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Master of Electrical Engineering

**Voltage Profile Improvement Using DSTATCOM Based on
Artificial Intelligent Techniques**

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In Partial Fulfillment of the Requirements for the Degree of Master
of Electrical Engineering

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Voltage Profile Improvement Using DSTATCOM Based on Artificial In-telligent Techniques

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Abstract

Recently the demand of electric power is increased due increasing the residential and industrial facilities which may contain sensitive nonlinear loads that needed high power quality (PQ) on distribution system to avoid malfunction operation. One main PQ issue is voltage profile improvement with acceptable voltage harmonic distortion. It should be regulated to be within acceptable standard levels. In order to improve the voltage profile, the distribution static synchronous compensator (DSTATCOM) is used with developed control strategy.

In this research DSTATCOM control is developed based on artificial intelligent (AI) using artificial neural network(ANN), which depends on optimum values obtained by using particle swarm optimization (PSO). The results of simulation proved the superiority and robustness of the proposed control strategy of DSTATCOM for improving the voltage profile on distribution system. The validation of results have been done by MATLAB/Simulink software package.

ملخص

تحسين الجهد على نظام النقل الكهربائي باستخدام المعوض المتحكم به بطرق الذكاء الاصطناعي

زاهر عبدالله سعاين

ماجستير الهندسة الكهربائية

بإشراف

د. فؤاد الزرو

حديثاً تزايد الطلب على الطاقة الكهربائية نتيجة زيادة المرافق الصناعية والسكنية التي يمكن ان تحتوي على احمال غير خطية حساسة والتي تحتاج طاقة كهربائية بجودة عالية حتى لا يحدث خلل في عملها.

احد معضلات جودة الطاقة تحسين الجهد الكهربائي بتوافقيات مقبولة على نظام النقل الكهربائي. يجب تنظيم الجهد ليكون ضمن المعايير المسموحة ، لذلك تم تطبيق المعوض في هذه الدراسة تم اقتراح وتطبيق طريقة للتحكم في المعوض تعتمد على طرق الذكاء الاصطناعي باستخدام خوارزمية الشبكات العصبية المعتمدة على قيم مثالية تم الحصول عليها من تطبيق خوارزمية مستوحى من حركة اسراب الطيور وتطبيقها على شبكة توزيع كهربائية. أظهرت نتائج المحاكاة قوة الاستراتيجية المقترحة في التحكم في المعوض لتحسين الجهد على شبكة التوزيع. تم التحقق من النتائج من خلال برمجيات المتلاب.

DECLARATION

I declare that the Master Thesis entitled "Voltage Profile Improvement Using DSTATCOM Based on Artificial Intelligent Techniques" is my own original work, and hereby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

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DEDICATION

This work is dedicated to my Parents, my wife, my lovely sons, my lovely daughters, my brothers and my friends During the master journey they continued to support and encourage me until I accomplished this work.

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KEYWORDS

Artificial Neural Networks (ANNs), DSTATCOM, Particle Swarm Optimization(PSO), PI controller, Power Quality (PQ), Smart Grid (SG), Total Harmonics Distortion(THD), Voltage Profile.

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List of Abbreviations

The following table lists all abbreviations and acronyms used throughout the thesis and the page on which each is defined or first used.

Abbreviation	Description
AC	Alternating Current
AI	Artificial Intelligent
ANNs	Artificial Neural Networks
ASD	Adjustable Speed Drive
BESS	Battery Energy Storage
DE	Differential Evaluation
DGs	Distribution Generations
DSTATCOM	Distribution Static Synchronous Compensator
EESS	External Energy Storage System
FACTs	Flexible Alternating Current Transmission Systems
FFT	Fast Fourier Transform
GA	Genetic Algorithm
HS	Harmony Search
IEEE	Institute of Electrical and Electronics Engineers

IWD	Intelligent Water Drop
JDECO	Jerusalem District Electricity Company
3LNPC	Three Level Neutral Point Clamped
MI	Modulation Index
NPC	Neutral Point Clamped
PF	Power Factor
PI	Proportional Integral
PCC	Point of Common Coupling
PQ	Power Quality
PSO	Particle Swarm Optimization
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RMS	Root Mean Square
RMSE	Root Mean Square Error
SA	Simulated Annealing
SC	Super Capacitor
SOA	Seeker Optimization Algorithm
SPWM	Sinusoidal Pulse Width Modulation
SRF	Synchronous Reference Frame
THD	Total Harmonics Distortion
VRB	Vanactium Redox Battery
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
VVO	Volt VAR Optimization

Chapter 1

Introduction

1.1 Background

The rapid increase in electrical power demand lead emerging use of renewable energy sources (RES) and distributed generations (DGs) in electrical grid. Emerging new resources of energy into the grid and connecting different types of loads such as non-linear loads create different problems appears in current, voltage and/or frequency which causes error and malfunction of instrument and generally consider as power quality (PQ) problems [1].

Several studies are done regarding PQ issues using the benefits of huge developments in power electronics technologies, hence the network change from traditional network to smart network [2], [3]. Also, PQ may defined as electrical constraints that allows an equipment function properly with high performance [4], [5]. According to these definitions of PQ, poor PQ will affect badly on the reliability and stability of electrical network as well as on sensitive loads connected to the end user of distri-

bution bus. PQ is relate to the three main factors: voltage, current and frequency, all these factors should be remain within their standard limits [3], [4].

The problems of PQ in the network caused by different reasons such as connecting nonlinear loads especially large motors in industrial applications, power electronics devices, switching capacitor banks and connected new electrical resources to the grid [4], [5].

Indeed, these disturbances affect on the performance and functionality of both distribution system and sensitive equipment. The smart grid (SG) technology open a wide range for solving PQ problems [2], [3]. Family related to power electronics technologies called flexible alternating current transmission systems (FACTS) support SG system and provide solutions for PQ challenges. One application of FACTS family is called distribution static synchronous compensator (DSTATCOM), which is a shunt device connected with distribution bus.

Huge development in artificial intelligence (AI), electronic control and communication capabilities contribute the development of optimizations issues of power system aspects under SG umbrella. One of the main aspects of power system is voltage var control. So the voltage var optimization (VVO) is the main SG application that enhances both security and economy of power system [6].

In this work the voltage profile is improved to be within the standard acceptable levels by using DSTATCOM with developed control strategy. The control strategy is developed by using ANN as an AI technique, which also depends on optimum values of PI controller obtained by PSO. The study validated and tested on the proposed test feeder under MATLAB environment software package.

1.2 Thesis Contribution

The contribution of this thesis is developing controller for DSTATCOM based on AI Technique ANN, which its controller gains optimally obtained by PSO.

1.3 Thesis Objectives

The main objective of this thesis has been to examine using DSTATCOM with developed control strategy on distribution part of proposed electrical feeder in order to improve the voltage profile. To satisfy the defined main objective the following intermediate objectives are fixed to properly divide the work to be carried out:

1. Selecting a DSTATCOM for improving voltage profile for medium voltage feeder.
2. Developing control strategy for the proposed DSTATCOM based on AI technique ANN, which depends on optimum values of PI controller gains using PSO.
3. Simulating the proposed DSTATCOM on real feeder using MATLAB/Simulink package to validate the efficient of the developed control technique.

1.4 Thesis Organization

The remaining chapters of this thesis are organized as follows:

Chapter 2 Extensive literature reviews are discussed about PQ issues and their effects on distribution system performance. A considerable amount of research are

reviewed regarding the voltage profile improvement using DSTATCOM and their different control strategies used for this purpose. Also, reviewed researches deal with increase the performance of DSTATCOM using RES. Finally, the reviewed the AI techniques used for tuning PI controller of DSTATCOM and validate the research gap to do this research.

Chapter 3 provides an overview of PQ problems in distribution system their causes and classifications of events and discuss the solutions and evaluation of PQ issues in distribution system.

Chapter4 presents DSTATCOM operation, control strategy, mathematical model, DSTATCOM design equations.

Chapter 5 presents the case study for this research. Also, discussed the AI technique, which is ANN as well as the optimization technique which is PSO. In addition, MATLAB model is simulated according to the studied feeder (11kV/50Hz) for Abu Mashaal zone in Rammallah city. MATLAB design depends on given data for real electrical feeder. Then algorithms for ANN and PSO are discussed in details for a purpose to use them in developed controller.

Chapter 6 discuss the simulations results for developed controller of DSTATCOM and the improvement of voltage profile for extreme sag and extreme swell voltage events. Then proved the validation and the efficient of developed controller. Also, THD is evaluated for improved voltage signal. All in all, conclusions inferred during this work. In addition, ideas and recommendations drawn to be done as future work.

Chapter 2

Literature Review

2.1 PQ Problems in Power System

Several research studies are done regarding improvement PQ issues in electrical power system [1]- [4], [7]. More recent attention has focused on provision regarding enhancement the reliability and stability of electrical grid by means of improving the PQ issues. These research discussed problems of PQ such as voltage profile regulation, unbalance conditions causes by faults and load changing, system losses due to poor power factor (PF) and total harmonic distortion (THD). DSTATCOM and other FACTS devices with different control strategies are used to solve PQ challenges [8], [9].

2.2 Voltage Profile Improvement Using DSTATCOM

Several research studies validated the significant effect of DSTATCOM on PQ issues. In [10] the research proved the efficient performance of DSTATCOM for improving the voltage profile dynamically with high penetration level of wind turbine connecting on distribution bus. DSTATCOM is useful and efficient for reactive power compensation on distribution bus since it tested for PF correction, voltage regulation and load balancing especially where the DG is vital as alternative source of energy in applications such as ships, aircrafts and in the remote isolated power generation systems [11].

Research study [12] discussed the renewable DGs as a solution for voltage dip on distribution system which contain sensitive equipments. The study did not recommended increase the high penetration levels of DGs in the power system due to that will increase control and coordinations complexity. The study suggested using AI and control methodology for fast acting mitigation of voltage dip. Other study [13] supported study in [12] by validated DSTATCOM efficiently for mitigation of voltage sag as well as correct PF by compensation enough reactive power. Also in [14] a group of researchers examined using STATCOM on transmission system (132kV/50Hz) for compensation the voltage swell and the results validated STATCOM as efficient FACTS device for improving voltage profile on transmission system.

On the other hand, in [15] many PQ issues are mitigated including voltage regulation with unity power factor, harmonics distortion and unbalance voltage.

The study is implemented on the proposed network. PQ problems with different types of load examined were mitigated and DSTATCOM proved to use as a solution for improving power system stability and reliability.

2.3 Control Strategies of DSTATCOM

A considerable amount of literature has been published on DSTATCOM control strategies. The PWM connected to distribution bus by LCL filter is implemented using digital signal processing (DSP) controller in order to eliminate negative sequence for unbalance voltage and so improve the voltage profile during fault conditions. The results proved the vital of using LCL filter with DSTATCOM in order to mitigate the PQ problems [8], [16].

Different control strategies used in DSTATCOM are sensitive to non ideal supply conditions and load variation which needed careful design tuning controller for each specific insulation. Also, the cost of the system increase due to use special devices such as LCL filter [8], [16]- [17].

Other control strategies of DSTATCOM in literature needed complex control facilities and controllers, also needed additional supplementary components such as active filter. In addition, the controller may need additional delay time due the conversion from analogue to digital [17]- [19].

On the other side new proposed control strategies for DSTATCOM are implemented such as adaline based algorithm and direct method which depends mainly on position and magnitude control of output voltage. Although these methods are validated as efficient methods for controlling DSTATCOM, they are complex and expensive comparing with traditional methods [9], [18].

Different mathematical theories and physical models are used in analysis and implementing different control strategies of DSTATCOM. The cascaded technique is used and the voltage source inverter is linearized using average switch model(ASM) [8]. Instantaneous power theory, rotating reference frame(dq0), stationary reference frame($\alpha \beta$ 0), instantaneous reactive power (IRP) and Park's transformation are used to simplify the dynamic system equations [8], [9], [16]- [21]. The stationary reference frame transform balance three phase system into two phase (clark transformation) this reduce one phase variable implies the same reduction in the number of controllers required, which will reduce the complexity of the control system. On the other hand, dq0 provides a steady state control variable which is more simplicity and efficient for controller design [22]. The Phase Locked Loop(PLL) is used to provide a reference phase signal synchronize with the ac system [20]. Proportional Integral (PI) used to regulate and control firing angle provided to PWM, which generated switching pulses to IGBTs in VSI [18].

2.4 Merging RES with DSTATCOM in SG

Recently a SG technologies play an important role for improving reliability of electrical power system. SG contribute the improving of PQ issues with corporation of power electronics technologies and RESS. Few papers discussed the integration between RESS and DSTATCOM to improve PQ issues in the network [7], [22]. Significant research has been concerned with FACTS devices and smart control compatible with renewable energy resources. Existing RES and DGs in power system create different challenges especially when these resources with high penetration levels. To deal with these challenges a SG technology is vital to manage the power flow gener-

ated by grid. Power generated from RES and the compensation power generated or absorbed by FACTS devices. Using SG technology leads to increase the reliability and stability of power system regardless of high penetration level of RES connected to distribution bus [2], [6], [23]- [24].

The dynamic performance of DSTATCOM is studied by coupling it with external energy storage system (EESS) in order to enhance PQ at distribution system. Multilevel control techniques are used in VSI. Battery was used as energy storage system (BESS) and added to dc bus of the inverter. This is efficient to reduce investment cost by avoiding extra coupling interface. The VSI designed using multilevel topology which is neutral point clamped (NPC) provides conventional sinusoidal output voltage without increasing switching frequency, consequently lower losses and reducing size, but this topology needed to maintain a constant voltage at half dc bus voltage to prevent large distortion [20].

PHD thesis was done at ESTIA Institute of technology about using microgrid hybrid energy storage integration and control using a three level neutral point clamped (3LNPC) converter. The author studied the effect of microgrid in distribution system on power quality under high penetration level. In order to maintain stable power system and high power quality factors in distribution system. Special storage devices with specific requirements are used. The thesis focused on designing a power converter system to satisfy the defined requirement of hybrid energy storage system in order to improve the power quality under high penetration level. Two storage devices are used , super capacitor (SC) bank and vanadium redox battery (VRB) were examined to get suitable storage system. This hybrid system is controlled by using 3LNPC, which select the current reference of hybrid storage system and

controlled it by typical two loop PI controller. The power and energy management was studied to reduce the power losses and harmonic distortion. The control strategy is applied on dc side of 3LNPC converter and hence there is no effect on ac side. The author concluded that using hybrid energy storage system using SC and VRB is essential when there is high penetration level from microgrid connecting to distribution system [18].

2.5 Tuning DSTATCOM Controller Using AI Techniques and Optimization Methods

Huge development in AI, electronic control and communication capabilities contribute the development of optimizations issues of power system aspects under SG umbrella [25]- [42]. On other side, several research done regarding optimization methods for different issues in power system. These research include a comparative of meta-heuristic approach such as GA, PSO, differential evaluation(DE), harmony search(HS) and seeker optimization algorithm(SOA) [43]- [45].

In [26] nonlinear controller of DSTATCOM which connected to distribution system with DGs is tuned by using the controller parameters of PID controller of DSTATCOM is tuned using hybrid combination algorithm consists of simulated annealing(SA) and intelligent water drop(IWD). SA is motivated by analogy to annealing in solids [27] and IWD is a nature inspired algorithm that tries to mimic the behavior of swarm of natural water drops which creates complex paths which is optimum [28]. Researchers in [41] used SA as an optimization technique to identify controller parameters of STATCOM and their results compared with other opti-

mization techniques, which are PSO and genetic algorithm (GA) under the same disturbance conditions. SA proved its efficiency compared with other methods for voltage profile improvement. This hybrid tuning methods leads to better regulation of direct voltage for capacitor in DSTATCOM which improve the maximum overshoot, rising time and steady state errors values. Researchers in [29] suggested using PSO based tuning algorithm for tuning DSTATCOM controllers. They proved experimentally the efficient of PSO algorithm for tuning PI gains of controllers and compared the results with results obtained from using Ziegler-Nicholos methods. They supported the experimental results with simulation results which done under MATLAB/Simulink environment. Researchers concluded that using suggested PSO tuning is far superior than conventional Ziegler-Nicholos tuning method.

2.6 Research Gap

From above literature therefore a considerable amount of research about using DSTATCOM as an application of FACTs for PQ improvement in power system. The research divided generally in many sectors such as benefits of using DSTATCOM for voltage profile, decreasing THD, PF correction and solving unbalance conditions. On other side, DSTATCOM controller discussed in details to enhance the dynamic performance of its operations. Regarding to the control strategies tuning DSTATCOM controller gains has a great challenge. Several algorithm are used for optimally tuning PI controller of DSTATCOM, and the results are compared between some of these methods. Although different algorithms suggested as optimally tuning technique for DSTATCOM controller, the results are different with the objective function of optimization as well as dependent on the data given about

the distribution system which is in some cases needed real time monitoring and needed special control strategies as well as additional equipments, this lead to the importance of using AI techniques for controlling DSTATCOM.

From the literature review, therefore great challenges regarding using AI techniques for tuning PI controller of DSTATCOM. This work will suggest using ANNs as a technique for tuning controller of DSTATCOM, which its controller constants is selected optimally using PSO.

Chapter 3

Power Quality Factors

3.1 PQ Concept

PQ of distribution network is relate of powering and grounding sensitive equipment. Also PQ may defined as electrical constraints that allows an equipment to function properly with high performance. According to these definitions of PQ, poor PQ will affect badly on the reliability and stability of electrical network as well as on sensitive loads connected to grid. PQ is relate to the three main factors: voltage, current and frequency, all these factors should be remain within there standard limits [2, 3].

3.2 Importance of PQ Factors in Power System

The following major reasons may lead the importance of PQ factors in power system [30]:

- Huge development in power electronics technologies and microprocessor based

control in newer generation are sensitive to PQ factors variations.

- It essential to reduce losses, improving power factor and decreasing THD especially with industrial applications such as adjustable speed motor drives(ASD).
- SG technologies may depend on the integration and interconnection between the process of whole components in power system, this means any failure in any component may has great consequences on the normal operation and functionality of power system.
- Interruption of power system due the PQ issues will affects badly on the whole international economics. Accordingly, the above the electric utilities and users should concern about improve the PQ factors as well as electrical equipment manufacturers.

3.3 Voltage Events of PQ

3.3.1 Classifications Voltage Events

Voltage events of PQ are divided into short duration and long duration [30]:

1. Voltage sag(dip) : according to the IEEE Std.1159 define as decrease in RMS voltage to range between 10% to 90% for duration from 0.5 cycle to 1 min. Voltage sag may appear when a faults happened, turning on heavy loads or turning off large capacitor. Sag event have undesirable effects especially on sensitive electrical devices such as ASD.

2. Voltage swell : according to IEEE Std.1159 define as an increase in RMS voltage above 110% to 180% of nominal voltage for duration of 0.5 cycle to 1 min. Voltage swell is occurred in case of unsymmetrical single line to ground fault, switching off a large load or when energizing a large capacitor bank. The effects of this event are memory loss, data errors, bright lights, false tripping and equipment shutdown [30].
3. Voltage interruption : according to IEEE Std.1159 occurs when the supply voltage decreases to less than 10% of nominal RMS voltage for time period not exceeding 1 min. Different causes for interruption in network such as utility faults, circuit breaker tripping and components failure. The effect of interruption are loss of data when false shutdown happened damage the electronics devices. Figure 3.1 shows the three short duration events and RMS voltage waveforms [30].

