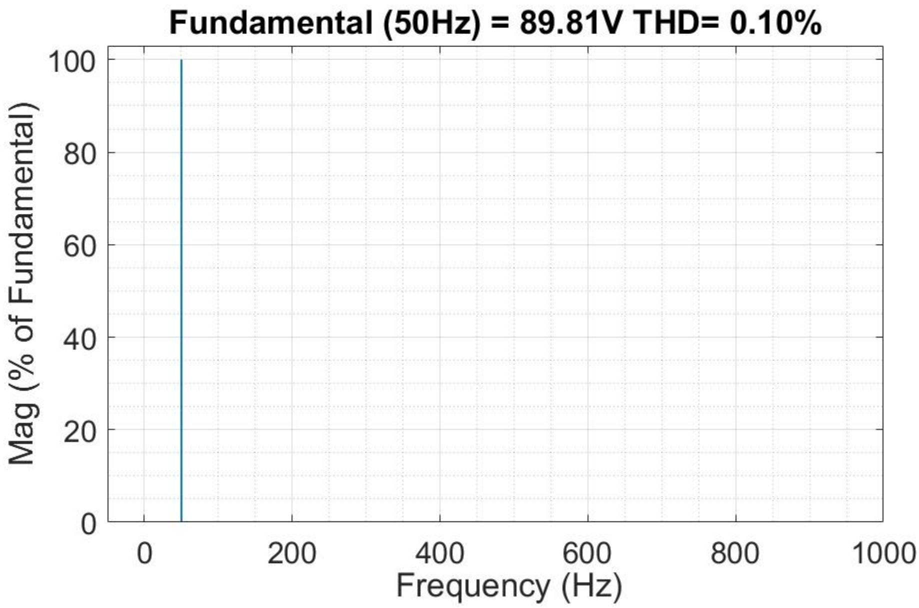


Fig. 5.6. THD of source voltage using IRPT

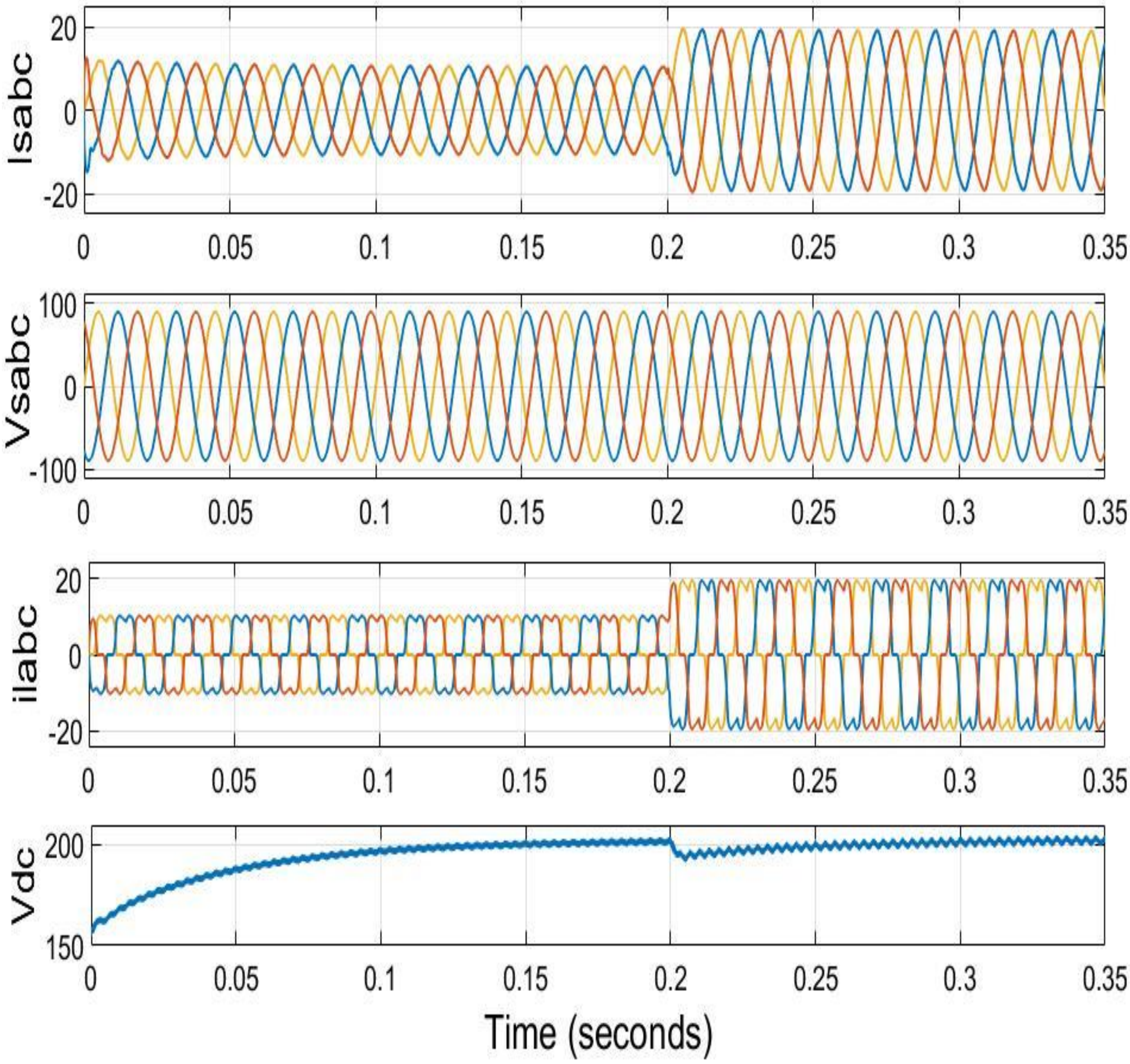


Fig. 5.7. Waveforms obtained using IRPT

5.2.2. Results obtained using ANN based controller

The Neural Network is trained with Levenberg-Marquardt Algorithm. The load current is used as input to the neural network and direct current is obtained as output. Required Datasets are extracted using IRPT controller. Neural network is then trained using these datasets and the Function Fitting Neural block is obtained. Neural Network enhances the efficiency of the system and making it cost effective. Simulink model of ANN based control algorithm is depicted in Fig. 5.8. It is observed that THD of load current is 21.01% but with the implementation of ANN, THD of source current is minimized to 1.78%, with the fulfilment of IEEE 519 standards. The waveform of dc side capacitor voltage settles at t=0.04sec and on increasing the load at t=0.2 sec it shows little perturbation but settle down fast. Fig. 5.10. shows the result. Source current is approximately sinusoidal as depicted in the figure. THD of source voltage is 0.10%, load current is 21.01%, and source current is 1.78%.