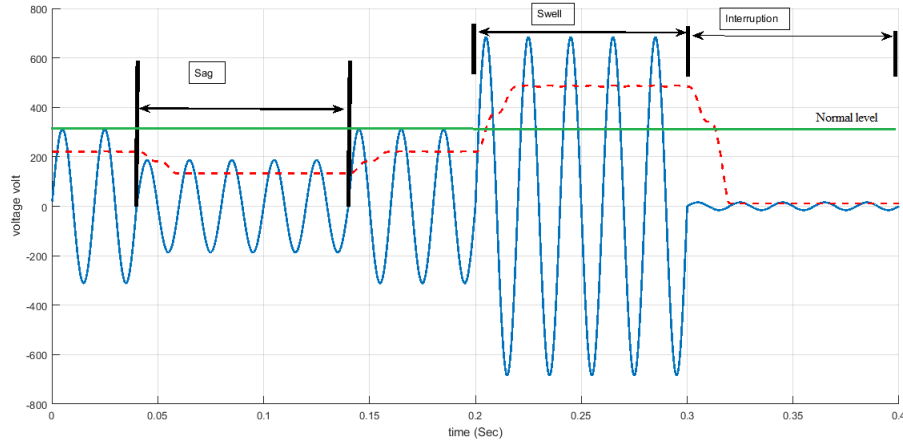


Figure 3.1: Short duration voltage events [30]

Table 3.1 [30] summarizes the PQ classification regarding their time range according IEEE std.1159

Table 3.1: PQ events classification (IEEE std 1159) [30]

Voltage Event	Magnitude	Duration
Sag	90%-10%	≤ 1 min
Under Voltage	90%-10%	> 1 min
Interruption	$< 10\%$	≤ 1 min
Sustain Interruption	$< 10\%$	> 1 min
Swell	$> 110\%$	≤ 1 min
Over Voltage	$> 110\%$	> 1 min

3.3.2 Measurement of Duration and Amplitude of Voltage Event

According to IEEE Std.1159 and IEC (6100-4-30) the events quantified by measuring duration and amplitude. Two methods used to calculate the RMS value

1. Conventional RMS Calculation Method. The RMS value can be calculated if the waveform is sampled given by Eq. (3.1) [31]

$$V_{rms}(i) = \sqrt{\frac{1}{N} \sum_{i=1}^N (V_i)^2} \quad (3.1)$$

where :

N : is the number of samples per cycle .

V : is the instantaneous sample voltage .

k : is the instant when the rms voltage is estimated.

2. The Quadrature Method [31] This method also used to calculate RMS voltage

based on the sampled time domain , but it uses only two samples per a half cycle with 90 degree distance between them Figure 3.2 [31]

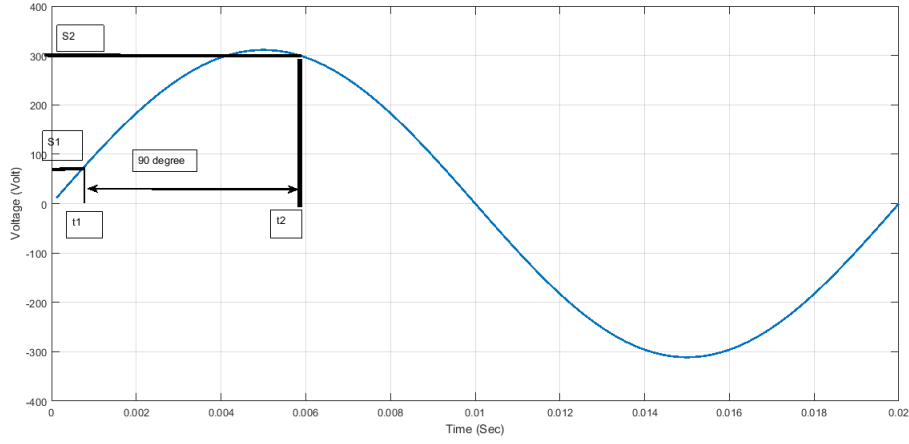


Figure 3.2: Quadrature method [31]

The following equations derive the value of RMS voltage using quadrature method

$$V(t) = V_p \sin(\omega t) \quad (3.2)$$

$$S_1 = V_p \sin(\theta) \quad (3.3)$$

$$S_2 = V_p \sin\left(\theta + \frac{\pi}{2}\right) \quad (3.4)$$

$$S_2 = V_p \cos(\theta) \quad (3.5)$$

$$S_1^2 + S_2^2 = V_p^2(\sin^2(\theta) + \cos^2(\theta)) \quad (3.6)$$

$$\sqrt{S_1^2 + S_2^2} = \sqrt{V_p^2} \quad (3.7)$$

$$\sqrt{S_1^2 + S_2^2} = V_p \quad (3.8)$$

$$V_{rms} = \frac{V_p}{\sqrt{2}} = \frac{\sqrt{S_1^2 + S_2^2}}{\sqrt{2}} \quad (3.9)$$

where :

$V(t)$: instantaneous voltage .

V_p : peak voltage .

S_1 : sample number 1 .

S_2 : sample number 2 .

V_{rms} : root mean square voltage .

3.4 PQ Problems Evaluation

In order to deal with PQ problems. Generally, several steps may consider as follows [32]:

1. Identification of problem category. Monitoring the system voltage, current and frequency on the define time period lead to classify the PQ problems such

as voltage regulation, voltage unbalance, voltage sag, voltage swell, voltage interruption, flicker, transients, harmonic distortion and other problems.

2. Problem characterization the data measurements of the system give indications about the problems characteristics, causes and equipments impacts.
3. Identification range of solutions diagnose the problems according to data collection leads to the range of solutions. These solutions may in utility transmission system, utility distribution system, end use customer interface, end use customer system or equipment design/specifications.
4. Evaluate range of solutions. The modeling and analysis procedures done to select the suitable solutions or the alternatives.
5. Finally find the optimum solution which is the best solutions and also the most economic one between the range of solutions and alternatives.

Chapter 4

DSTATCOM Configuration and Design

4.1 Principle and Operation of DSTATCOM

4.1.1 Equivalent Model of DSTATCOM

DSTATCOM consists of three phase bus, shunt transformer, VSC and DC capacitor. Figure.4.1 shows the equivalent model of DSTATCOM [21].

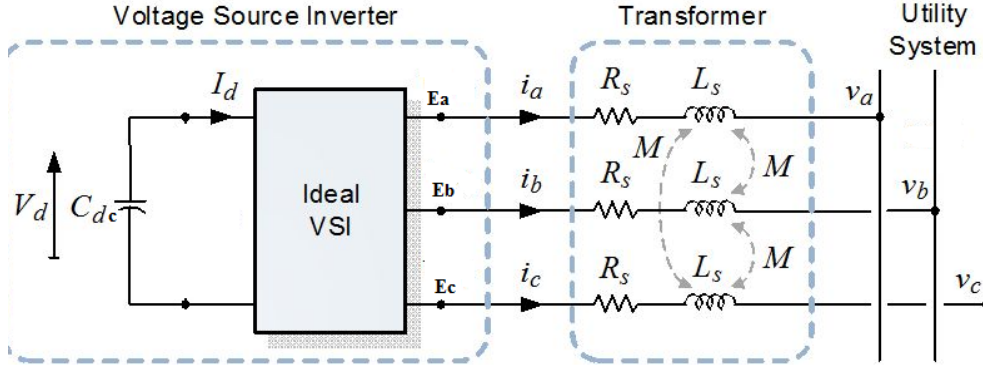


Figure 4.1: Equivalent model of STATCOM [21]

Where:

R_s and L_s : DSTATCOM transformer resistance and inductance respectively .

E_{abc} : are converter AC side phase voltages.

V_{abc} : are the ac system side phase voltages.

i_{abc} : are phase currents.

I_d : is capacitor current.

C_{dc} : is dc capacitor value.

The main electronic part of DSTATCOM is VSC, the function of this part is to convert dc input voltage to ac output voltage. There two types of VSC used:

1. Square wave inverters using Gate Turn-off Thyristor four three level inverters are utilized to make 48-step voltage waveform, beside that special inter connection transformers are used to eliminate harmonics from the output voltage.
2. PWM, this inverter use isolated gate bipolar transistor (IGBT). This type used PWM technique to convert dc voltage to ac sinusoidal waveform.

The function of coupling shunt transformer is to connect the converter to high

voltage power system. From the above model the equivalent circuit of STATCOM simplified as shown in Figure4.2 [21].

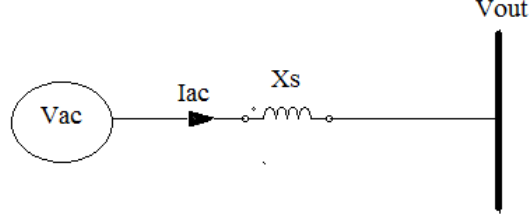


Figure 4.2: Equivalent circuit of STATCOM [21]

Where:

V_{ac} : ac voltage of the system

V_{out} : output voltage of the converter

I_{ac} : ac current flows through the reactance between the converter and ac system

The phasor diagram for the system when resistance of the transformer not neglected shown in Figure4.3 [46].

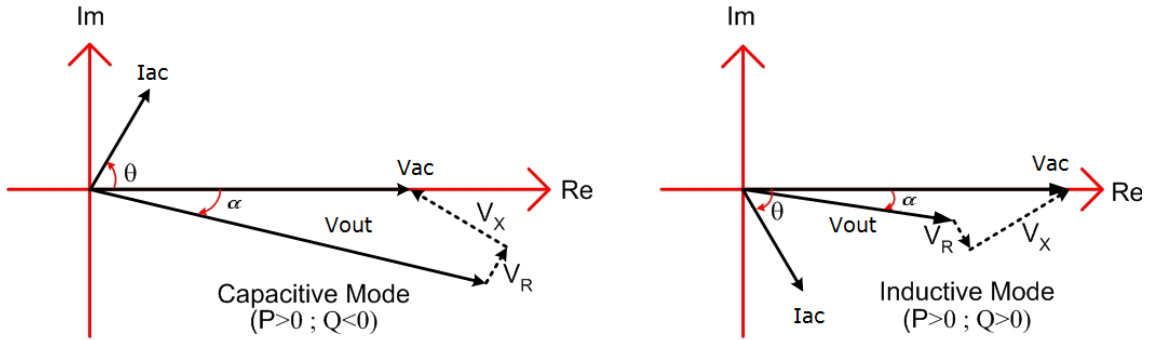


Figure 4.3: Phasor diagram for the system (R not neglected) [46]

The resistance of the transformer is very small, it may be neglected. So that, there is no dissipated power in ideal DSTATCOM. The phasor diagram for the

system shown in Figure4.4 [46].

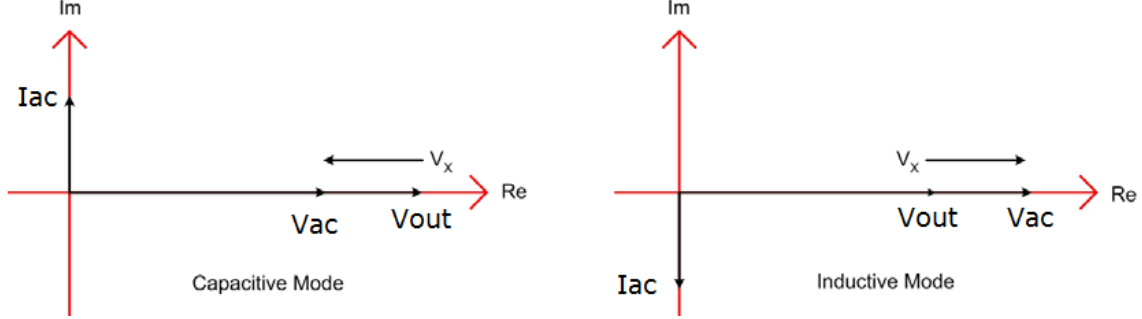


Figure 4.4: Phasor diagram for the system (R neglected) [46]

4.1.2 Principle of Operation

To study the operation of STATCOM, a functional model of the device drawn as shown in Figure4.5 [21].

The operation of STATCOM is summarized by three modes:

- Mode1: STATCOM supplies reactive power to AC system. If the amplitude of V_{out} is increased above that of utility bus voltage V_{ac} , the current flows through the reactance from the converter to AC system and the converter generates capacitive reactive power for the AC system. The phasor diagram shown in Figure4.4 [46] the current lag V_x but this current leads V_{ac} .
- Mode2: STATCOM absorbs reactive power from AC system. If the amplitude of V_{out} is decreased below the utility bus voltage, the current flows from the AC system to the converter which absorbs inductive reactive power from the

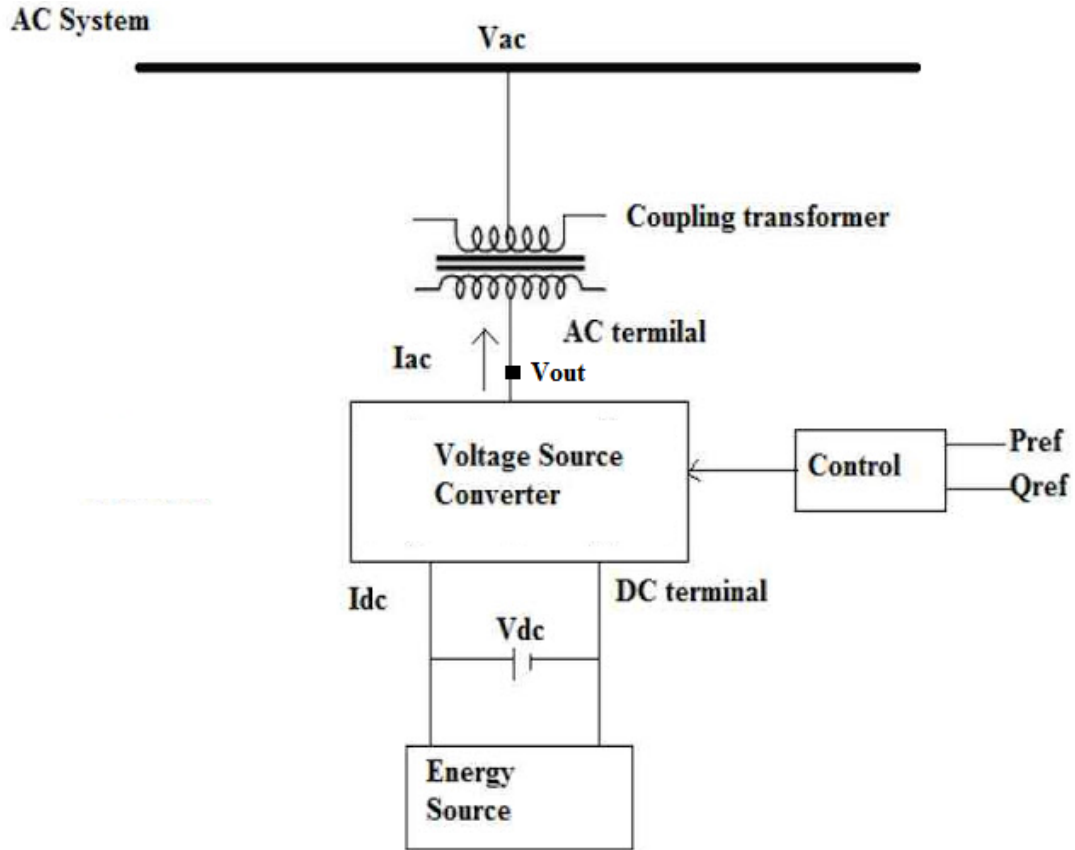


Figure 4.5: A functional model of STATCOM [21]

AC system. From the phasor diagram shown in Figure 4.4, the current lags V_x and also the current lags V_{ac} .

- Mode3: STATCOM is in floating state. If the V_{out} equals the AC system voltage, there is no exchange of reactive power.

4.1.3 STATCOM V-I Characteristic

When the STATCOM operates as voltage regulation on a distribution system, the V-I curve describes its operation as shown in Figure 4.6 [45].

From the V-I characteristic, the STATCOM can supply both capacitive and inductive

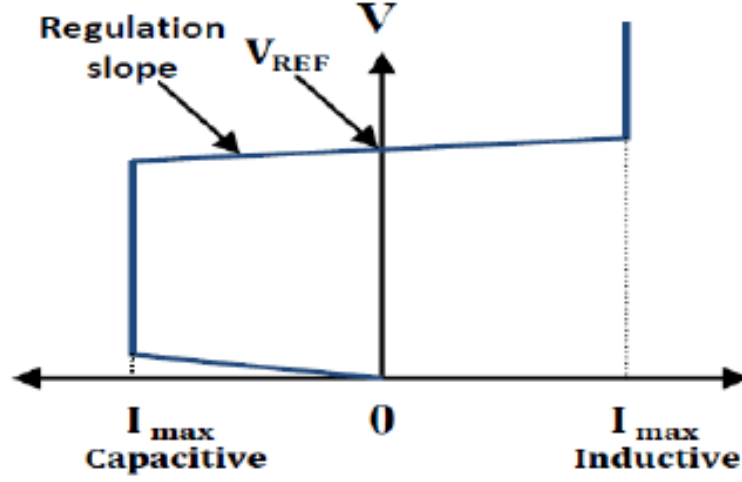


Figure 4.6: STATCOM V-I characteristic [45]

compensation and it is able to independently control its output current over maximum capacitive and maximum inductive as long as the reactive current stays within ($-I_{\max}$ in capacitive mode and I_{\max} in inductive mode). The slope regulation is define as difference between the reference voltage and voltage bus of ac system.

DSTATCOM has a nonlinear structure, so that in order to study the operation and it control strategy a simplified mathematical formula is needed. Figure4.7 shows the configuration parameters of power system with DSTATCOM [22]. DSTATCOM operation based on the fact that the real and reactive power can be adjusted by voltage magnitude of the inverter V_c and the angle difference between the bus and the inverter output (α). The Eq. (4.1) and Eq. (4.2) are describe the active and reactive power compensation respectively [29]:

$$P = \frac{V_{pcc} V_c \sin \alpha}{X} \quad (4.1)$$

$$Q = \frac{V_{pcc}(V_{pcc} - V_c \cos \alpha)}{X} \quad (4.2)$$

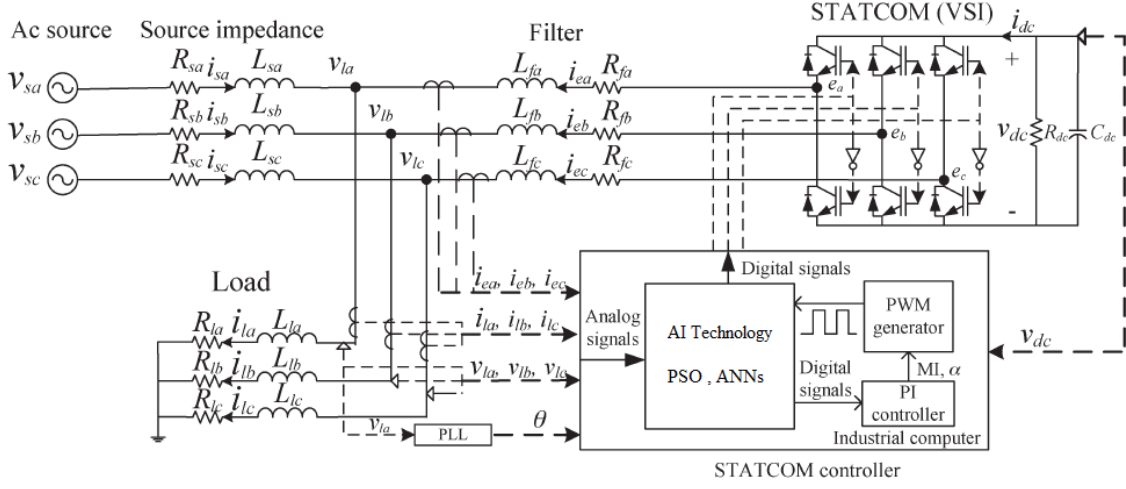


Figure 4.7: Configuration of power system with DSTATCOM [22]

Where:

P: Active Power.

Q: Reactive Power.

V_c : Inverter Voltage.

V_{pcc} : Voltage at the point of common coupling.

α : Angle of V_{pcc} with respect to V_c .

X: Reactance of the branch and the transformer.

DSTATCOM connected to the grid through coupling transformer at PCC exchanges reactive power with the grid. If the magnitude of the DSTATCOM voltage V_c is greater than the grid voltage V_{pcc} ($V_c > V_{pcc}$), then DSTATCOM supplies reactive power to the grid and hence DSTATCOM is operating in the capacitive mode. If the grid voltage V_{pcc} is greater than the DSTATCOM voltage ($V_{pcc} > V_c$) the DSTATCOM absorbs reactive power from the grid and then DSTATCOM is operating in inductive mode. If the grid voltage (V_{pcc}) and DSTATCOM voltage (V_c) are the same magnitude ($V_{pcc} = V_c$) there is no exchange of reactive power between the grid and

DSTATCOM. On the other hand, active real power can flow through the DSTATCOM in either direction from DC link capacitor to PCC and from PCC toward the DC link capacitor.

4.2 DSTATCOM Control Strategy

The function of DSTATCOM under justified condition is to inject the required reactive current to the load. DSTATCOM inject these current by using PI controller. The control strategy scheme is shown in Figure 4.8 [22]. The output voltages for VSI

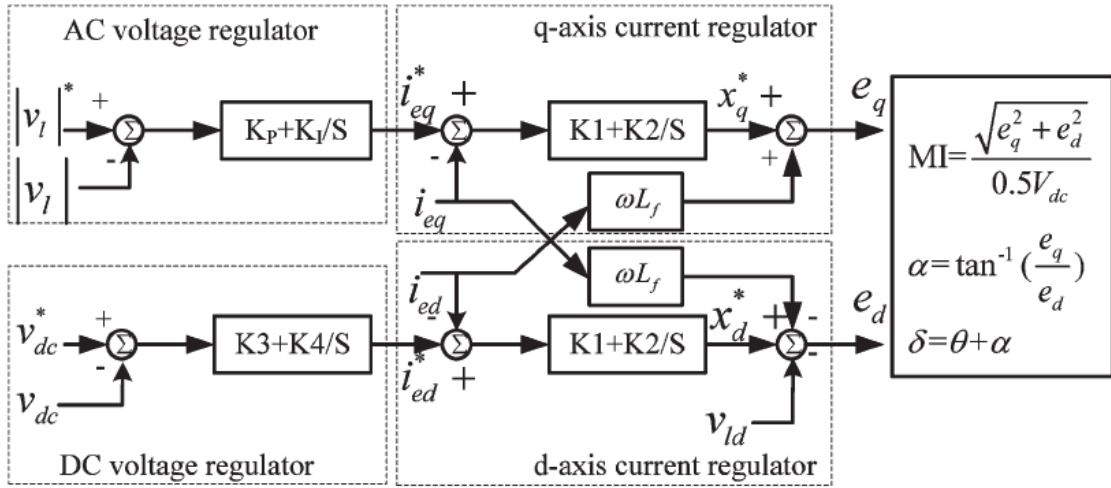


Figure 4.8: DSTATCOM control strategy [22]

are controlled by PWM, which is related to modulation index (MI) and phase angel α . The required control variables are generated by adjustable tuned PI controller in DSTATCOM scheme.

The output voltage of DSTATCOM is controlled in such away that the phase angle between the inverter voltage and line voltage is dynamically adjusted so that the DSTATCOM generates or absorbs the desired reactive power at PCC [47]. The

goal of such control is to maintain constant voltage magnitude at PCC under system disturbances [49]. Figure 4.9 shows the controller input is an error signal which is

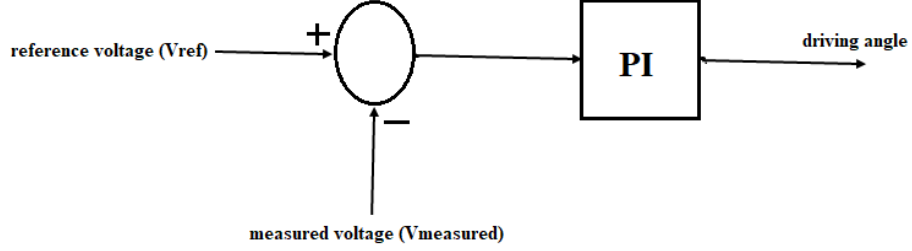


Figure 4.9: Direct PI control of DSTATCOM [49]

the difference between the RMS reference voltage(1pu) and the RMS value of the terminal voltage measured. The PI controller process the error signal and generate the required drive angle to minimize the error to zero.

4.3 System Mathematical Model

According to the dynamic equations of the system, the controller of DSTATCOM is designed. Assuming that the system is considered as linear system [22].

4.3.1 Load Model Mathematical Equations

According to system configuration shown in Figure 4.7, the three phase load voltages coordinates may be written as in Eq. (4.3) [22] :

$$\begin{bmatrix} v_{la} \\ v_{lb} \\ v_{lc} \end{bmatrix} = R_l \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} + L_l \frac{d}{dt} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (4.3)$$

The load is assumed to be balanced, the park transformation is used to convert three phase system in to two phase dq system.

The park transformation [6] is given as in Eq. (4.4)

$$T = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (4.4)$$

Then the Eq. (4.3) can transformed to rotating reference frame as in Eq. (4.5) [22]

:

$$\begin{bmatrix} v_{ld} \\ v_{lq} \end{bmatrix} = R_l \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} + L_l \frac{d}{dt} \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} + L_l \begin{bmatrix} 0 & -w \\ w & 0 \end{bmatrix} \begin{bmatrix} i_{ld} \\ i_{lq} \end{bmatrix} \quad (4.5)$$

where:

$$\theta = \tan^{-1}(v_{lq}/v_{ld})$$

4.3.2 VSI AC-Side Model

The source voltage V_s and inverter output voltage may be written as given in Eq. (4.6) and Eq. (4.7) respectively [22].

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \frac{a_1}{L_l} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{b_1}{L_l} \frac{d}{dt} \begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{c_1}{L_1} \begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{d_1}{L_l} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (4.6)$$

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = \frac{a_2}{L_l} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{b_2}{L_l} \frac{d}{dt} \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} + \frac{c_2}{L_1} \begin{bmatrix} i_{ea} \\ i_{eb} \\ i_{ec} \end{bmatrix} + \frac{d_2}{L_l} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \quad (4.7)$$

Where:

$$a_1 = (R_s L_l - R_l L_s)$$

$$b_1 = -(L_s L_f + L_s L_l + L_l L_f)$$

$$c_1 = -(R_f L_s + R_l L_s + R_f L_l)$$

$$d_1 = (L_s + L_l)$$

$$a_2 = -(R_s L_f + R_l L_f + R_s L_l)$$

$$b_2 = -(L_s L_f + L_f L_l + L_l L_s)$$

$$c_2 = (R_f L_l - R_l L_f)$$

$$d_2 = (L_f + L_l)$$

4.3.3 VSI DC-Side Model Equations

The power balance equation for VSI [6] is expressed as Eq.(4.8) [22]

$$v_{dc} i_{dc} = \frac{3}{2} (e_d i_{ed} + e_q i_{eq}) \quad (4.8)$$

v_{dc} can be derived from a current balancing formula as in Eq.(4.9) [22] :

$$\frac{d}{dt} v_{dc} = - \left(\frac{v_{dc}}{R_{dc} C_{dc}} + \frac{i_{dc}}{C_{dc}} \right) \quad (4.9)$$

The current i_{dc} can be expressed in Eq.(4.10) [22]:

$$i_{dc} = \frac{3}{2v_{dc}}(e_d i_{ed} + e_q i_{eq}) \quad (4.10)$$

4.4 DSTATCOM Design

According to the mathematical model equations of the system the selection of DSTATCOM components should be calculated [34]

4.4.1 Design DC Bus Voltage

Sufficient enough DC link voltage is vital to obtain current compensation which can be calculated as in Eq.(4.11) [34]:

$$V_{dcmin} > \sqrt{2}V_{L-L(r.m.s)} = \sqrt{2}\sqrt{3}V_{L-N(r.m.s)} \quad (4.11)$$

4.4.2 Design DC Bus Capacitor

Referring to the principle of energy conservation, the C_{dc} may be calculated in Eq. (4.12) [34]

$$\frac{1}{2}C_{dc}[V_{dc}^2 - V_{dc1}^2] = 3KaVIt \quad (4.12)$$

Where:

V_{dc} : is the reference DC bus Voltage.

V_{dc1} : is the minimum level of the DC bus voltage.

a: is the over loading factor.

V: is the phase voltage.

I: is the phase current.

t: is the time for which the DC bus voltage is to be recovered.

k: factor for variation of energy during dynamics.

4.4.3 Design AC Interfacing Inductor(L_f)

The selection of suitable filter depends on the ripple current(i_{cr-pp}), switching frequency(f_s) and DC bus voltage (V_{dc}) is given in Eq. (4.13) [34]

$$L_f = \frac{\sqrt{3}mV_{dc}}{12af_s * i_{cr-pp}} \quad (4.13)$$

Where:

m: is modulation index.

4.4.4 Design Passive High Pass Ripple Filters

This filter is need to deal with high frequency noise from the voltage at PCC and it may calculated as given in Eq.(4.14) [34]:

$$R_r C_r = \frac{T_s}{10} \quad (4.14)$$

Chapter 5

Methodology

5.1 Case Study

The work is applied on real network with data given by Jerusalem District Electricity Company (JDECO). The network is for Abu Mashaal zone in West Bank (appendix B). The voltage on this network drops below the standard level (11kV) on distribution bus due the industrial nonlinear loads. The single line diagram of the given radial network is shown in Figure 5.1 Description of the system configuration

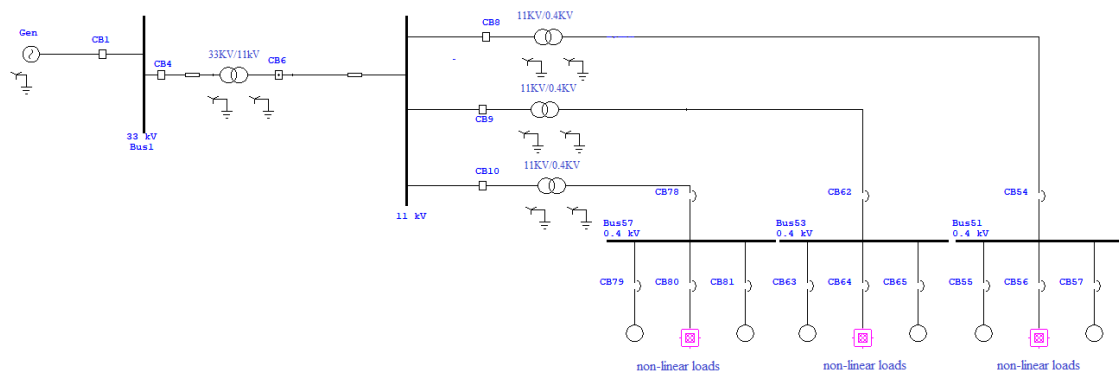


Figure 5.1: Single line diagram for radial network

is summarized in table. 5.1,the details data is given in (appendix B).

Table 5.1: Description of proposed distribution feeder

Parameter	Value
3phase ac source	$V_{s(rms)} = 11\text{kV}$, $f=50\text{Hz}$
Line impedance	$L_s = 3.851\text{mH}$, $R_s = 0.121\Omega$
Distribution transformer (3kVA)	1. 33 kV/11kV 2. 11kV/0.4kV

5.2 Calculation of DSTATCOM Configurations

Configurations of DSTATCOM are calculated using mathematical equations design given in Eq.(4.11) into Eq.(4.14).

The rated load connected on the end user of distribution system is 1MVA, according to this the rating current may calculated as follows:

$$\text{Rated RMS current} = \frac{kVA * 10^3}{\sqrt{3} * 400} = \frac{1000 * 10^3}{\sqrt{3} * 400} = 1443.3A \quad (5.1)$$

The Peak value of line current may calculate:

$$I_{Peak} = 1443.3 * \sqrt{2} = 2041.2A \quad (5.2)$$

The DC link Bus Voltage calculate:

$$V_{dc} = \sqrt{2} * 11kV = 15556.3V \quad (5.3)$$

The DC bus capacitor value may estimated as:

$$C_{dc} = \frac{[3 * 0.1 * 1.5 * 6350.8 * 2041.2 * 20 * 10^{-3}] * 2}{(16000)^2 - (15556.3)^2} = 16.665mF \quad (5.4)$$

The AC interfacing inductor (Lf) calculate as:

$$L_f = \frac{\sqrt{3}(1) * 16000}{12 * 1.2 * 200 * 10^3 * (0.15 * 2041.2)} = 31.42\mu H \quad (5.5)$$

The RrCr high pass filter design as:

$$R_r C_r = \frac{T_s}{10} = \frac{5 * 10^{-6}}{10} \quad (5.6)$$

$$\text{Let } C_r = 1.8 * 10^{-3} \text{ F, } \Rightarrow R_r = 0.0027\Omega$$

5.3 MATLAB Model Simulation

5.3.1 MATLAB Simulink Simulation

Figure 5.2 shows the over all power system for given case study with DSTATCOM connecting on 11kV distribution bus

5.3.2 MATLAB Simlink For DSTATCOM

The DSTATCOM configuration is simulated as shown in Figure 5.3 [39]. There are two IGBT bridges in DSTATCOM configurations this may reduce the harmonics.

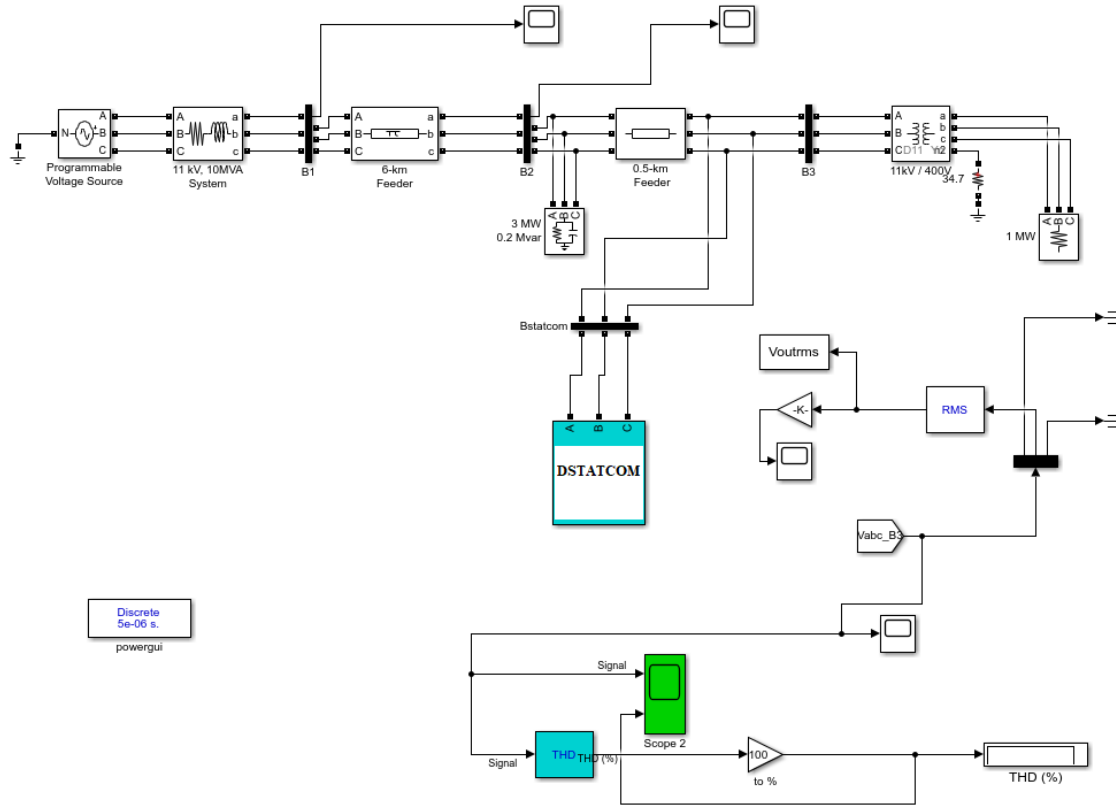


Figure 5.2: Matlab Simulink simulation

5.3.2.1 DSTATCOM Controller Simulation

DSTATCOM control strategy mainly based on PI controller used to regulate the error and so minimize the voltage derivation between the reference value and the actual measured value. The controller performance depending upon the characteristics of the plant and the values of K_p and K_i parameters used in PI controller. Figure 5.4 [39] shows the close loop control system contain Function of PI controller $G_c(s)$ and objective function $G(s)$. In order to derive the transfer function of control system which given in Eq. (5.7) [39] :

$$TransferFunction = \frac{G_c(s) + G_s}{1 + G_c(s)G_s} \quad (5.7)$$

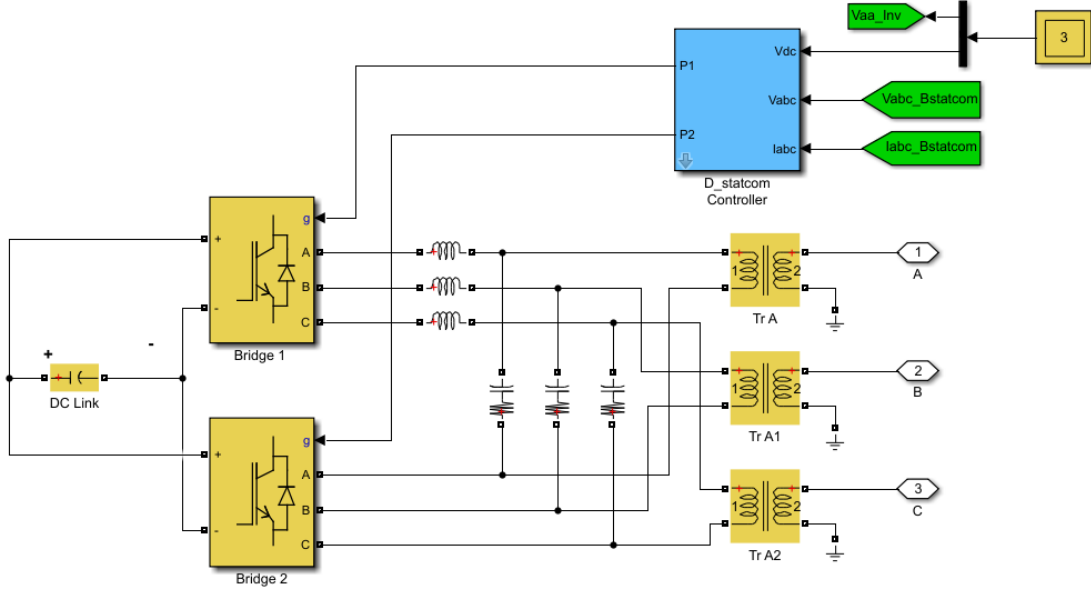


Figure 5.3: MATLAB Simulink model for DSTATCOM configurations [39]

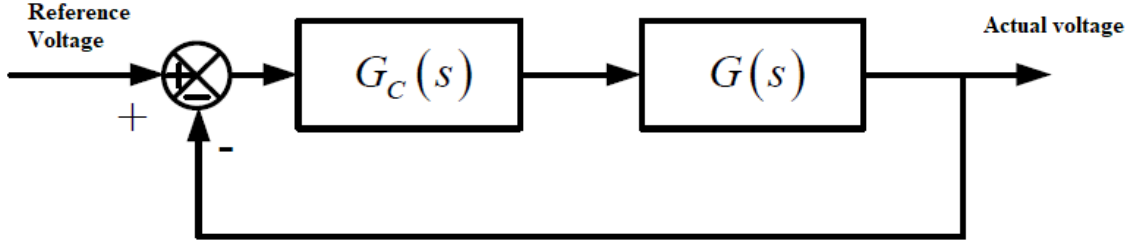
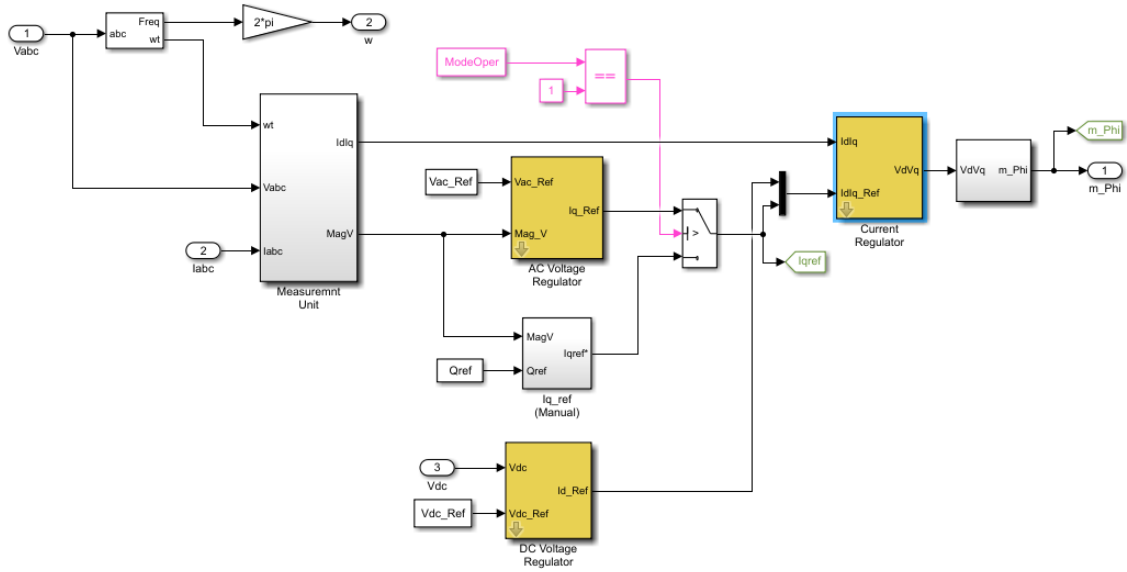


Figure 5.4: Control system block diagram for DSTATCOM [39]

The PLL is used as a control strategy for DSTATCOM. The control strategy is shown in Figure 5.5 [39]. The controller of DSTATCOM consists of PLL, measurement systems, current regulation loop, voltage regulation loop and a dc link voltage regulation.