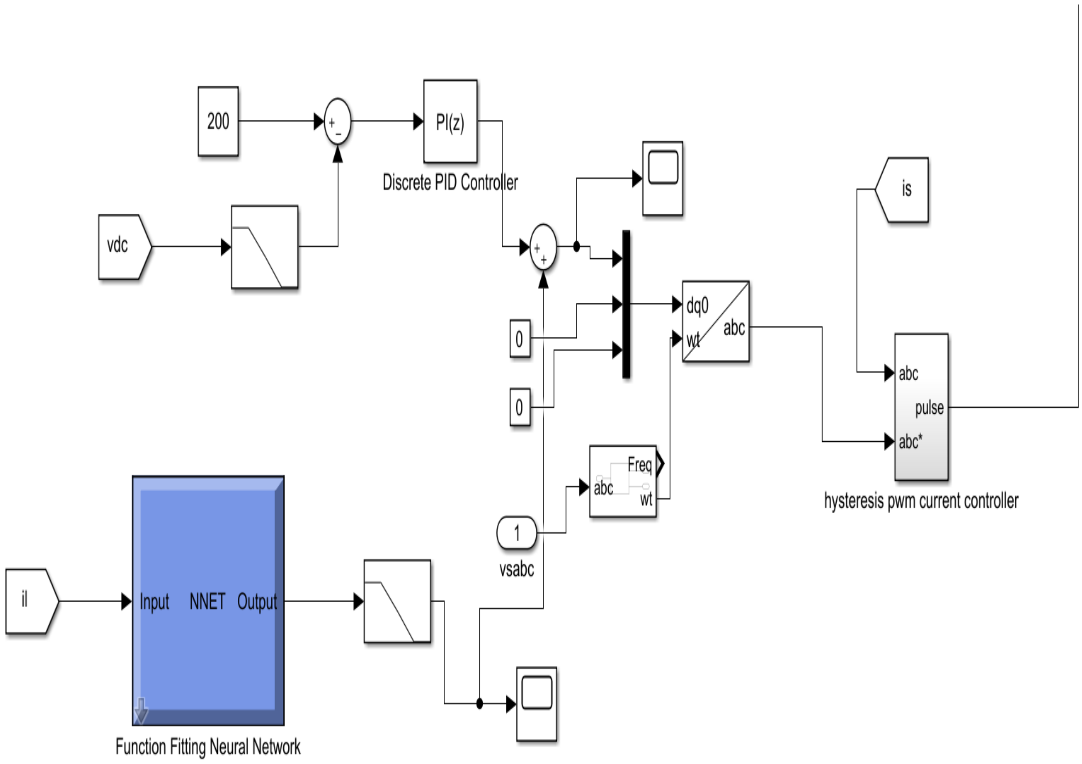


Fig. 5.8. SIMULINK model for ANN control algorithm

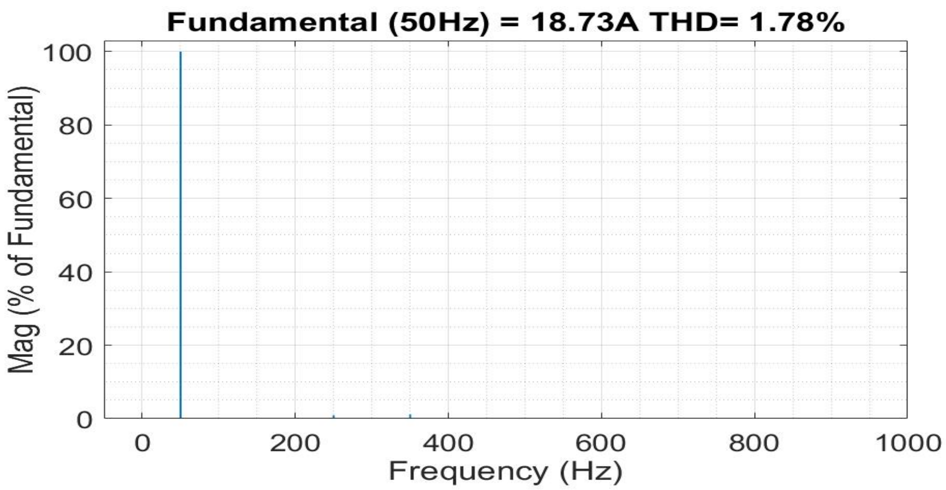


Fig. 5.9. THD of source current using ANN

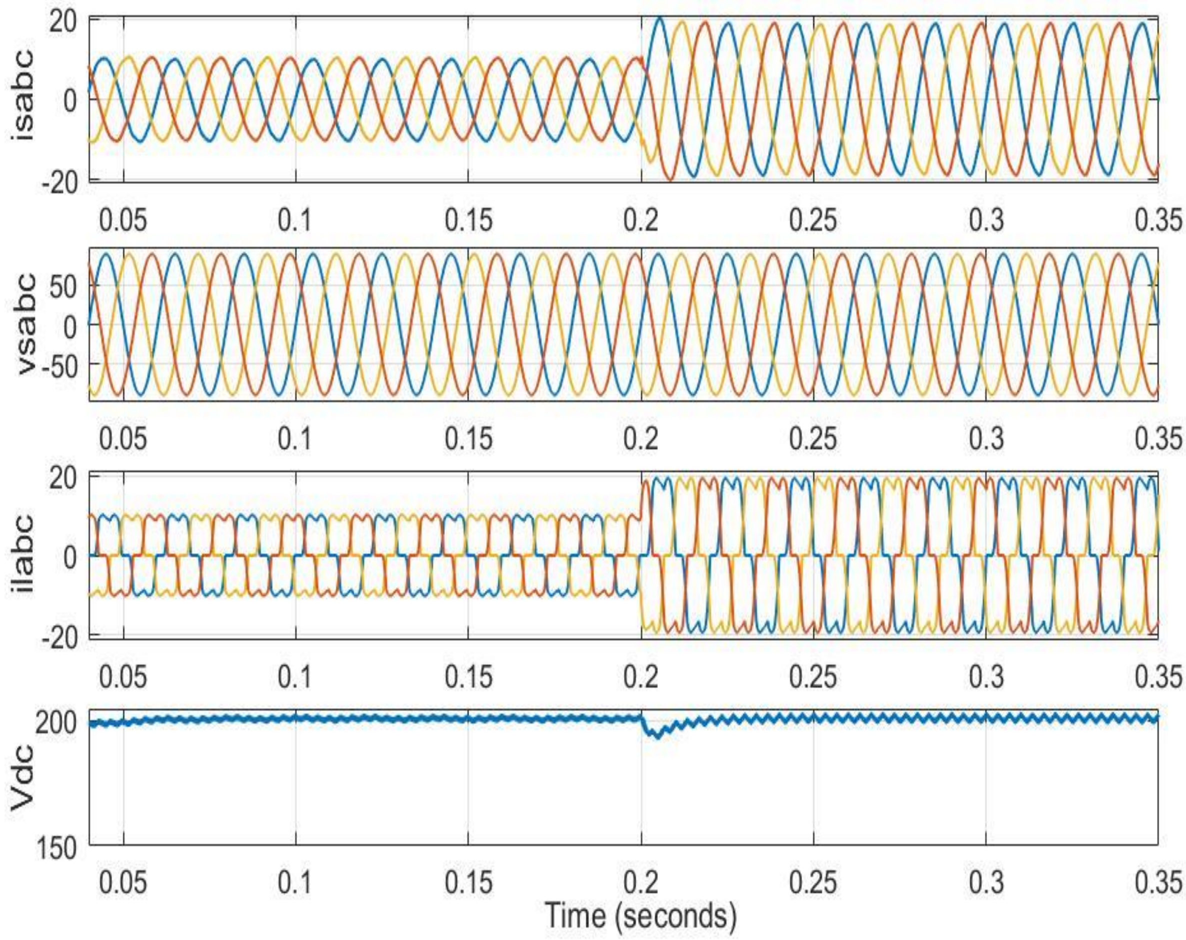


Fig. 5.10. Waveforms obtained using ANFIS

5.2.3. Results obtained using ANFIS based controller

The Adaptive Neuro Fuzzy Inference Block is trained using the inbuilt neural network training feature of MATLAB. For training the ANFIS structure 10 epochs are used and Grid partition is employed to generate FIS. Triangular membership function is assigned at each input. For training 200001 data are used. For training 78 nodes, 27 linear parameter and 27 nonlinear parameters and 27 fuzzy rules are utilised and the Mean Square Error (MSE) obtained is 0.607807. ANFIS enhances the accuracy of the result thus making it more reliable. Simulink model of ANFIS based control algorithm is depicted in Fig. 5.11. The THD of load current is obtained as 21.01%. ANFIS control is employed to minimize the THD to 1.06% thus fulfilling IEEE519 standards. It is analysed that dc link capacitor voltage settles at t=0.03 sec and when load increases at t=0.2 sec it illustrates few disturbances but settles fast. Fig. 5.13. illustrates the result of source current, source voltage, load current and dc link capacitor voltage. Fig. 5.12. illustrates THD of source current is 1.06%.