The PLL is synchronized to the fundamental of the transformer primary voltage to provide synchronous reference trigonometric functions required for the abc-dq transformation. The inner current regulation loop consists of two PI controllers that



control the dq components for currents. The controllers outputs are the voltage direct axis and quadrature axis V_d and V_q that the PWM has to generate. The inverse park transformation is used to convert V_d and V_q back to V_{abc} , which are used to synthesize the PWM voltage. The distribution bus voltage is regulated by the PI controller which produces I_q reference for current controller. The I_d reference comes from dc link voltage regulator which maintain the dc link voltage constant [34].

PSO is used as a tool to select the optimum values for tuning PI controllers of DSTATCOM. Then ANNs trained according to the PSO results. The ANNs used to control DSTATCOM real time according to disturbance on distribution bus.

5.4.1 Particle Swarm Optimization

5.4.1.1 PSO Topology

PSO is a heuristic search optimization method. PSO inspired by social and cooperative behaviors. The technique is related to the main parts. One is guided by personal behavior (Pbest) and the other part guided by social experience (Gbest). The position of particle in search space is updated depends on these two parts. The behaviors of particles are accelerated by two factors c_1 and c_2 and random number r_1 and r_2 numbers generated between $[0, 1]$ whereas the present movement is multiplied by an inertia factor ω varying between $[\omega_{min}, \omega_{max}]$. The initial population (swarm) of size N and dimension D is denoted as $X = [X_1, X_2, \dots, X_N]^T$, where 'T' denotes the transpose operator. Each individual (particle) X_i ($i = 1, 2, \dots, N$) is given as $X_i = [X_{i,1}, X_{i,2}, \dots, X_{i,D}]$. Also, the initial velocity of the population is denoted as $V = [V_1, V_2, \dots, V_N]^T$. Thus, the velocity of each particle X_i ($i = 1, 2, \dots, N$) is given as $V_i = [V_{i,1}, V_{i,2}, \dots, V_{i,D}]$. The index i varies from 1 to N whereas the index j varies from 1 to D. The detailed algorithms of various methods are described below for completeness [43]- [44].

$$V_{i,j}^{k+1} = w \times V_{i,j}^k + c_1 \times r_1 \times (Pbest_{i,j}^k - X_{i,j}^k) + c_2 \times r_2 \times (Gbest_j^k - X_{i,j}^k) \quad (5.8)$$

$$X_{i,j}^{k+1} = X_{i,j}^k + V_{i,j}^{k+1} \quad (5.9)$$

In Eq. (5.8) $Pbest_{i,j}^k$ represent personal best j^{th} component of i^{th} individual,

whereas $Gbest_j^k$ represents j^{th} component of the best individual of population up to iteration k .

Figure 5.6 [44] shows the search mechanism of PSO in multidimensional search space.

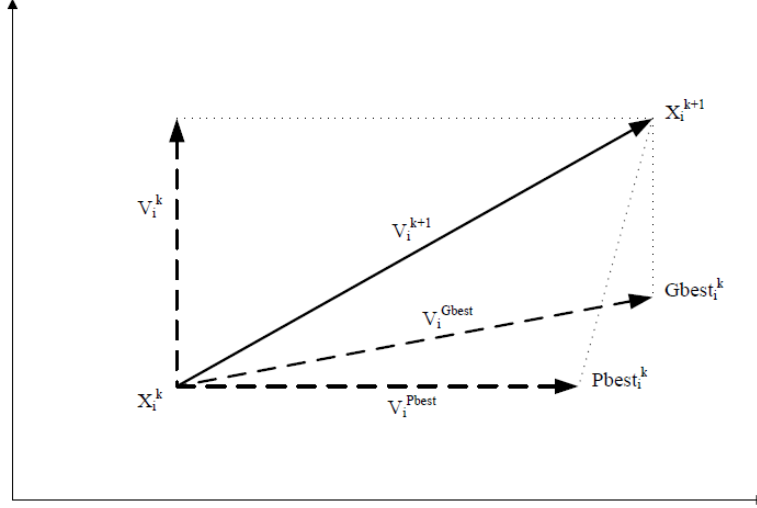


Figure 5.6: PSO search mechanism of PSO in multidimensional search space [44]

A detailed flowchart of PSO considering the above steps is shown in Figure 5.7.

5.4.1.2 Tuning PI Controller Gains of DSTATCOM Using PSO

PSO algorithm is applied to find the optimum controller gains of DSTATCOM (V_{ac} regulator, V_{dc} regulator, current regulator and PLL regulator). The algorithm parameters are selected as given in table. 5.2. The objective function is minimization of root mean square error (RMSE) between the actual measured voltage and reference voltage (1pu). The RMSE and the objective function are as given in Eq. (5.10)

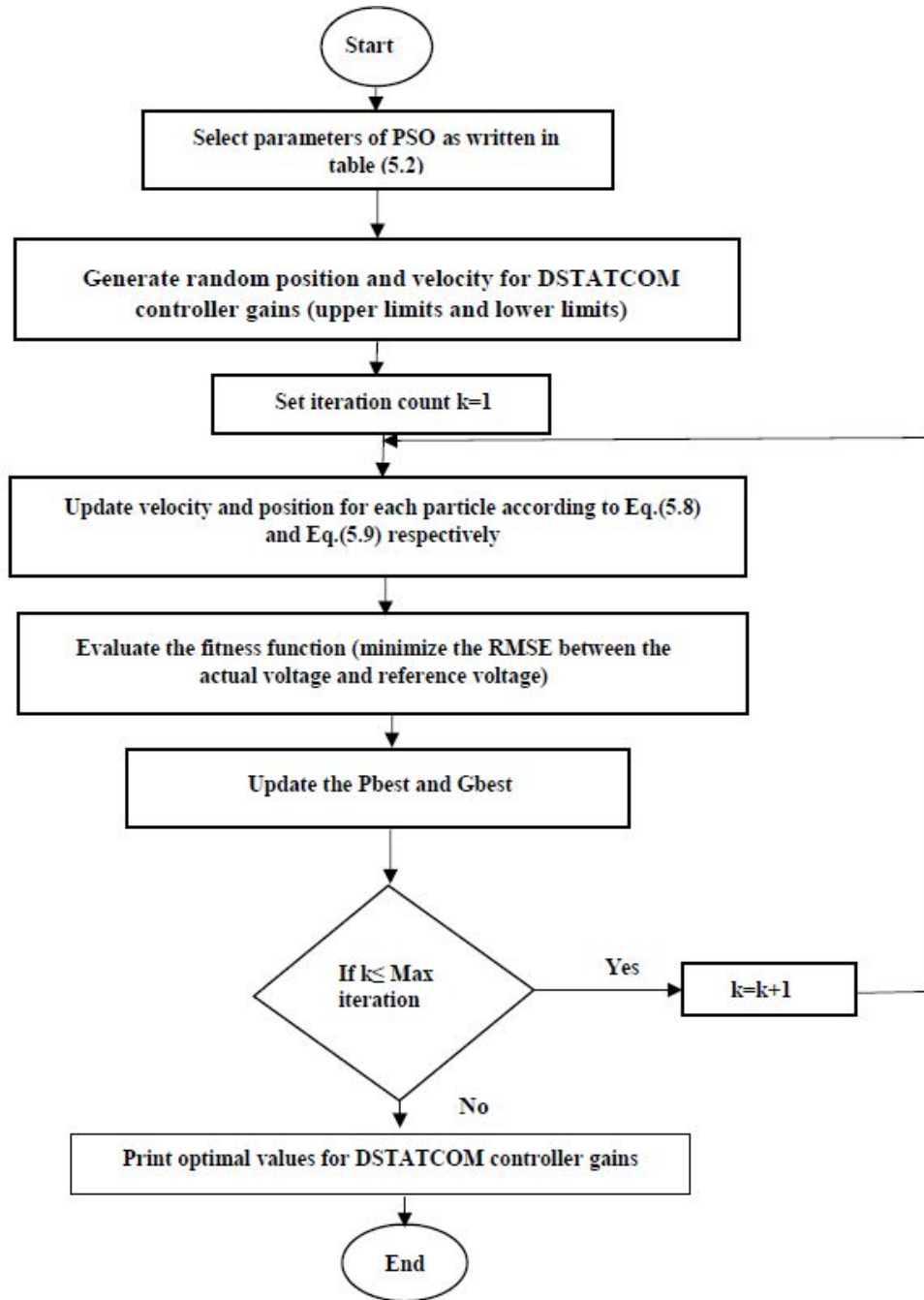


Figure 5.7: Flowchart of PSO algorithm

and Eq. (5.11) respectively [48]:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (V_i - V_{ref})^2} \quad (5.10)$$

Table 5.2: Parameters of PSO algorithm

Parameter	Size
Population size	N=50
Accelerated factors	$C_1=1, C_2=1.5$
Inertia	w=1.2
Number of iteration	i=100
Upper limits for controller gains	[10 3500 10 20 5 1500 1500 3000]
Lower limits for controller gains	[0.01 10 0.0001 0.01 1 100 10 10]

$$J = \min[RMSE] \quad (5.11)$$

Where:

J: fitness function.

RMSE: Root mean square error.

V_i : actual voltage.

V_{ref} : reference voltage(1pu).

n: number of samples.

Matlab code is written for the objective function and the PSO algorithm is running for voltage profile improvement(appendix A). Sag and swell events are created in order to obtain controller gains for deviation of voltage from 1pu. The simulation is running for every deviation of (0.05pu) from extreme swell to extreme sag (appendix C). At every case of sag and swell event the percentage error is calculated as well the THD%.

5.4.2 Artificial Neural Networks (ANNs)

In this part an ANNs are used to control DSTATCOM real time according to distribution bus voltage level.

5.4.2.1 ANN Topology

ANN is a common statistical learning algorithm in data mining. The main idea of ANN was inspired by the biological neural network of the human brain. The human brain is composed of a vast number of neurons that interconnected in an incredibly complex structure. ANN has a similar structure to the human brain; that is, it predicts events by learning the information and stores it within the neurons by interchanging connections and weights [50].

For many complex issues, which are hard to solve by traditional mathematical and computation methods, ANN might be a suitable solution. As such, this research uses a well used type of neural network model, which is known as feed forward for tuning DSTATCOM controller gains. Figure 5.8 shows the basic architecture of a feed forward of ANN [51]. The ANN has three layers architecture: input nodes, hidden nodes and output nodes, each node (neurons) in one layer is connected to each node in the next layer. The number of nodes in the input layer is the same as the input features in the training dataset and the number of nodes in the output layer is the number of output. The number of hidden nodes in the middle layer is normally between those two numbers. The number of hidden nodes is very important since both over fitting and under fitting will effect on the training results.

The procedure of training the ANN is depending on the varying the weights W_{ij} and the biases B_j [36]. The training criterion is taken as the mean square error of

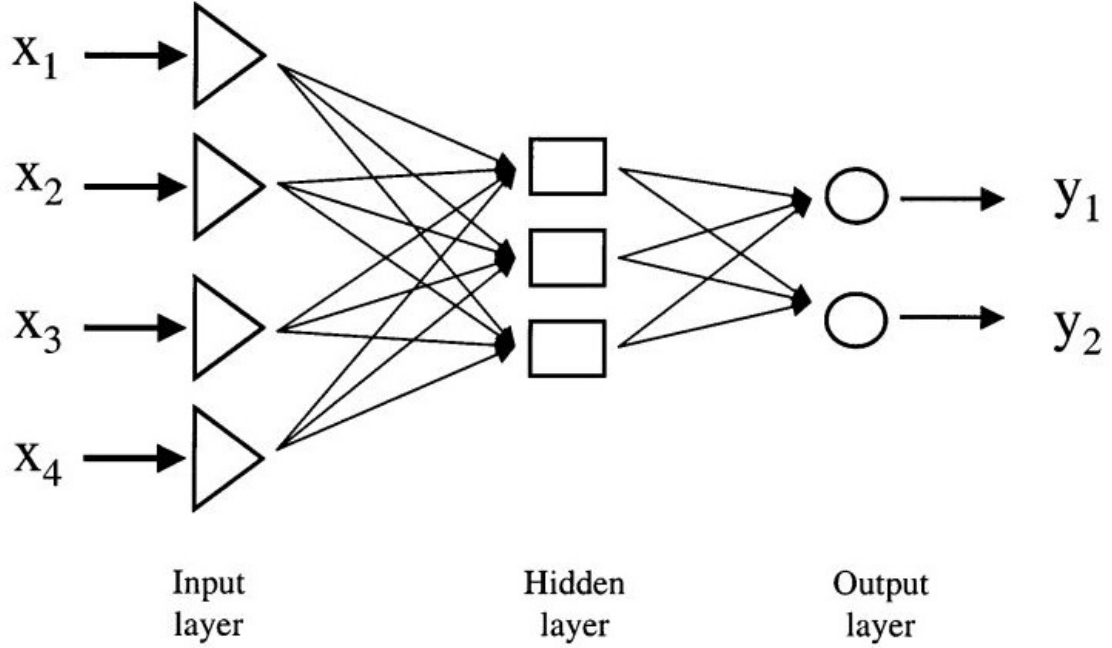


Figure 5.8: Basic neural network structure [51]

ANN output with value of (0.0001) and error function is defined as given in Eq. (5.12) [36]

$$J = \sum_{i=1}^N e(i)^2 \quad (5.12)$$

Where N is the number of output neurons and $e(i)$ is instantaneous error between the actual and estimated value of the output. The hidden layer has no target values, so a procedure of optimize the W_{ij} is continued until minimization the error [37]. The j th neuron in the hidden layer is assigned the value y_j , given in terms of the input values x_i by [36]

$$y_j = \tanh(\sum W_{ij}x_i + b_j) \quad (5.13)$$

The hyperbolic tangent function is used as activation function. Other functions could be used for activation function, which was designed originally to simulate

the neuron upon receiving input signals from its neighbors. If the hidden layer increases, then Eq. (5.13) will be used to calculate the values of the next layer of hidden neurons from the current layer of neurons. The output neurons z_k may calculate by a linear combination of the neurons in layer just before the output layer as given in Eq. (5.14) [36]

$$z_k = \sum_j W_{kj} y_j + b_k \quad (5.14)$$

5.4.2.2 Employ ANN to Control DSTATCOM

ANN is proposed as AI method used for controlling DSTATCOM. A PI controller calculates an error value as the difference between a measured process and desirable set point. The controller attempts to minimize the error by adjusting the process through use of a manipulated variables. The PI controller algorithm involves two separate constant parameters; P depends on the present error and I depends on the accumulation of past errors. The weighted sum of PI components actions is used to adjust the process via control element to control various system [38].

The environment of ANN controller has made them a wide area of interest among researches in extensive field, due ANN can proficiently learn the unknown continuously varying environment and act accordingly. The results from PSO for wide range of sag and swell events (0.7-1.3) processed and nearly 70% of these data(appendix C) considered as a data base for ANNs training process. Then the results of ANNs provides real time to control DSTATCOM.

The learning process of ANN is developed in MATLAB, aided by the toolbox neural network(appendix A). For this study eight networks are defined in MATLAB code in order to applied the ANNs algorithm for learning and find the best optimal

value of controllers gains according to disturbance voltage level, the networks is define as shown in table. 5.3:

Table 5.3: Define networks in ANN algorithm

ANN_s	Controller Gains
net1	$V_{ac} (k_p)$
net2	$V_{ac} (k_i)$
net3	$V_{dc} (k_p)$
net4	$V_{dc} (k_i)$
net5	$i(k_p)$
net6	$i(k_i)$
net7	$PLL(k_p)$
net8	$PLL(k_i)$

5.4.3 ANNs Structure

5.4.3.1 AC Voltage Regulator Proportional Gain ANN

This network has been designed to select the value of $V_{ac} (k_p)$. It consists of an input layer of 50 neurons, a hidden layer of 60 neurons and an output layer of a single neurons. Figure 5.9 shows the structure of this network.

5.4.3.2 AC Voltage Regulator Integral Gain ANN

This network has been designed to select the value of $V_{ac} (k_i)$. It consists of an input layer of 40 neurons, a hidden layer of 50 neurons and an output layer of a single neurons. Figure 5.10 shows the structure of this network.