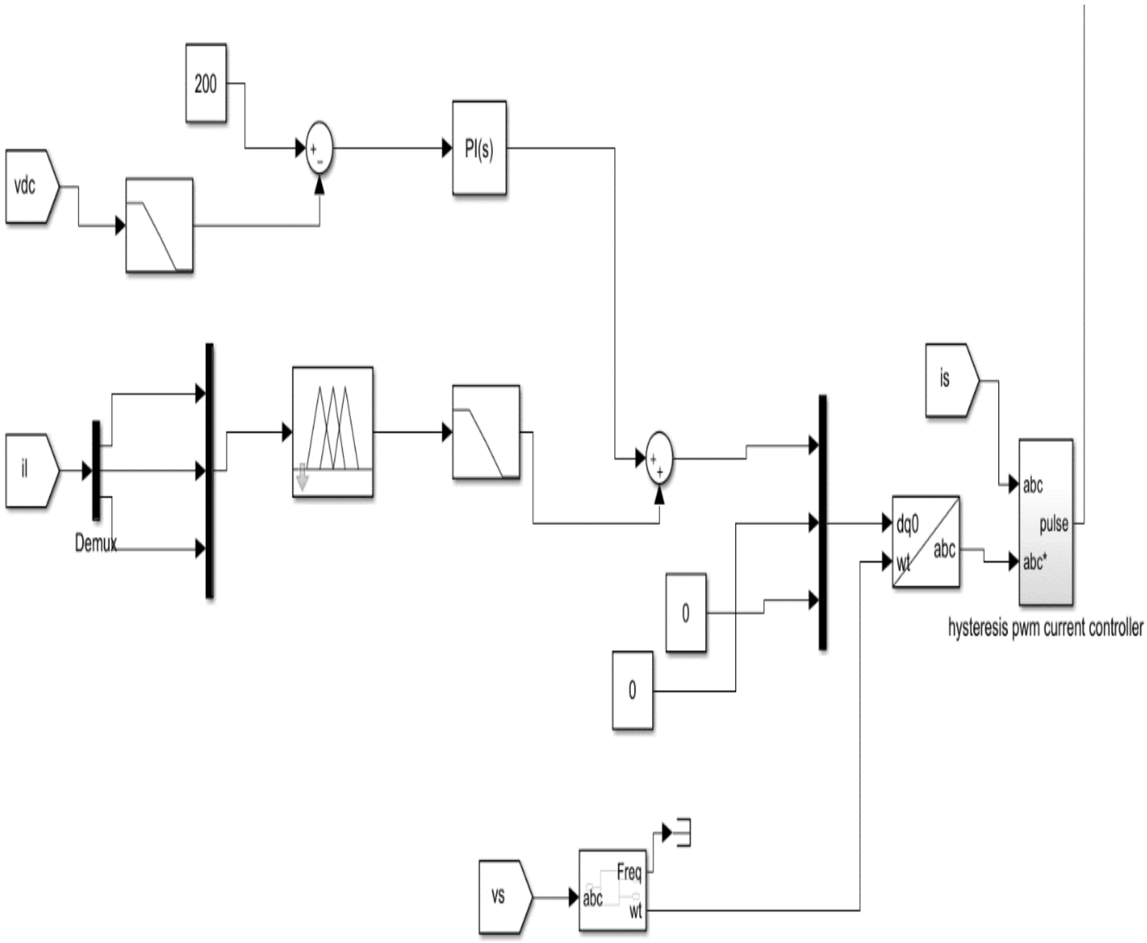


Fig. 5.11. SIMULINK model for ANFIS control algorithm

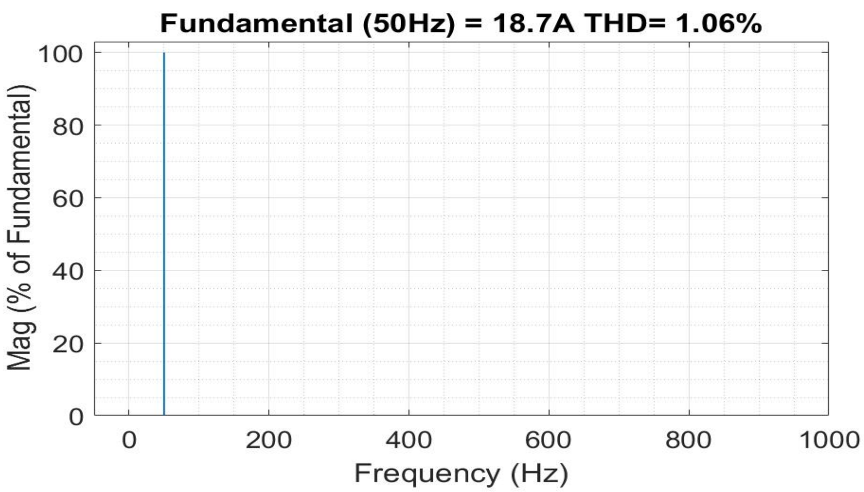


Fig. 5.12. THD of source current using ANFIS

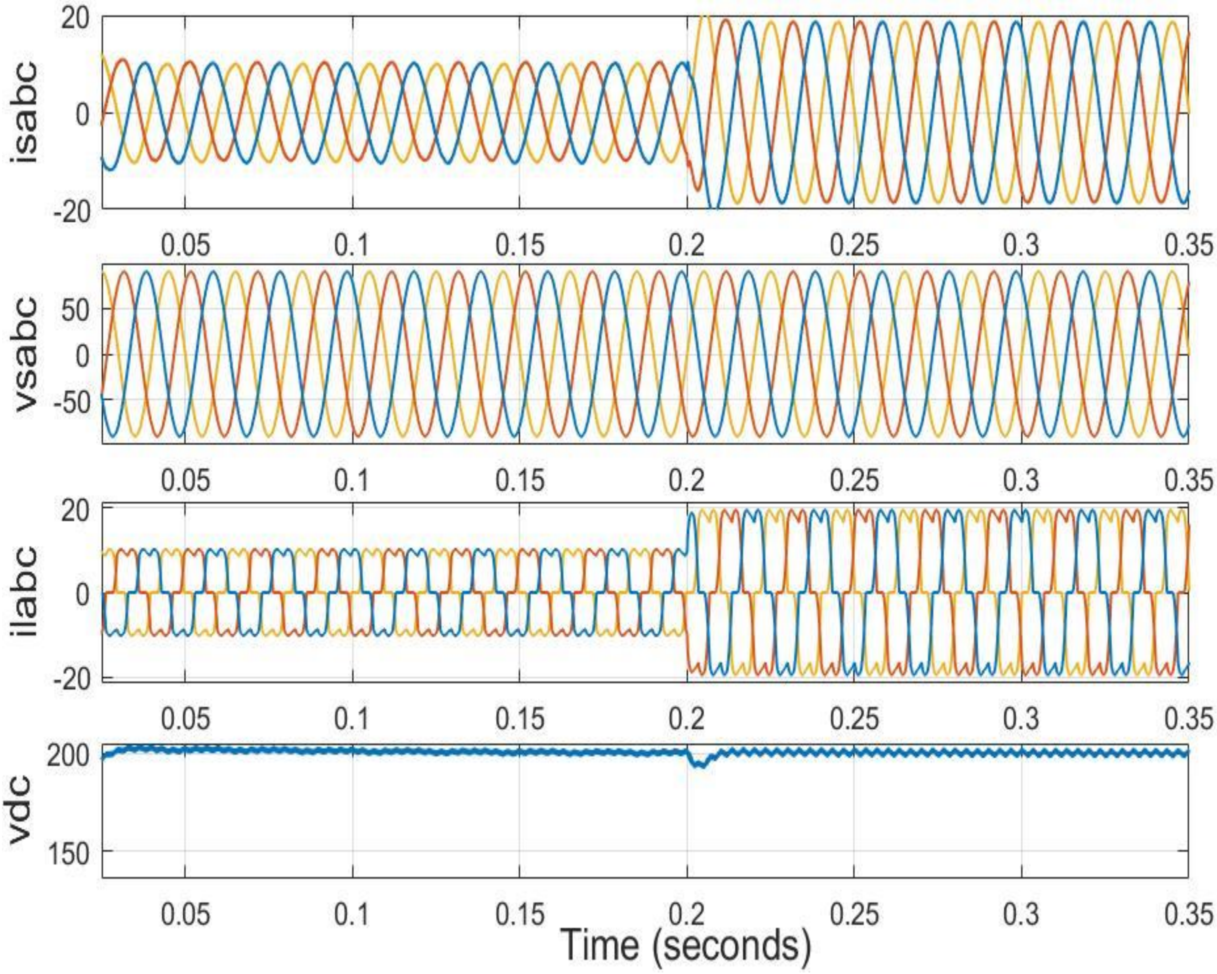


Fig. 5.13. Waveforms obtained using ANFIS

5.2.4. Comparison between the control algorithms

The fundamental component of current of IRPT, ANN and ANFIS is extracted and is compared. Table 5.1 shows the obtained rise time, peak overshoot, THD and convergence rate. The rise time is 0.00076 sec in case of IRPT, 0.00332 sec in case of ANN and 0.00201 sec in case of ANFIS. Peak overshoot obtained is 3.984% in case of IRPT, 2.312% in case of ANN and 1.06% in case of ANFIS. THD of source current is 2.03% in case of IRPT, 1.78% in case of ANN and 1.06% in case of ANFIS. The convergence rate is high in IRPT, low in ANN and ANFIS. Fundamental component of current obtained using IRPT, ANN and ANFIS is shown in Fig. 5.14, Fig. 5.15 and Fig. 5.16 respectively. Fig. 5.17. shows comparison-based analysis of fundamental component of current obtained using IRPT, ANN and ANFIS.