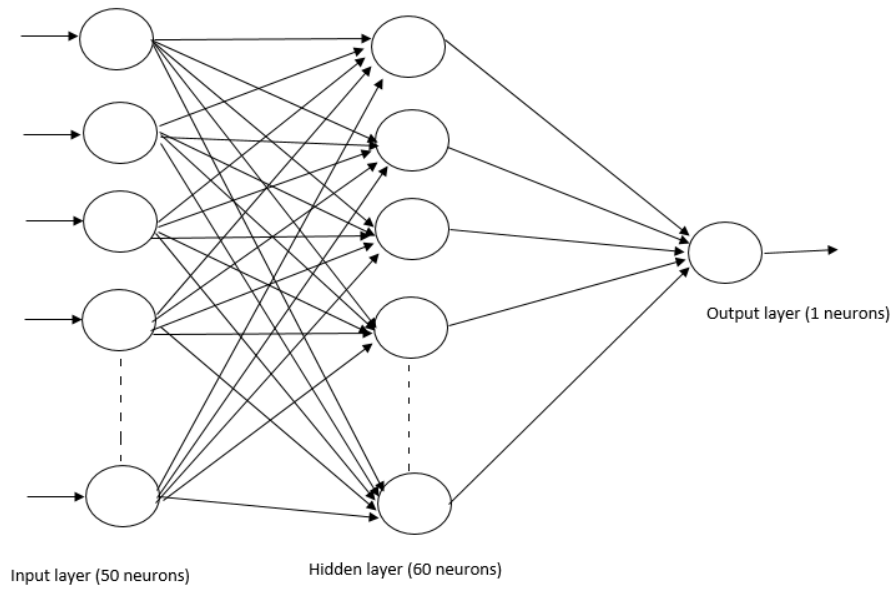


Figure 5.9: AC voltage regulator proportional gain ANN

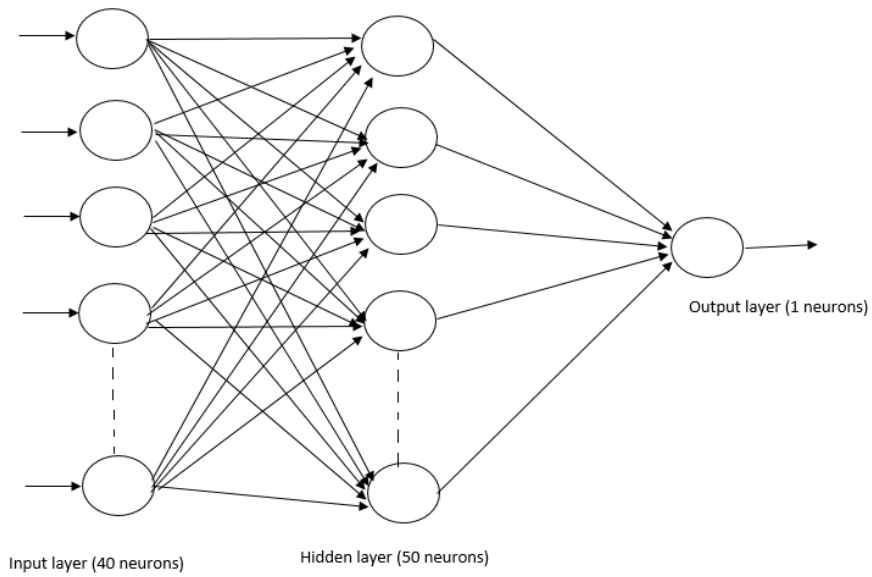


Figure 5.10: AC voltage regulator integral Gain ANN

5.4.3.3 DC Voltage Regulator Proportional Gain ANN

This network has been designed to select the value of $V_{dc} (k_p)$. It consists of an input layer of 60 neurons, a hidden layer of 65 neurons and an output layer of a single neurons. Figure 5.11 shows the structure of this network.

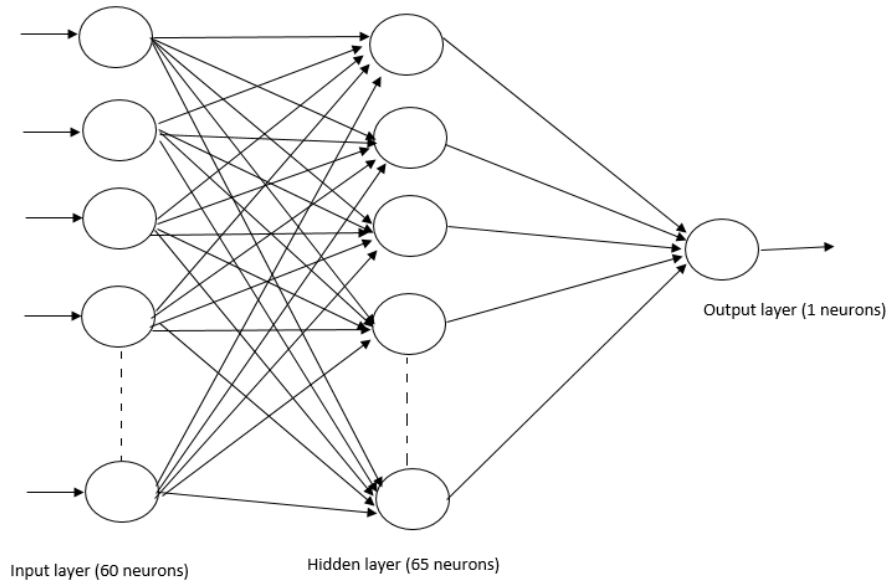


Figure 5.11: DC voltage regulator proportional gain ANN

5.4.3.4 DC Voltage Regulator Integral Gain ANN

This network has been designed to select the value of $V_{dc} (k_i)$. It consists of an input layer of 60 neurons, a hidden layer of 65 neurons and an output layer of a single neurons. Figure 5.12 shows the structure of this network.

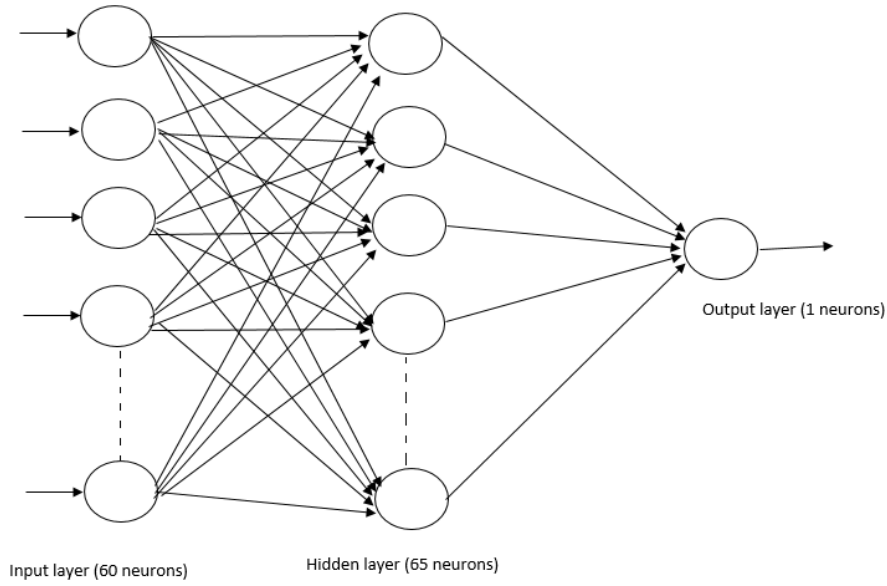


Figure 5.12: DC voltage regulator integral gain ANN

5.4.3.5 Current Regulator Proportional Gain ANN

This network has been designed to select the value of $i(k_p)$. It consists of an input layer of 50 neurons, a hidden layer of 55 neurons and an output layer of a single neurons. Figure 5.13 shows the structure of this network.

5.4.3.6 Current Regulator Integral Gain ANN

This network has been designed to select the value of $i(k_i)$. It consists of an input layer of 60 neurons, a hidden layer of 70 neurons and an output layer of a single neurons. Figure 5.14 shows the structure of this network.

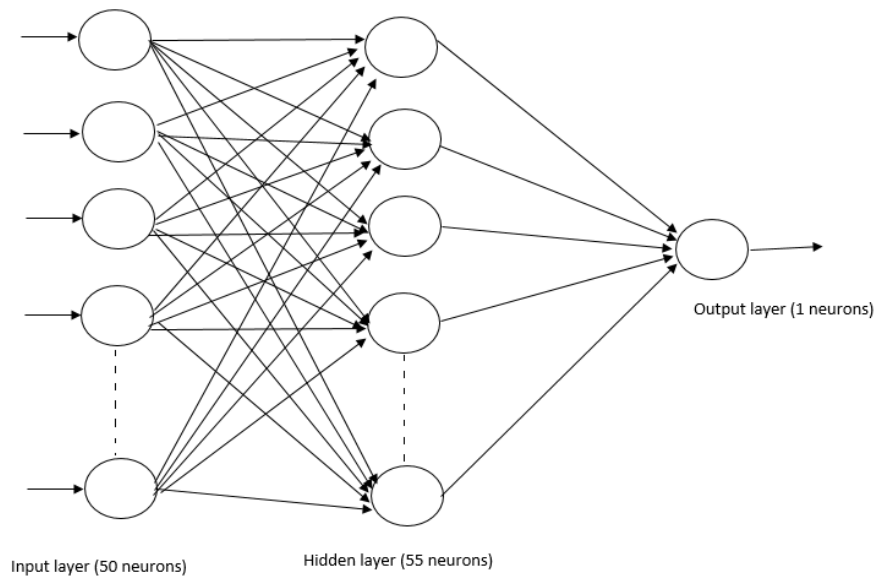


Figure 5.13: Current regulator proportional gain ANN

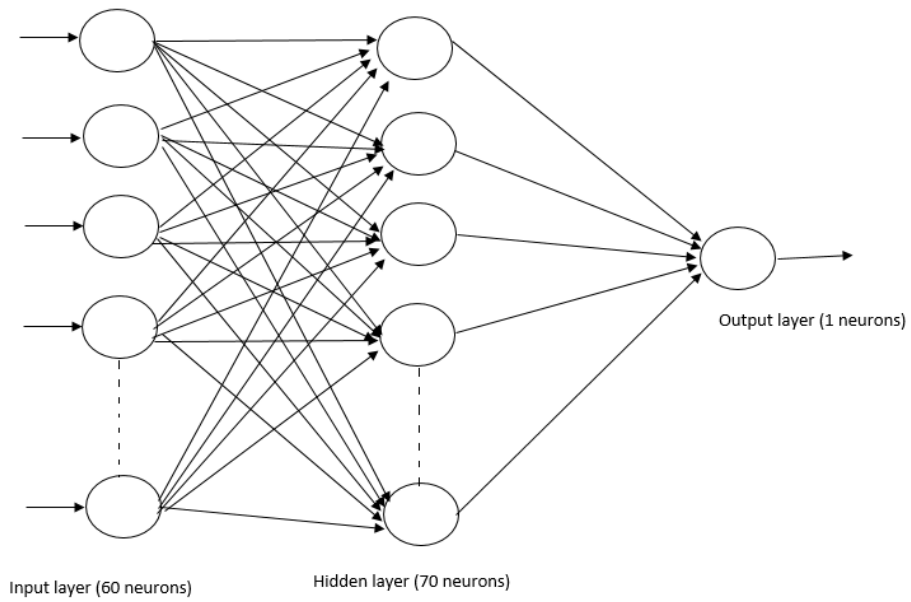


Figure 5.14: Current regulator integral gain ANN

5.4.3.7 PLL Proportional Gain ANN

This network has been designed to select the value of $PLL(k_p)$. It consists of an input layer of 50 neurons, a hidden layer of 55 neurons and an output layer of a single neurons. Figure 5.15 shows the structure of this network.

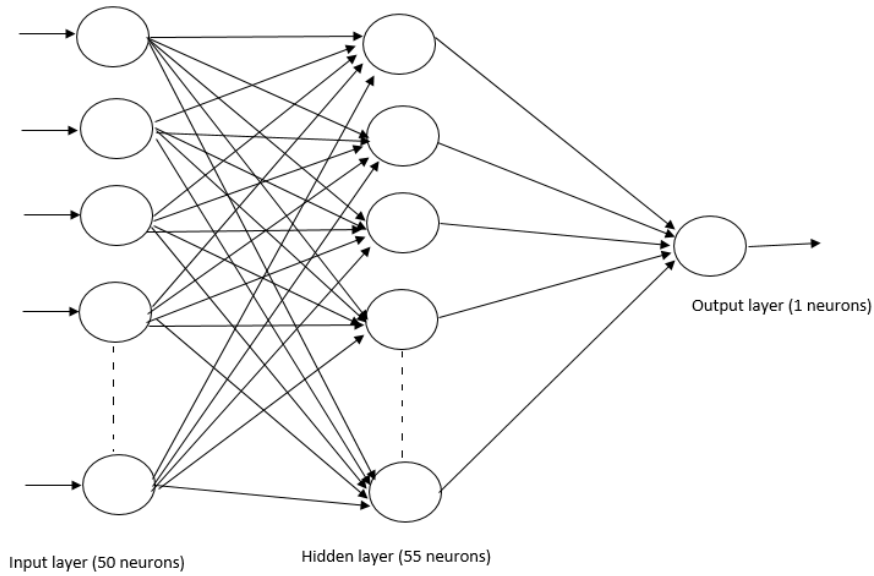


Figure 5.15: PLL proportional gain ANN

5.4.3.8 PLL Integral Gain ANN

This network has been designed to select the value of $PLL(k_i)$. It consists of an input layer of 50 neurons, a hidden layer of 55 neurons and an output layer of a single neurons. Figure 5.16 shows the structure of this network.

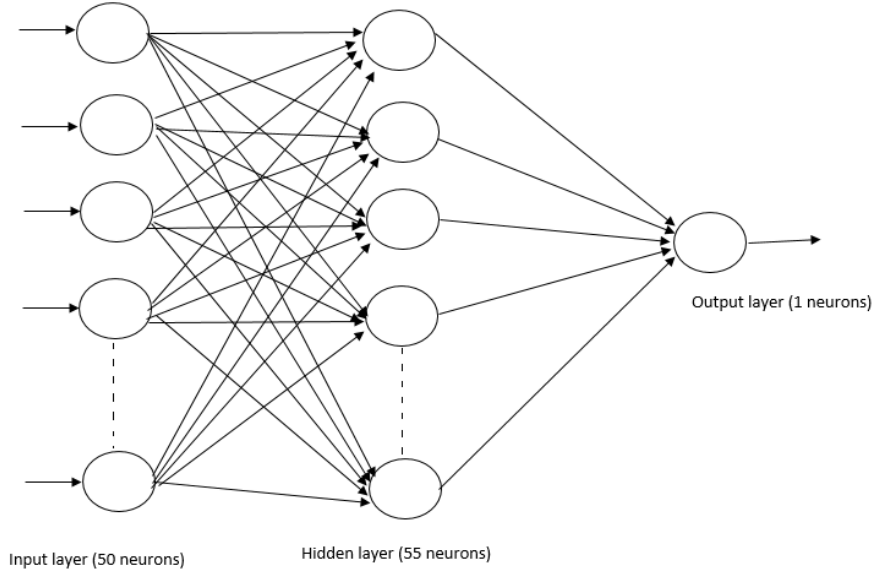


Figure 5.16: PLL integral gain ANN

5.4.4 Designing and Programming

Generally, programming ANNs follow a number of systemic procedures:

- Collecting of data from the PSO: the values of k_p and k_i for each case of sag and swell events using PSO.
- Data reprocessing in this step the data is normalized and the missing data are replaced by average of neighboring values.
- Building the network: in this step specification of hidden layers, neurons in each layer, transfer function in each layer, training function, weight/bias learning and performance function.
- Training the network during the training process, weights are adjusted in order to make the actual outputs (predicated) close to the measured outputs of the network.

- Testing the network by used the targets output in simulation model.

Figure 5.17 describe the Basic flowchart for designing ANN Model.

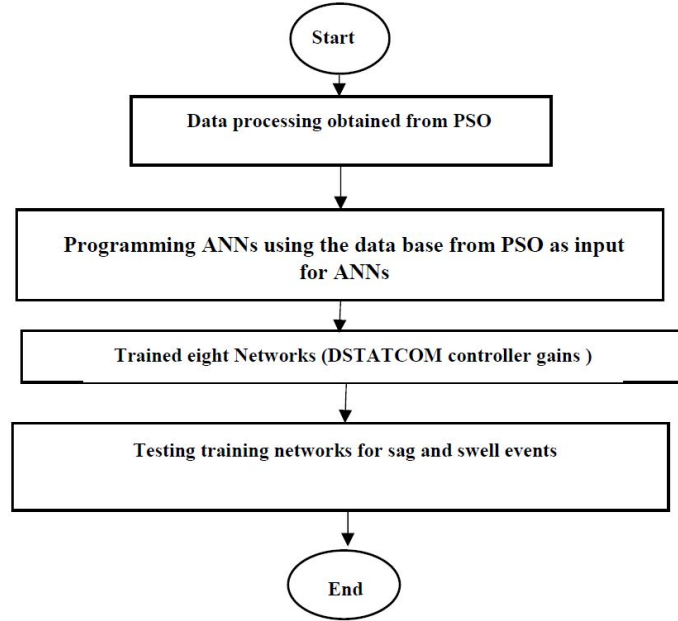


Figure 5.17: Basic flowchart for designing ANNs model

5.5 Total Harmonic Distortion

5.5.1 Harmonics Formulation

The harmonic distortion may be present by Foureier series as given in Eq. (5.15) [39]

$$V(t) = V_0 + \sum_{n=1}^{\infty} \sqrt{2}V_n \cos(n2\pi f_0 t + \phi_n) \quad (5.15)$$

Where:

V_0 : is the value of the dc component.

V_n : RMS value of nth harmonic component

f_0 : fundemetal frequency(50Hz)

ϕ_n : the phase angle of the nth harmonics component.

5.5.2 Measurement of THD% In Distribution System

There are many indication for harmonic distortion in the system appear as harmonic spectrum, RMS voltage and current level. THD giving the power of all harmonics in relation of fundamental frequency as given in Eq. (5.16) [39]

$$THD\% = \frac{\sqrt{\sum_{n=2}^n V_n^2}}{V_1} * 100\% \quad (5.16)$$

Where:

V_n : the RMS value of the harmonic components of order n of the voltage.

V_1 : the RMS value of the fundamental component of the voltage.

The THD% is measured for each case of all events (appendix C). MATLAB code is built for this purpose using the concept of discrete fourier transform(appendix A). IEEE standard 519-1992 [39] provides the limits of THD% for normal operation. Table. 5.4 shows the IEEE standard limits for THD%.

Table 5.4: Voltage distortion according to IEEE 519-1992 [39]

Bus Voltage(kV)	THD%
69 and bellow	5.0
69 through 161	2.5
161 and above	1.5

Chapter 6

Results and Conclusions

6.1 Results and Discussion

6.1.1 Creation of Sag and Swell Events on Distribution Bus

A wide range of extreme sag(0.7pu) and extreme swell(1.3pu) are created on distributed bus. This may represent the different disturbances occur on distribution system such as faults or over voltage due switching capacitor bank and other electrical disturbance may occur. Figure 6.1 and Figure 6.2 show the extreme sag and extreme swell respectively.

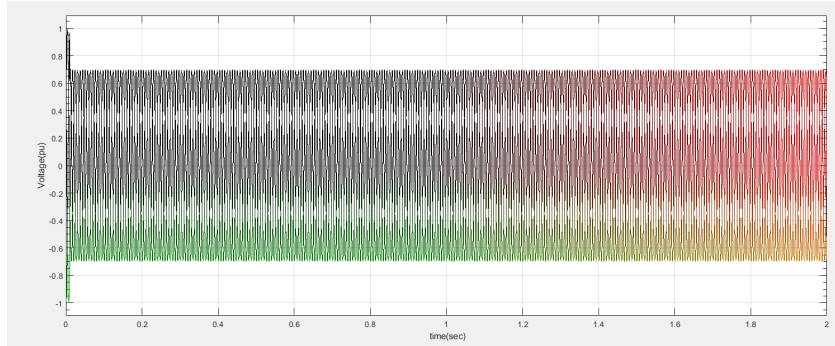


Figure 6.1: Extreme sag event 0.7pu

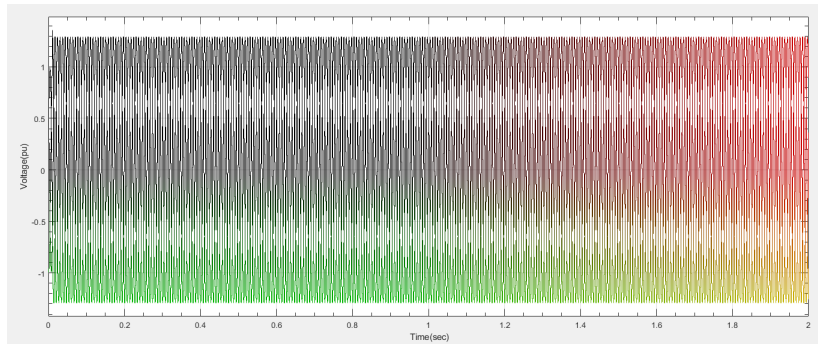


Figure 6.2: Extreme swell event 1.3pu

These events are simulated by network model using MATLAB/Simulink. The deviation of voltage on distribution bus is considered to be around (0.05)pu. DSTAT-COM controller gains are obtained for each created event using PSO algorithm as well as the percentage error is also calculated according to the objective function of the optimization function. Table. 6.1 and table. 6.2 shows the results of DSTAT-COM controller gains for the main steps disturbances of swell and sag voltage events respectively (see all data base for created events and optimal values for controller gains using PSO in appendix C).