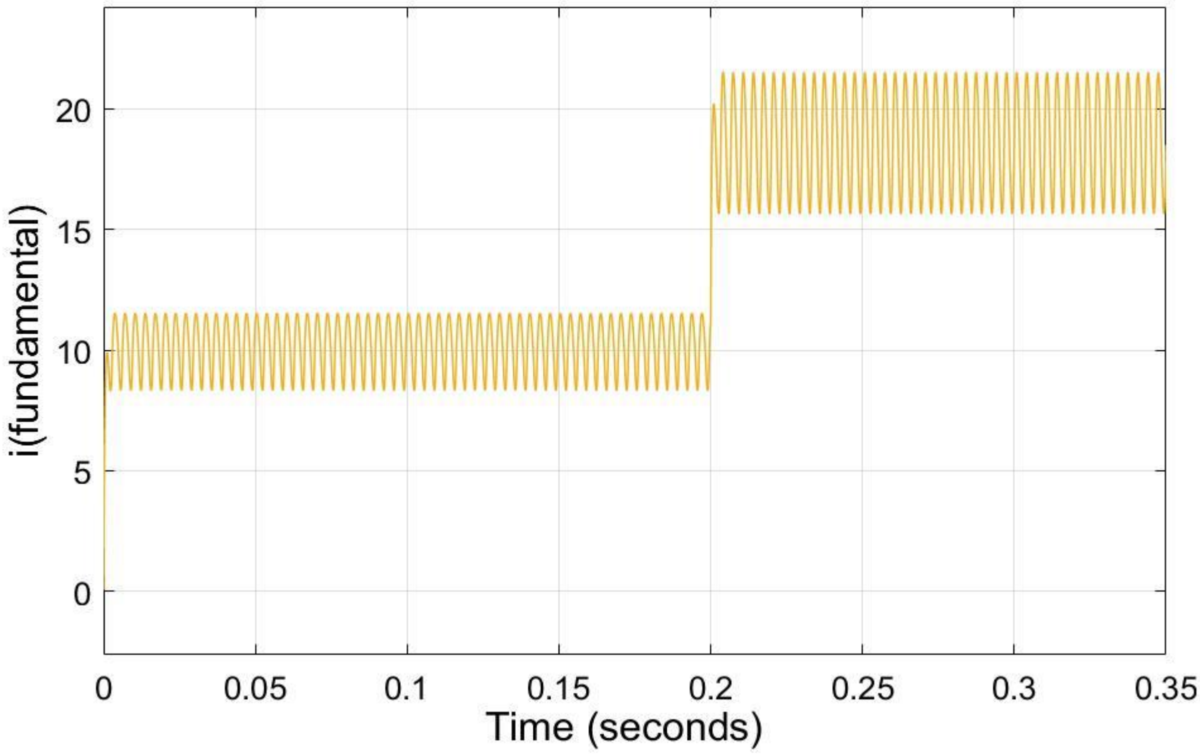


Fig. 5.14. Fundamental component of load current extracted from IRPT Algorithm

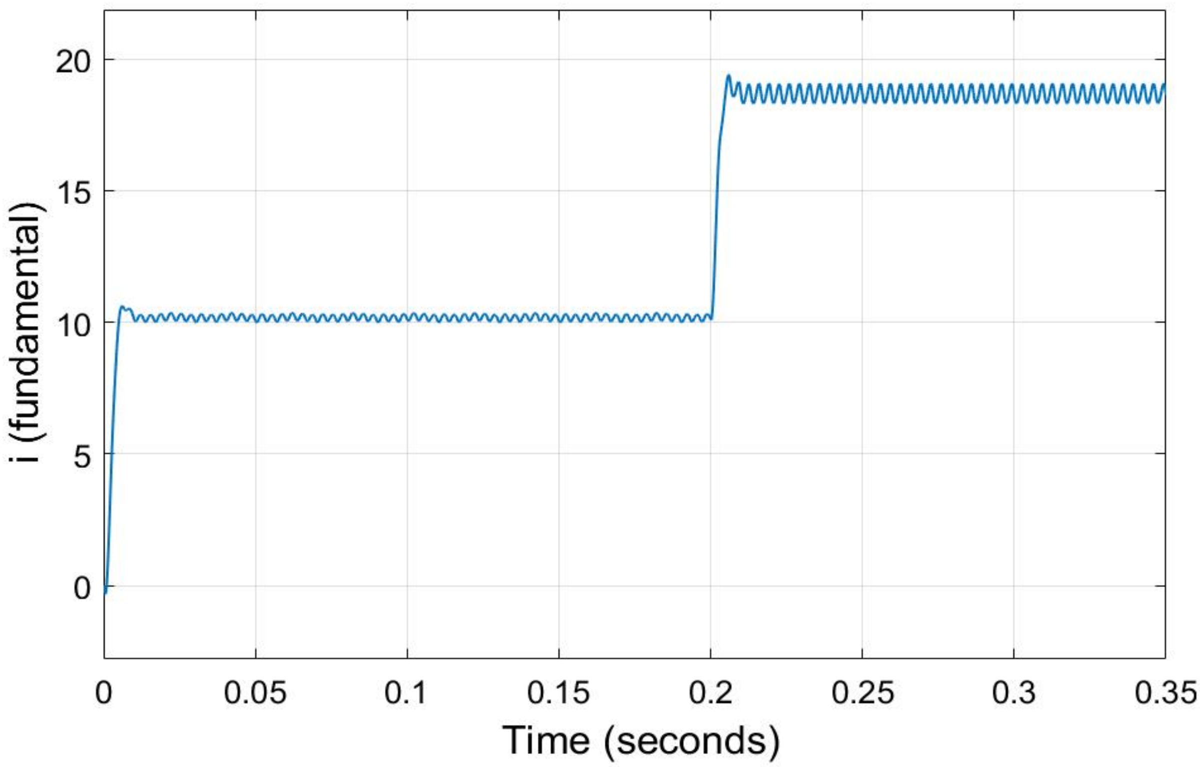


Fig. 5.15. Fundamental component of load current extracted from ANN Algorithm

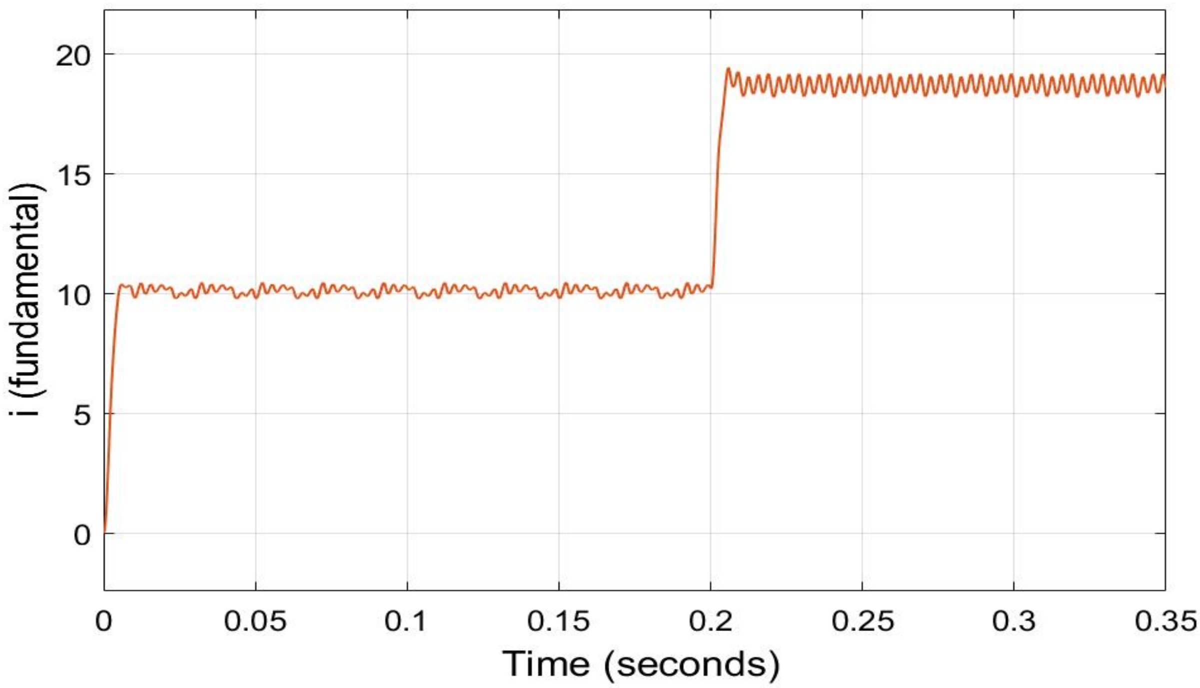


Fig. 5.16. Fundamental component of load current extracted from ANN Algorithm

Table 6.1. Performance analysis Comparison of ANFIS with IRPT and ANN in tracking fundamental component of load current

DSTATCOM Control Algorithm	Rise Time (second)	Peak Overshoot	%THD	Convergence Rate
IRPT	0.00076	3.984%	2.03%	High
ANN	0.00332	2.312%	1.78%	Low
ANFIS	0.00201	1.531%	1.06%	Low

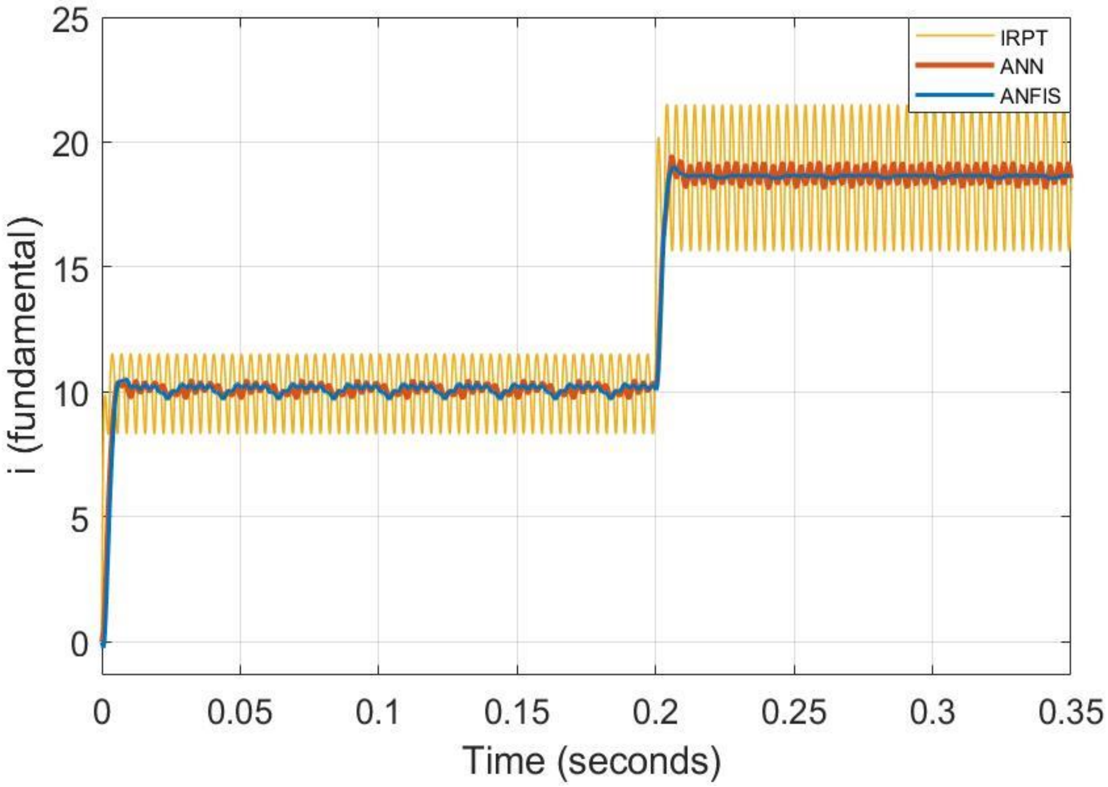


Fig 5.17. Comparison results of performance analysis of fundamental component of current extracted using IRPT,ANN and ANFIS

The dc link capacitor voltage is obtained using IRPT, ANN and ANFIS and is compared. Table 5.2 shows the obtained dc link capacitor voltage in case of IRPT, ANN, ANFIS. The dc link capacitor voltage settles at 0.13 sec in case of IRPT, 0.07 sec in case of ANN and 0.04 sec in case of ANFIS. Fig. 5.18. shows the comparison result of dc link capacitor voltage of IRPT, ANN and ANFIS. Comparison based interpretation of control algorithm (IRPT, ANN and ANFIS) on the basis of Rise time, Peak Overshoot and percent THD is illustrated in Fig. 5.19, Fig.5.20, Fig. 5.21 respectively.