The simulation results of proposed network under extreme sag and extreme swell

Table 6.1: Optimal values of DSTATCOM controller gains during main steps of swell events using PSO

Event	Vac(kp)	Vac(ki)	Vdc(kp)	Vdc(ki)	i(kp)	i(ki)	PLL(kp)	PLL(ki)	error%
1.30pu	10	10	10	20	2.75	415	1170	3000	4.0009
1.25pu	7.43	3500	1e-4	1.23e1	2.17	1500	1500	10	4.580
1.20pu	3.82	1.98e2	6.22	1.55e1	2.05	4.36e2	1.38e3	2.64e3	5.457
1.15pu	10	10	1e1	1e-2	5	1.28e3	1.50e3	3000	8.866
1.10pu	10	10	10	20	5	1500	1.8e3	3000	5.925

Table 6.2: Optimal values of DSTATCOM controller gains during main steps of sag events using PSO

Event	Vac(kp)	Vac(ki)	Vdc(kp)	Vdc(ki)	i(kp)	i(ki)	PLL(kp)	PLL(ki)	error%
0.9pu	1e-2	10	1e-4	1e-2	1	1e2	2.1e2	2.38e1	9.989
0.85pu	1e-2	3500	10	1.67	1	1.17e3	9.88e2	3000	9.552
0.80pu	10	3500	1e-4	20	5	7.01e2	1.13e3	3.24e2	9.141
0.75pu	10	3500	1e-4	20	1	1.37e3	6.59e2	10	9.171
0.70pu	10	10	1e-4	20	1	100	4.55e1	10	0.999

conditions without using DSTATCOM is showed in Figure 6.3.

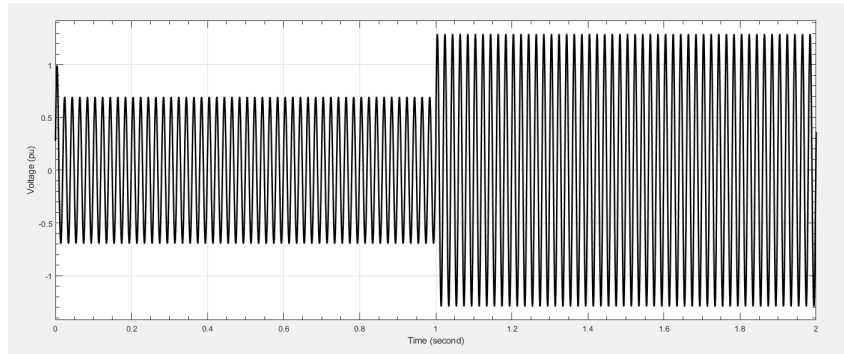


Figure 6.3: Extreme sag and extreme swell events

6.1.2 Selection of Controller Gains Using PSO

The controllers gains of DSTATCOM are selected and optimized according to the objective function which is minimization the RMSE between the measured bus voltage and the reference value (1pu). The sag events via error is drawn as in Figure 6.4 while for swell events via error drawn in Figure 6.5. From the charts of sag and swell via percentage error, it clear that the worst case of error is below 10% which acceptable referring to IEEE Standards.

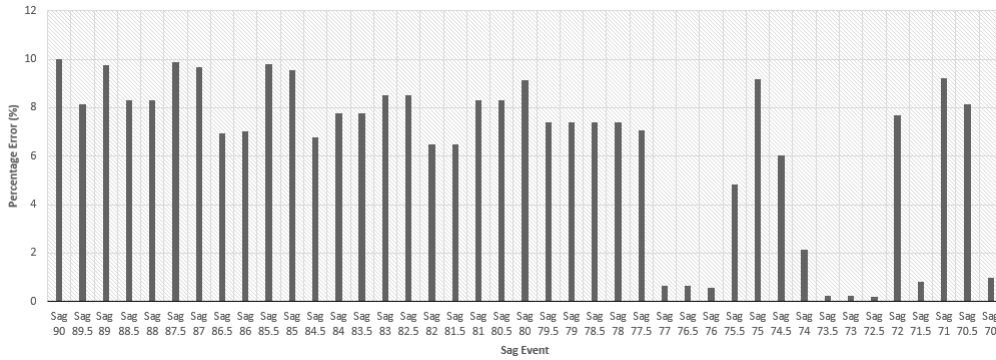


Figure 6.4: Sag events via error%

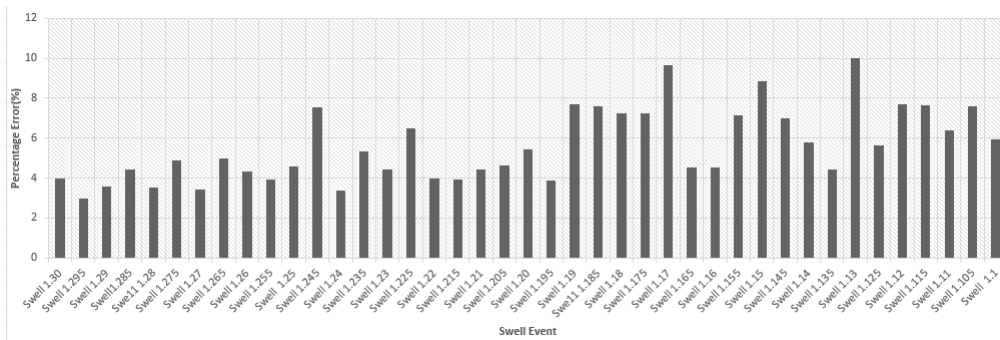


Figure 6.5: Swell events via error%

6.1.3 Control DSTATCOM using ANNs

PSO is used as a tool to obtain the optimum values of controller gains. Then data processing is done and nearly 70% of these data is used to train eight networks that control DSTATCOM as mention in table. 5.3. Values for controller gains is applied to ANNs in training phase, to obtain a set of weights that will minimize the error function in competitive time. ANN logarithm is used for practice the controller and select the gains constants according to activations elements. The controller constants is used as inputs to train the eight controller constant networks.

Figure 6.6 and Figure 6.7 are show the training, validation, and test errors used to check the progress of training for eight trained networks. These results are reasonable since the test set error and the validation set error have similar characteristics, it does not appear that any significant over fitting has occurred. The best validation performance for chosen network gave the overall minimum of system, are reported as given in table. 6.3 for different trained neural networks.

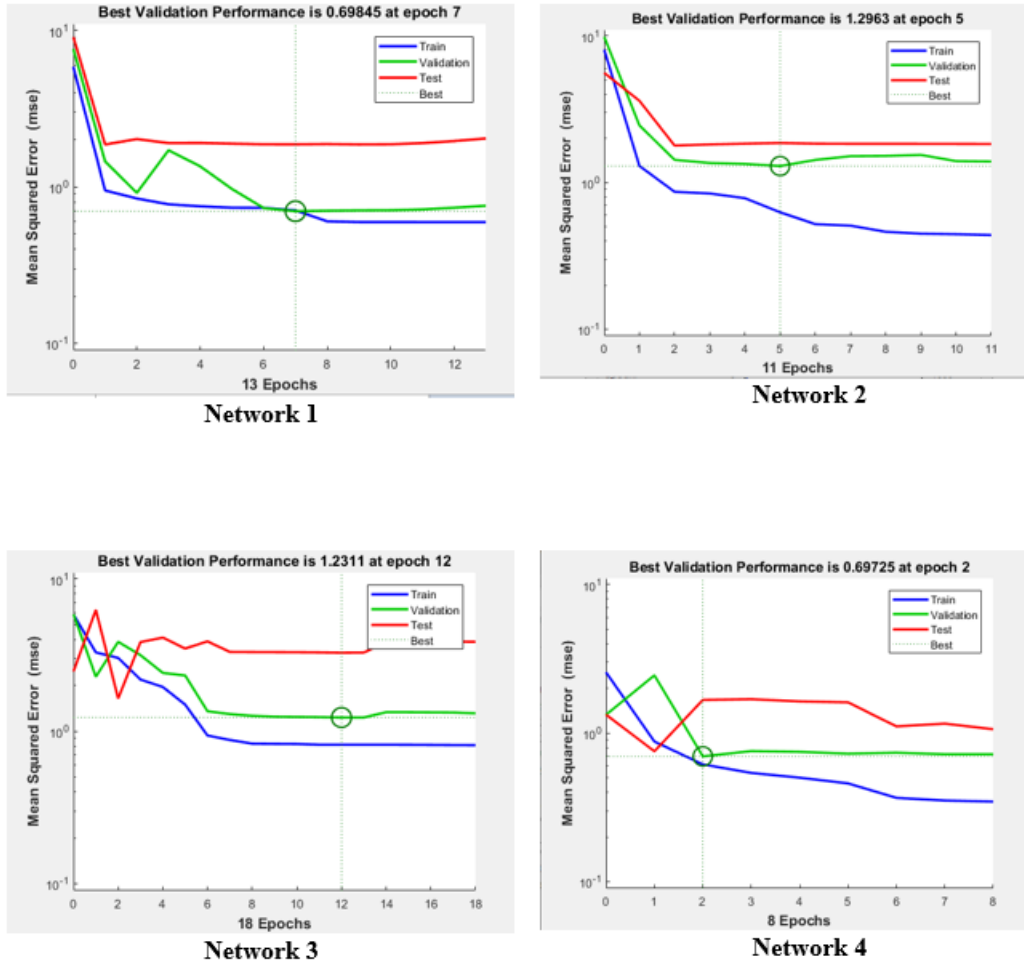


Figure 6.6: Training validation and test curves for neural networks (1-4)

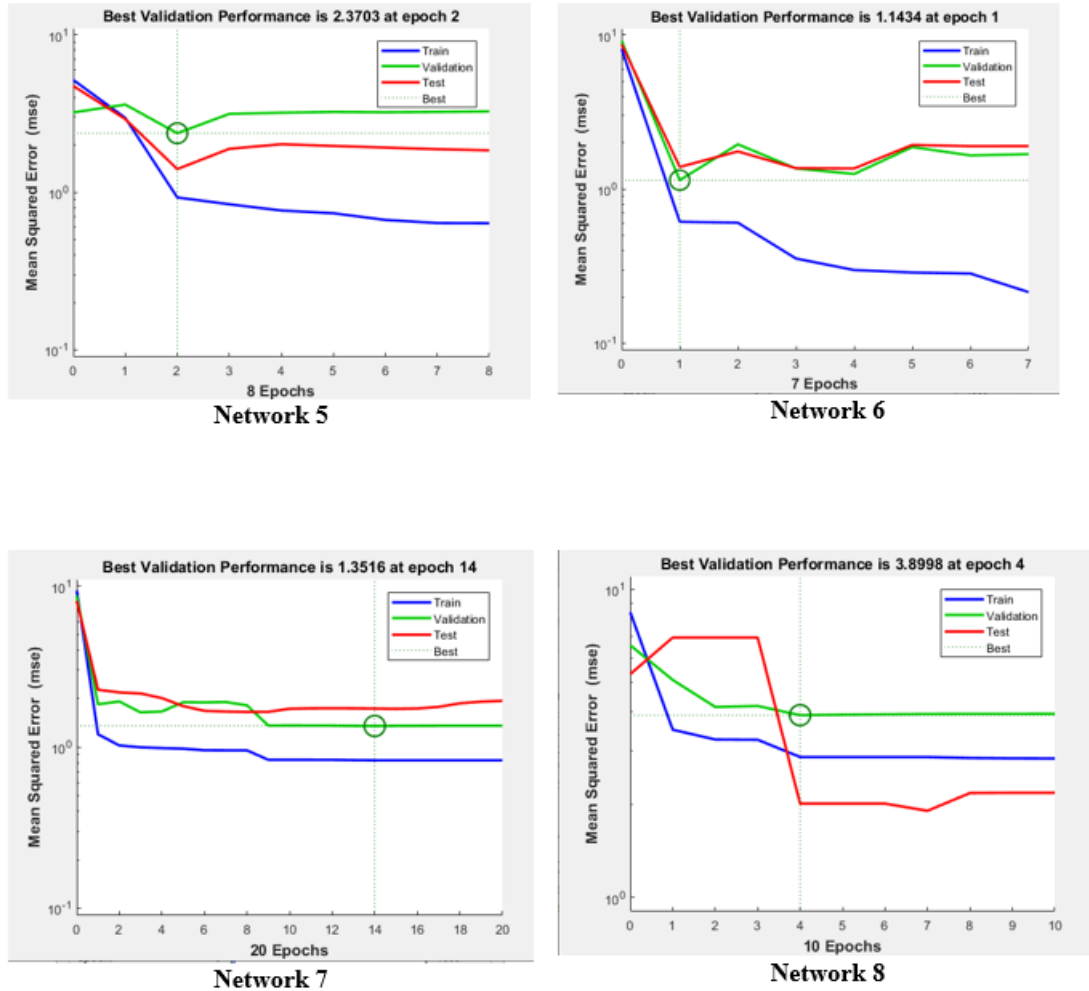


Figure 6.7: Training validation and test curves for neural networks (5-8)

Figure 6.8 and Figure 6.9 describe the estimation function by the ANN. The network outputs are plotted versus the targets as open circles. The best linear fit is indicated by dashed line. The perfect fit (the output equal to target) is shown by solid line. The output seem to track the targets perfectly with regression as reported in table. 6.3. The R value is an indication of the relationship between outputs and

targets. If R is close to zero, then there is no linear relationship between outputs and targets, but the research results showed that R value is greater than 0.75 this indication to the acceptable relationship between outputs and targets for different neural trained networks.

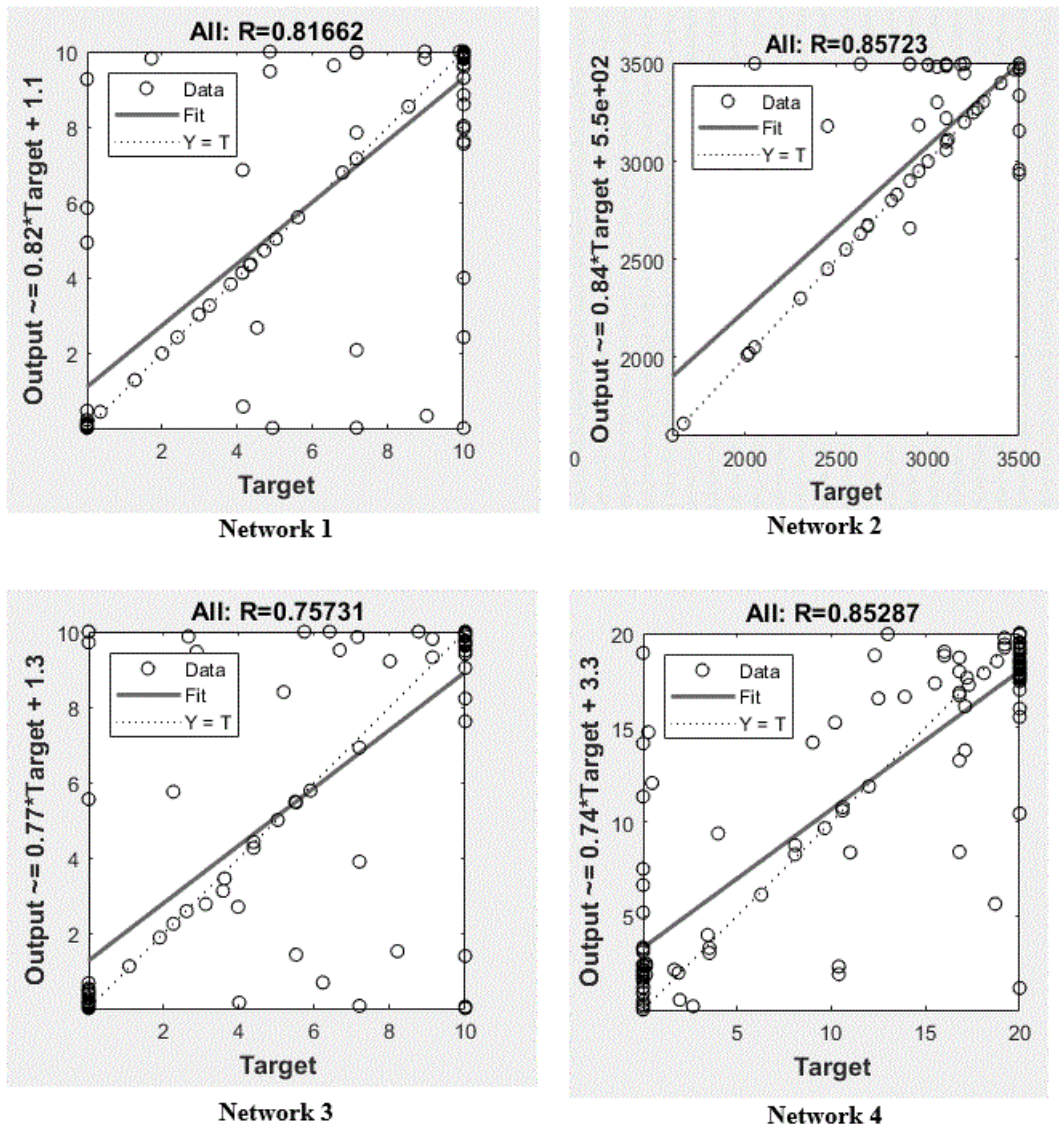


Figure 6.8: Estimation and fitting for neural networks (1-4)

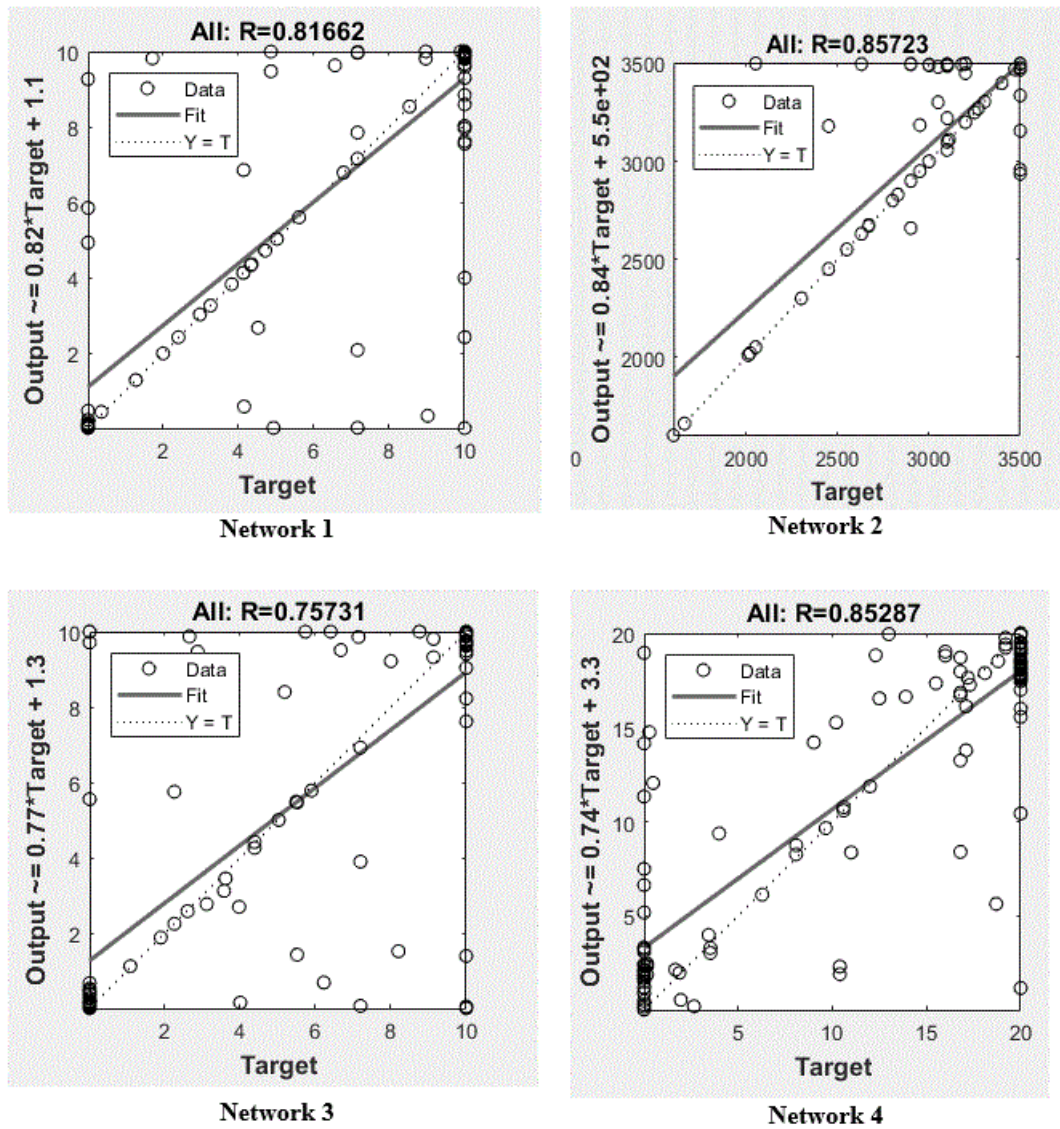


Figure 6.9: Estimation and fitting for neural networks (5-8)

Table 6.3: Evaluation of MSE and fitting function R for eight neural networks

Neural Network	number of epoch	MSE	R
Network1	7	0.69845	0.81662
Network2	5	1.2963	0.85723
Network3	12	1.2311	0.75731
Network4	2	0.69725	0.85287
Network5	2	2.3703	0.81662
Network6	1	1.1434	0.85723
Network7	14	1.3516	0.75731
Network8	4	3.8998	0.85287

6.1.4 Effect of ANNs Controller on Performance of DSTAT-COM for Improve the Voltage Profile

ANN logarithm is used for practice the controller and select the its gains constants according to activations elements. ANNs is quite easy but requires a large a mount of data related to the input parameters to cover a wide range of possibilities to predict the output. The algorithms is employed using nearly 70% of data obtained from PSO. Table. 6.4 shows the results and controller gains for extreme swell and extreme sag by using developed controller of DSTATCOM.

The DSTATCOM is improve the voltage profile in both cases (swell and sag) to nearly 1.05pu which acceptable according to IEEE Std.1159 as shown in Figure 6.10 and Figure 6.11 respectively. After the ANNs is applied on cases between sag and swell for controllers gains obtained by PSO The DSTATCOM improve the voltage profile around (1.02pu) and the THD is decrease more than using only PSO. This lead to use ANN as an AI technique to control DSTATCOM for voltage profile improvement on distribution system for the goal of real time control rather than

Table 6.4: Voltage profile improvement using developed DSTATCOM controller

Event	Controllers	k_p	k_i	THD%	Voltage profile improvement
Swell(1.3)pu	V_{ac} Regulator Gains	7.429	3500	3.26%	1.02pu
	V_{dc} Regulator Gains	1e-4	1.225e+1		
	Current Regulator Gains	2.176e+4	1500		
	PLL Regulator Gains	1500	10		
Sag(0.7)pu	V_{ac} Regulator Gains	10	3500	9.23%	1.07pu
	V_{dc} Regulator Gains	1e-1	1e-2		
	Current Regulator Gains	5	1500		
	PLL Regulator Gains	200	500		

traditional off line control.

From the above results using combined AI techniques with optimization topology give more accuracy for power system this lead to increase the reliability of power system for solve PQ problems in distributions system especially when a nonlinear and sensitive loads connect on the end user side. Also the controller is examined for improving the voltage profile for continuous extreme sag and extreme swell, the results proved the robust and efficient of developed controller as shown in Figure 6.12 and Figure 6.13 for rms voltage and phase voltage respectively.

6.1.5 THD Measurement

MATLAB code is written for purpose of evaluation THD based on FFT, which is calculated during all created events. It's observed that the THD in sag case is greater than in swell case this due in this mode DSTATCOM supplied reactive power to the grid. The THD via voltage events are plotted, the results shown in figure 6.14

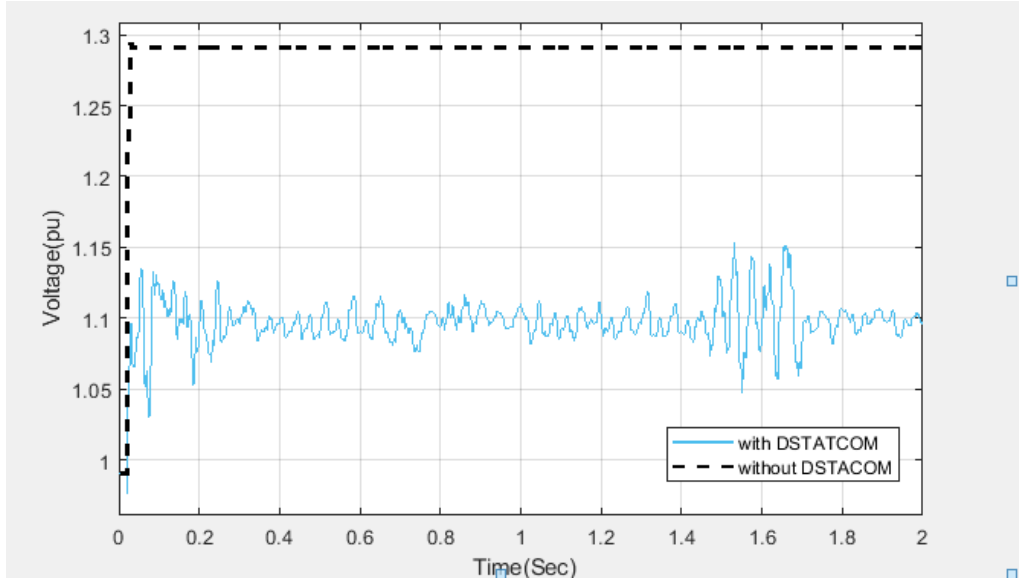


Figure 6.10: Voltage profile improvement for extreme swell event

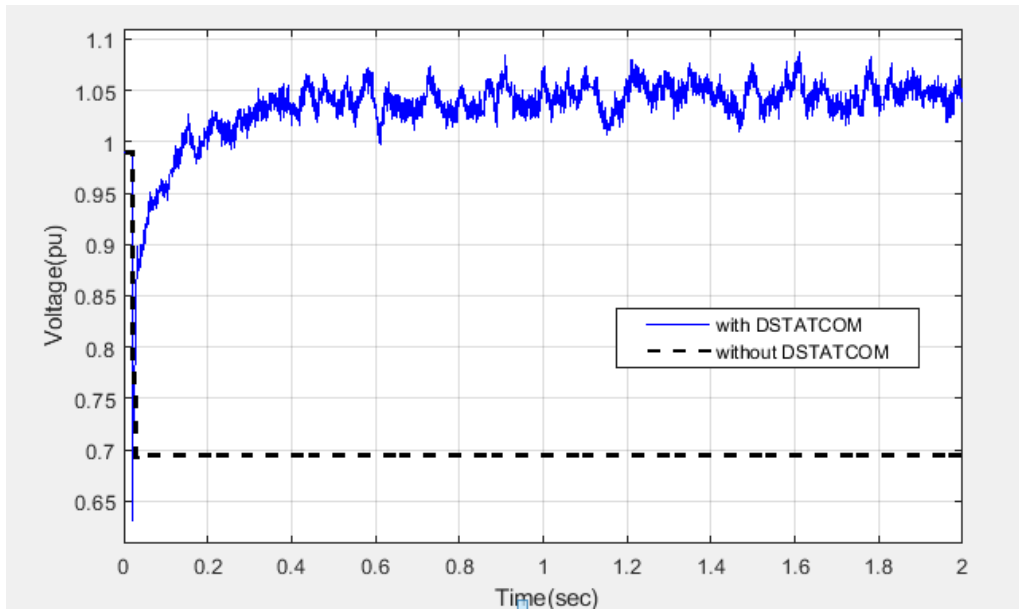


Figure 6.11: Voltage profile improvement for extreme sag event

and figure 6.15 for swell and sag respectively. Frequency spectrum is plotted using MATLAB code(appendix A) as shown in figure 6.16 and figure 6.17 for extreme sag and extreme swell respectively.

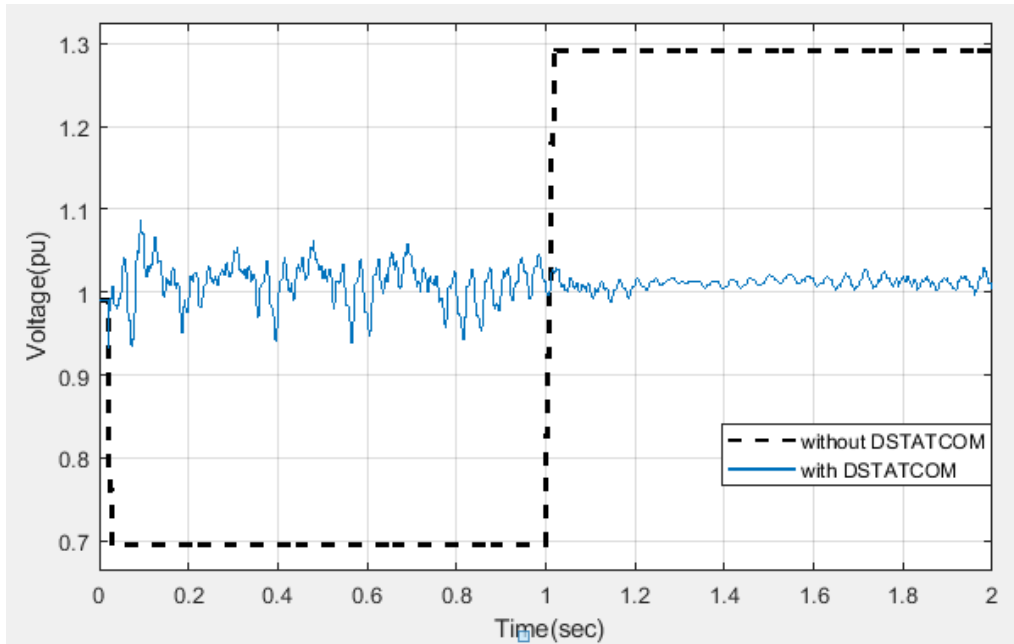


Figure 6.12: rms voltage profile improvement using DSTATCOM tuned by developed DSTATCOM controller using AI

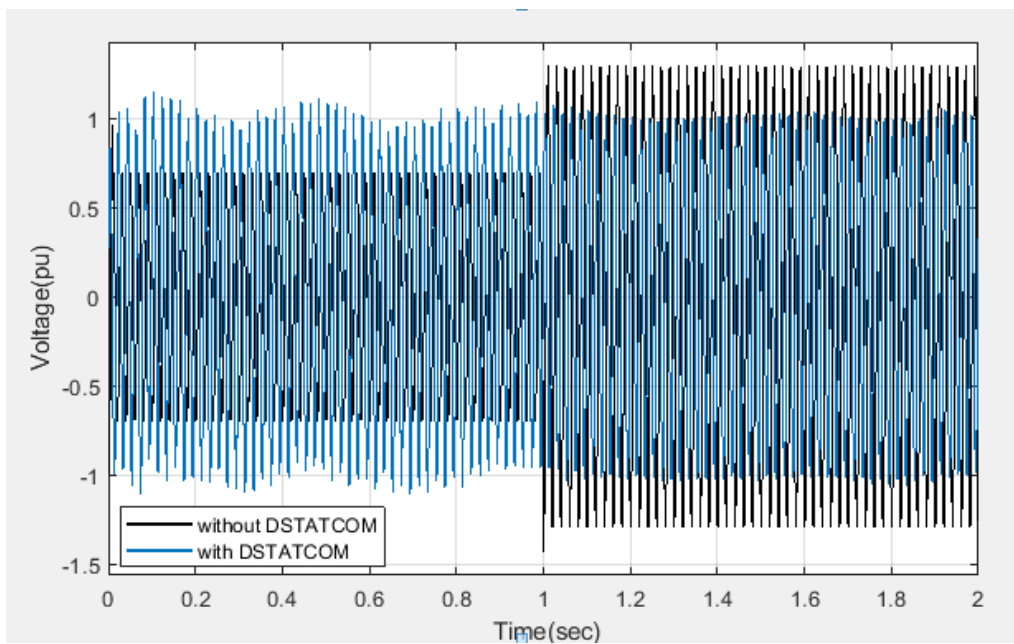


Figure 6.13: Phase voltage profile improvement using DSTATCOM tuned by developed DSTATCOM controller using AI

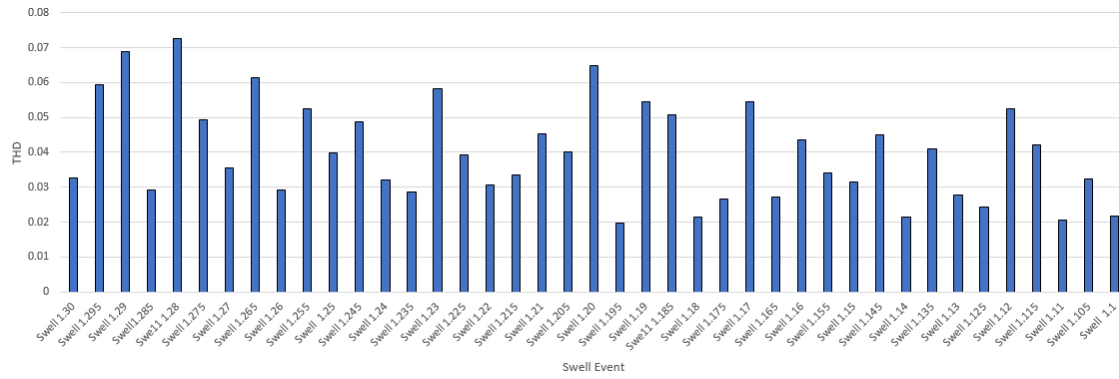


Figure 6.14: THD for swell events

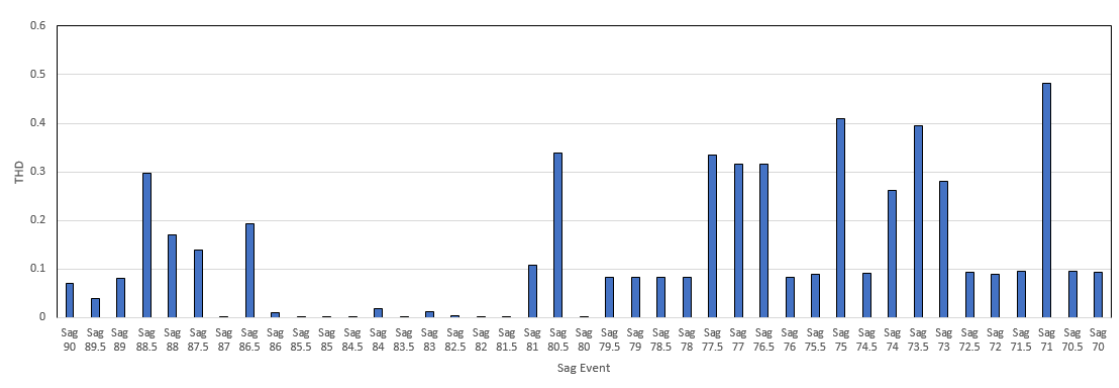


Figure 6.15: THD for sag events

The results proved the importance of using AI in controller design of DSTATCOM. In This work the voltage profile is improved for extreme sag and extreme swell events real time. On the other hand, THD decrease more that other methods as mentioned in literature [43]- [45], but still needed more improvement may be done by modifying the filter design of DSTATCOM.

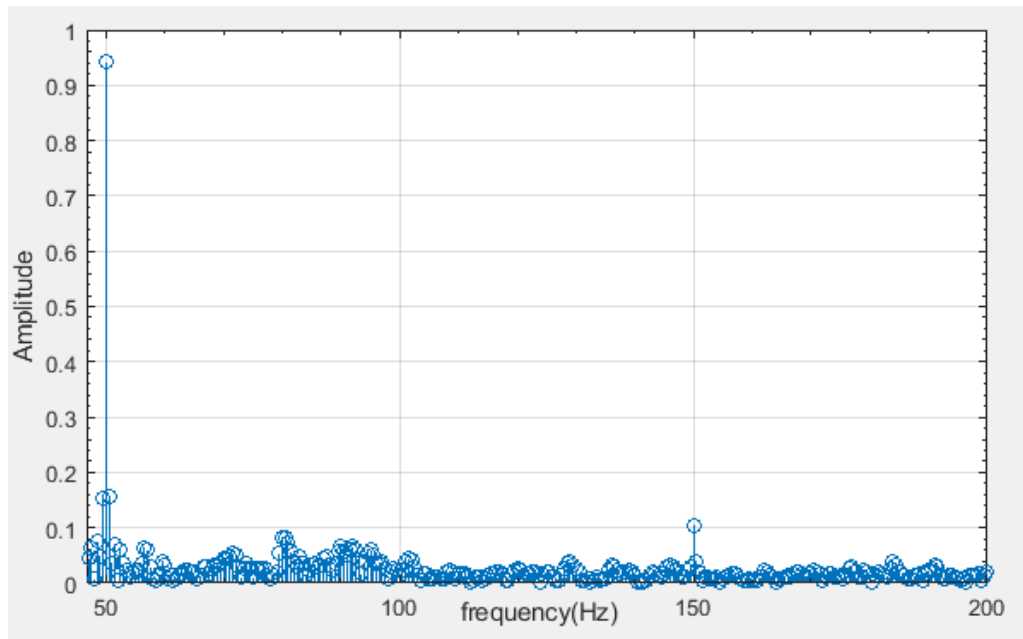


Figure 6.16: Frequency spectrum for extreme sag event

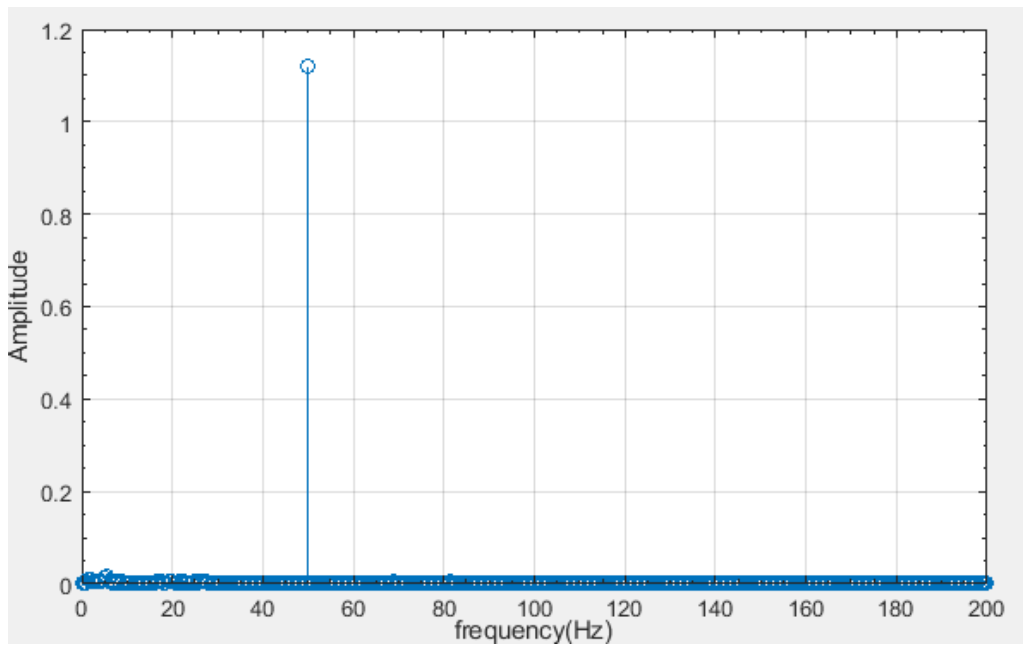


Figure 6.17: Frequency spectrum for extreme swell event

6.2 Conclusions

The main goal of this thesis is to improve the voltage profile of distribution system using DSTATCOM, which controlled by AI Technique. The PSO is used as a tool for obtained the optimum values of DSTATCOM controller gains and then ANN is used as AI technique for real time control of DSTATCOM. The work proved the efficient of using ANN as an AI technique for tuning PI controller of DSTATCOM in order to improve the voltage profile on distribution system. The DSTATCOM with developed controller validated the importance of AI methods such as ANN. Using such this developed controller may increase stability and reliability of power system and hence the network convert to smart network.