Table 6.2. Performance analysis Comparison of ANFIS, ANN and IRPT in tracking DC Link Voltage

DSTATCOM Control Algorithm	Settling Time (seconds)
IRPT	0.13
ANN	0.07
ANFIS	0.04

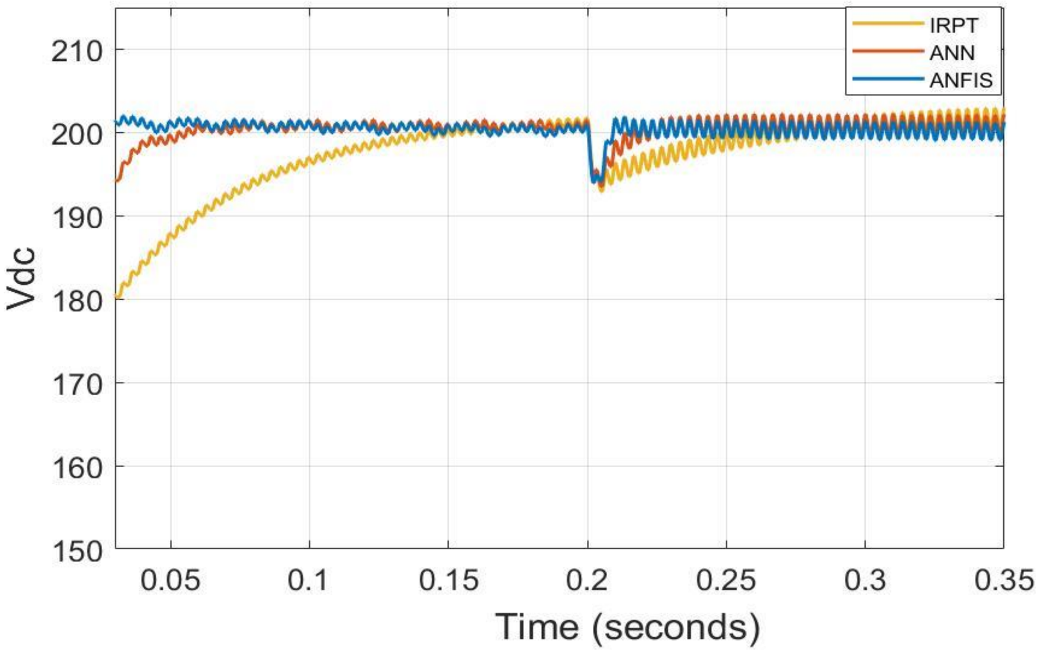


Fig. 5.18. Comparison results of performance analysis of DC Link voltage using IRPT, ANN and ANFIS

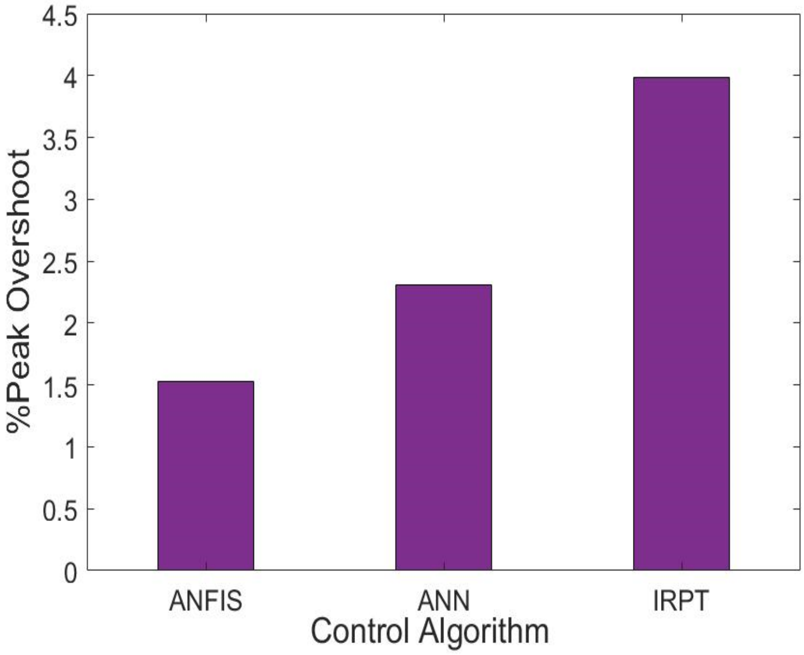


Fig. 5.19. Comparison result of %Peak Overshoot obtained using IRPT, ANN and ANFIS based control algorithm.

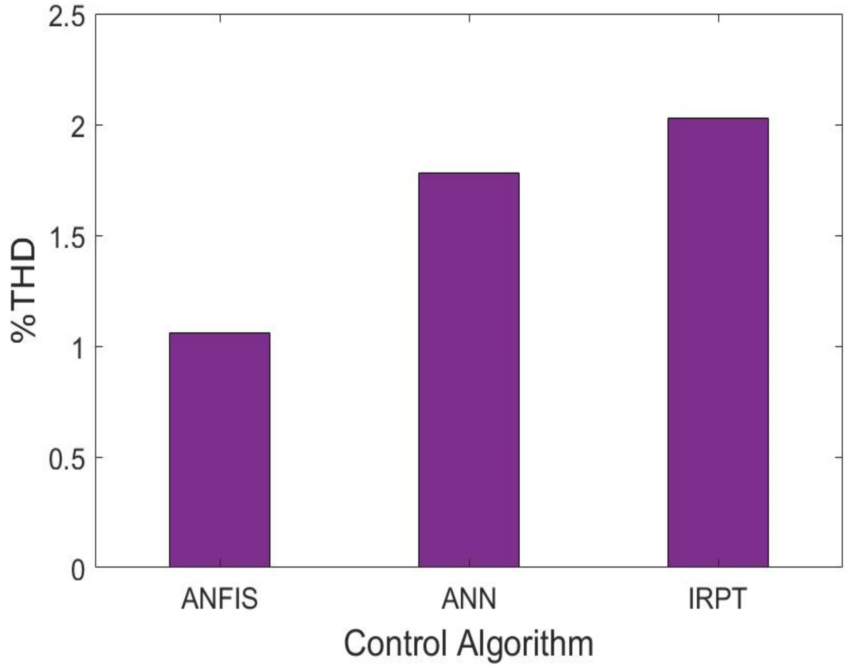


Fig.5.20. Comparison result of %THD obtained using IRPT, ANN and ANFIS based control algorithm.

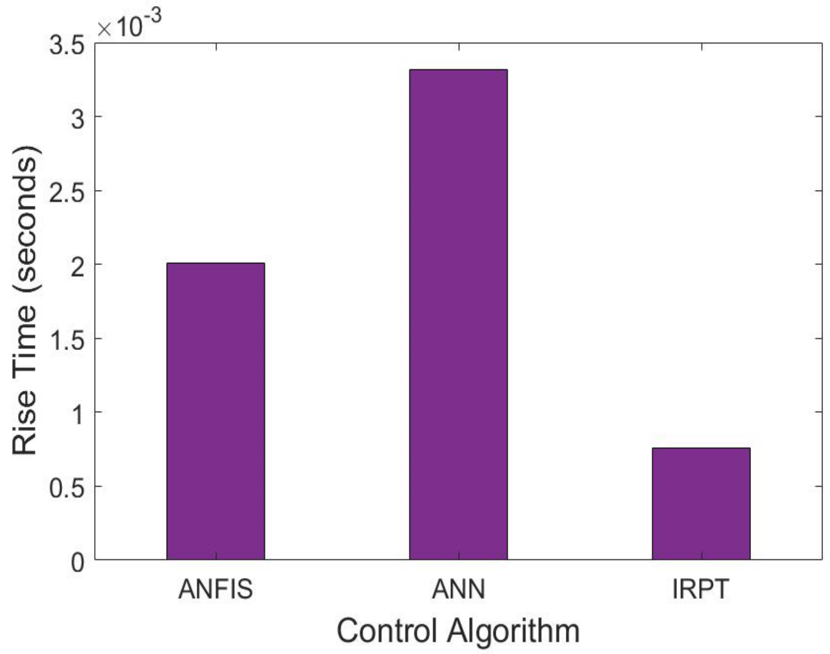


Fig. 5.21. Comparison result of Rise Time obtained using IRPT, ANN and ANFIS based control algorithm.

CHAPTER 6

CONCLUSION

To improve the power quality compensation, I have employed IRPT, ANN and ANFIS based control algorithm. IRPT theory, ANN and ANFIS control algorithm have manifested satisfactory performance of DSTATCOM. The fundamental component of current of IRPT, ANN and ANFIS are extracted and compared. A comparative analysis of dc link capacitor voltage is also done. THD in case of IRPT, ANN and ANFIS is analysed and all the demonstration is carried under dynamic load condition. THD in ANFIS is 1.06% which is better when compared to IRPT and ANN. The dc link capacitor voltage also settles earlier in case of ANFIS when compared to ANN and IRPT. Thus, ANFIS has been manifested to be more efficient and effective methodology when compared to ANN and IRPT in order to control the DSTATCOM for the power quality improvement.

APPENDIX

Shunt Capacitor Capacitance and Initial Voltage	1500 µF, 156 V
Sampling Time	5 µs
PI Controller (Proportional, Integral)	3.5, 1
Source Inductance	0.002mH
Load Inductance	3 mH
Shunt Inductance	2 mH
Source RMS Voltage	110 V

RESEARCH PUBLICATION

- Shreya Sinha and Ankita Arora," Comparison of IRPT and ANN based Control Algorithm for Shunt Compensation in Grid Connected Systems," IEEE 2021 International Conference on Intelligent Technologies (CONIT)
- Shreya Sinha and Ankita Arora," Comparison of IRPT, ANN and ANFIS based Control Algorithm for Shunt Compensation in Grid Connected Systems," 2021 IEEE Sponsored Asian Conference on Innovation in Technology (ASIANCON) 2021

REFERENCES

[1] Tey LH, So PL, Chu YC. Improvement of power quality using adaptive shunt active filter. IEEE Trans Power Deliv 2005;20(April (2)):1558–68.

[2] J.e. Das, "Passive filters - potentialities and limitations," Industry Applications, IEEE Transactions on, vol. 40, pp. 232-241, 2004.

[3] N.G. Hingorani, "Introducing custom power," Spectrum, IEEE, vol. 32, pp. 41-48,1995.

[4] K. R. Padiyar, "FACTS Controllers in Power Transmission and Distribution," New Age International (P) Limited, Publishers, New Delhi, 2007.

[5] S. G. Seifossadat, R. Kianinezhad, A. Ghasemi and M. Monadi, "Quality improvement of shunt active power filter, using optimized tuned harmonic passive filters," 2008 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, Ischia, Italy, 2008, pp. 1388-1393, doi: 10.1109/SPEEDHAM.2008.4581063.

[6] A. Moreno-Munoz, Power Quality: Mitigation Technologies in a Distributed Environment. London, U.K.: Springer-Verlag, 2007.

[7] B. Singh, K. Al-Haddad, and A. Chandra. “A review of active filters for power quality improvement”. Industrial Electronics, IEEE Transactions on, 46(5):960–971, 1999.

[8] Saha Shib Shankar, Suryavanshi Ramesh. Power system harmonic mitigation of an offshore oil rig using passive shunt filter. Presented in IEEE India Conference (INDICON), Kolkata, India; December 2010.

[9] B. Singh and J. Solanki, “A comparative study of control algorithms for DSTATCOM for load compensation,” in Proc. IEEE ICIT, Dec. 15–17, 2006, pp. 1492–1497.