Developed controller using ANN supports DSTATCOM with robust tuning system, since its responds to different real time voltage disturbances that may occur in distribution system with efficient enhancement for voltage profile compared with conventional control strategies.

The simulation results proved the efficient of suggested method for controlling DSTATCOM in order to improve voltage profile on distribution system.

6.3 Future Works

Although this work covered using ANN as an AI technique tuning PI controller of DSTATCOM for purpose of improve the voltage profile on distribution system additional work is vital for future research.

It is interesting to extend this work by employ DSTATCOM with improved AI control technique on the real distribution system with various load conditions and

evaluate the efficient of using developed controller of DSTATCOM to improve different PQ issues.

The operation of DSTATCOM is mainly dependent on an important factor which is dc storage element, this factor is affected on the voltage regulation on distribution system. So it may be one of considerable topics for researchers to study the facilities to combine the RESS as the main supply of energy for DSTATCOM as well as determine the optimum and most efficient dc storage device for DSTATCOM design. The filter design of DSTATCOM have a great challenges to decrease the THD%.

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Appendix A

MATLAB Codes

```
\\section{PSO Alogorithm}

%% -Help psoToolbox V1.0
% psoToolbox provides an interective GUI based Toolbox to solve
% optimization problems using particle swarm optimization.
% Creat a fitness function in M-file.
% Inputs:
%   Function      : Function handle of fitness function.
%   Nvars         : Number of variable to be optimized.
%   LB            : Lower Bound of Nvars (1 X Nvars)
%   UB            : Upper Bound of Nvars (1 X Nvars)
% Parameters:
%   C1             : Cognative Attraction
%   C2             : Social Attraction
%   W              : Inertial
%   Population Size : Number of Swarms
%   Max Iterations : Maximum number of epochs.
% Click on " RUN PSO " button to start PSO search. You will get the out put
% at Edit box below the axes.
%
% To solve problem on command prompt use "pso.m".
%% Figure and Back ground
set(0,'units','pixel');
screensize = get(0,'screensize');
height = 600;
width = 800;
```

```

basecolor = [rand 1 rand]./2;
imdata = creatback(height,width,basecolor);
fig_position = [(screensize(3)/2)-(width/2) (screensize(4)/2)-(height/2) width height];
handle.fig = figure('Name','PSOToolbox',...
'units','pixel',...
'position',fig_position,...
'numbertitle','off',...
'menubar','none',...
'resize','off');
'foregroundcolor','w',...
'horizontalalignment','left');
handle.text12 = text(35,160,'Nvars : ',...
'fontsize',14,...
'fontname','cambria',...
'color','w');
handle.edit12 = uicontrol('style','edit',...
'parent',handle.fig,...
'position',[132 428 150 25],...
'backgroundcolor',basecolor*(height-428)/height,...
'fontsize',14,...
'fontname','cambria',...
'foregroundcolor','w',...
'horizontalalignment','left');
handle.text13 = text(35,210,'Lower Bound : ',...
'fontsize',14,...
'fontname','cambria',...
'color','w');
handle.edit13 = uicontrol('style','edit',...
'parent',handle.fig,...
'position',[162 378 120 25],...
'backgroundcolor',basecolor*(height-378)/height,...
'fontsize',14,...
'fontname','cambria',...
'foregroundcolor','w',...
'horizontalalignment','left');
handle.text14 = text(35,260,'Upper Bound : ',...
'fontsize',14,...
'fontname','cambria',...
'color','w');
handle.edit14 = uicontrol('style','edit',...
'parent',handle.fig,...
'position',[162 328 120 25],...
'backgroundcolor',basecolor*(height-328)/height,...
'fontsize',14,...

```

```

'fontname','cambria',...
'foregroundcolor','w',...
'horizontalalignment','left');
handle.edit22 = uicontrol('style','edit',...
'parent',handle.fig,...
'position',[186 223 90 25],...
'backgroundcolor',basecolor*(height-223)/height,...
'fontsize',14,...
'fontname','cambria',...
'foregroundcolor','w',...
'horizontalalignment','left');
handle.text23 = text(35,415,'W : ',...
'fontsize',14,...
'fontname','cambria',...
'color','w');
handle.edit23 = uicontrol('style','edit',...
'parent',handle.fig,...
'position',[72 173 90 25],...
'backgroundcolor',basecolor*(height-173)/height,...
'fontsize',14,...
'fontname','cambria',...
'foregroundcolor','w',...
'horizontalalignment','left');
handle.text24 = text(35,465,'Population Size : ',...
'color',basecolor*(height-380)/height,...
'xcolor','w',...
'ycolor','w');
xlabel('Iteration');
ylabel('F(x)');
h=title('Convergence of F(x)');
set(h,'color','w');
grid on
'callback',@push1_callback);

%% Background Image
function cdata = creatback(height,width,basecolor)
cdata = zeros(height,width,3);
[height , ~, page] = size(cdata);
for i = 1:height
color = basecolor.*(i/height);
for j = 1:page
cdata(i,:,j) = color(j);
end
end

```

```

end
%% Default
set(handle.edit21,'string','1.2');%C1
dit12,'string'));% nvars
LB = str2num(get(handle.edit13,'string'));% LB
UB = str2num(get(handle.edit14,'string'));%UB
if isempty(ObjectiveFunction)
errorldg('PSO : Define Objective Function');
else
ObjectiveFunction=str2func(ObjectiveFunction);
end
if ~isequal(Nvars,size(LB,2),size(UB,2))
errorldg('PSO : Invalid Arguments : isequal(Nvars,size(LB,2),size(UB,2)) should be true ');
end
str{1} = get(handle.edit3,'string');
str{2} = sprintf('\nRunning Optimization....');
set(handle.edit3,'string',str);
% PSO
CurrentPosition = zeros(N,Nvars); % Initial Position
for i = 1:Nvars
CurrentPosition(:,i) = random('unif',LB(i),UB(i),N,1);
end
Velocity = W.*rand(N,Nvars) ; % Initial Velocity
% Evalute Initial Position
CurrentFitness = zeros(N,1); % Fitness Value
for i = 1:N

assignin('base','x',CurrentPosition(i,:));
[CurrentFitness(i) errorr1] = ObjectiveFunction(CurrentPosition(i,:));
end
for i = 1:Nvars
indexes = CurrentPosition(:,i) < LB(i).*ones(N,1);
CurrentPosition(indexes,i) = LB(i);
indexes = CurrentPosition(:,i) > UB(i).*ones(N,1);
CurrentPosition(indexes,i) = UB(i);
end
if (Iter==1)|| (rem(Iter,1)==0)
p;
xlabel('Iteration');
ylabel('F(x)');
h = title(['Best Value : ' num2str(GlobalBestFitness)]);
set(h,'color','w');
grid on

```

```

end
end
str{3}= sprintf('\nOptimization Complete. ');
set(handle.edit3,'string',str);
str{4} = sprintf('\nF(x) = %d',GlobalBestFitness);
str{5} = sprintf('\nx = %d',GlobalBestPosition(1,:));
set(handle.edit3,'string',str);
clear('str');
end
end

```

\\ Objective function code

```
function [F,errorr1]= tracklnoise(z)
```

```
% Track the output of optsim to a signal of 1
```

```
% Variables a1 and a2 are shared with RUNTRACKLSQ
```

```
Kd =0 ;
```

```
% Compute function valuew
```

```
simout=sim('power_dstatcom_pwm2swell1844');
```

```
m=length(voutrms(20000:end,2));
```

```
t=0:5e-6:5e-6*(m-1);
```

```
signal=sin(2*pi*50*t+asin(three_pahe(20000,2)));
```

```
e=sqrt(sum((signal-three_pahe(20000,2)).^2)/length(voutrms(20000:end,2))) ; % compute the error
```

```
errorr1=100*sum((1-voutrms(20000:end,2)).^2)/length(voutrms(20000:end,2)) ; % compute the error
assignin('base','errorr1',errorr1);
```

```
F= errorr1;
```

```
end
```

\\ NNs Code

```

Target=table(:,8)';
Input=x;
net8= newff(Input,Target, [3], {'tansig','tansig'},'trainlm', 'learngdm','mse');
% Define learning parameters
net.trainParam.epochs=1000000; % Maximum number of epochs to train
net.trainParam.goal = 1e-12; %Performance goal
net.trainParam.lr=0.15;%Learning rate
net.trainParam.mc=0.6;%Momentum constant
net.trainParam.lr_inc=1.05; %Ratio to increase learning rate
net.trainParam.lr_dec=0.7; % Ratio to decrease learning rate%
net.trainParam.max_fail=1000; %Maximum validation failures
net.trainParam.max_perf_inc=1.04; % Maximum performance increase%
net.trainParam.min_grad=1e-10; %Minimum performance gradient
net.trainParam.show=300; %Epochs between displays (NaN for no displays)
net.trainParam.time=inf;%Maximum time to train in seconds
find_gain_constants = train(net8,Input,Target);

-----

\\ THD Code
clear all;close all; clc;
rms_value(k,:)=voutrms(:,2)';
erorr(k)=100*sum((1-voutrms(20000:end,2)).^2)/length(voutrms(20000:end,2)) ; % compute the error
signal=three_pahe(1900001:2000001,2);
Y=fft(signal);
L=length(signal);
P1=abs(Y/L);
P2=P1(1:L/2+1);
P2(2:end-1)= 2*P2(2:end-1);
f=(0:L/2)/(L*Ts);
P3=sqrt(sum((P2.^2))-max(P2)^2)/max(P2);
stem(f,P2)
THD(k)=P3;
k=k+1;
end

}

```


Real feeder given by JDECO

1. Abu Mashaal given by JDECO as a case study

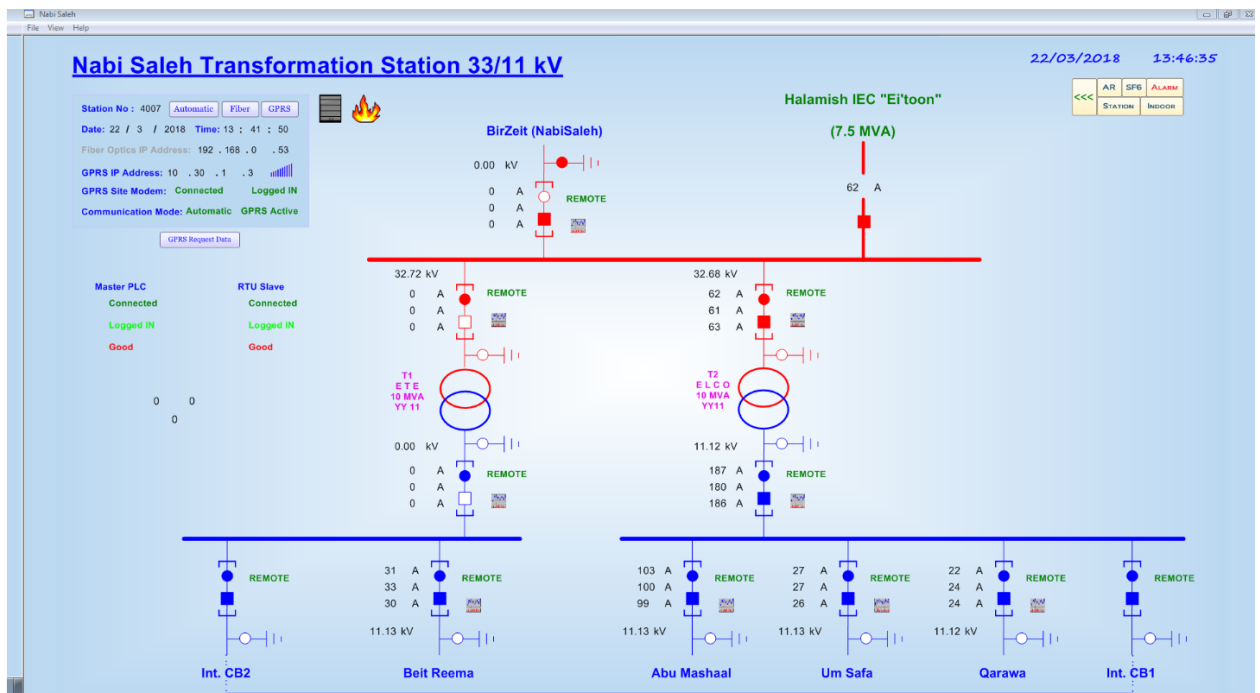


Figure B.1: Abu Mashaal case study given by JDECO

2. Load and voltage profile

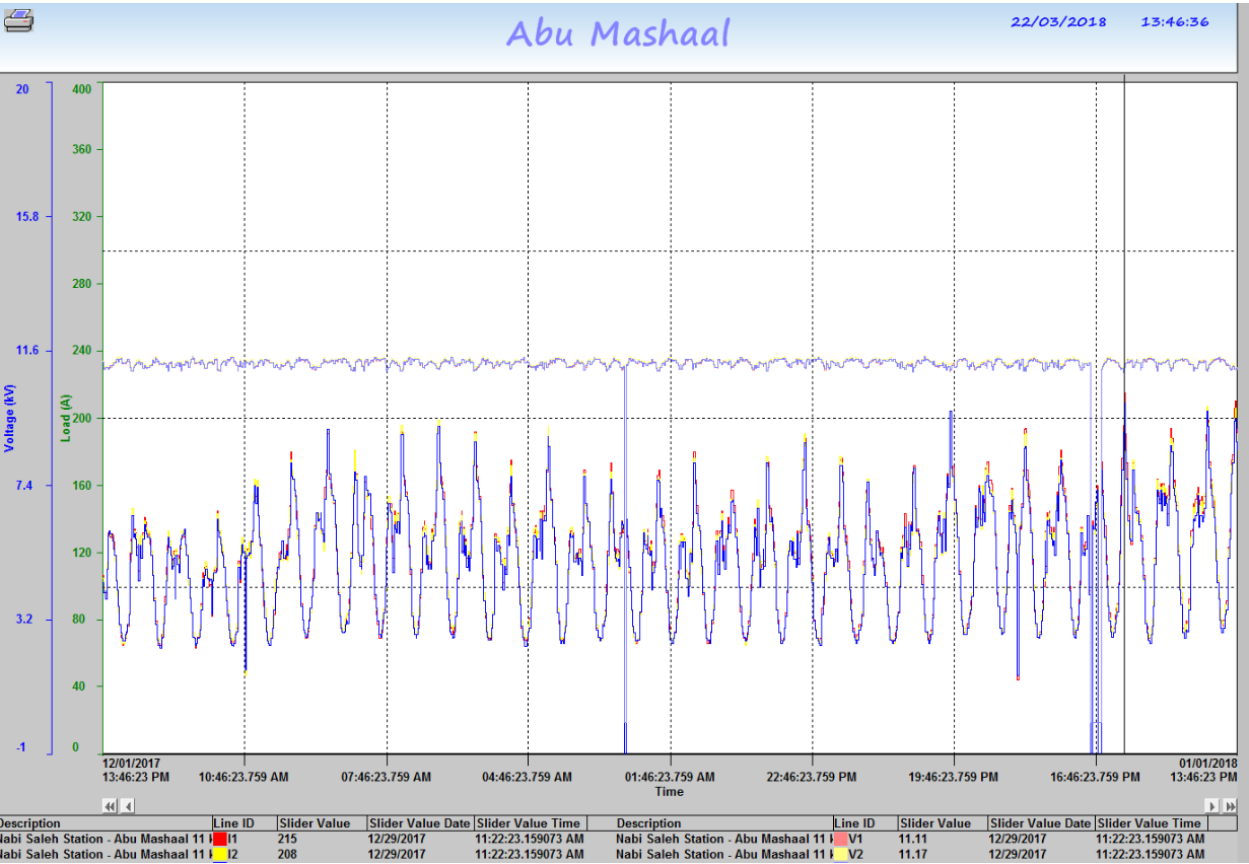


Figure B.2: Load and Voltage Profile

3. Data for line feeder (Der Abu Mshaal)

Der Abu Mshaal Data Feeder\Ramallah							موقع المحول	قدرة المحول
From	To	Type designation	Length	Resistance	Reactance			
TS225-1 NABI SALIH	DAM1	DKBA 1X3X120 CU	0.042	0.008232	0.004536			
DAM1	DAM2	FEAL 1X95	0.048	0.009168	0.016848			
DAM2	DAM3	FEAL 1X95	0.084	0.016044	0.029484			
DAM3	DAM4	FEAL 1X95	0.068	0.012988	0.023868			
DAM4	DAM5	FEAL 1X50	0.13	0.070538	0.04849			
DAM5	DAM6	FEAL 1X50	0.125	0.067825	0.046625			
DAM6	DAM7	FEAL 1X50	0.055	0.029843	0.020515			
DAM7	DAM8	FEAL 1X50	0.056	0.0303856	0.020888			
DAM8	DAM9	FEAL 1X50	0.086	0.0466636	0.032078			
DAM9	DAM10	FEAL 1X50	0.083	0.0450358	0.030959			
DAM10	DAM11	FEAL 1X50	0.073	0.0396098	0.027229			
DAM11	DAM12	FEAL 1X50	0.076	0.0412376	0.028348			
DAM12	DAM13	FEAL 1X50	0.076	0.0412376	0.028348			
DAM13	DAM14	FEAL 1X50	0.08	0.043408	0.02984			
DAM14	DAM15	FEAL 1X50	0.06	0.032556	0.02238			
DAM15	DAM16	FEAL 1X50	0.072	0.0390672	0.026856			
DAM16	DAM17	FEAL 1X50	0.07	0.037982	0.02611			
DAM17	DAM18	FEAL 1X50	0.07	0.037982	0.02611			
DAM18	DAM19	FEAL 1X50	0.081	0.0439506	0.030213			
DAM19	DAM20	FEAL 1X50	0.087	0.0472062	0.032451			
DAM20	DAM21	FEAL 1X50	0.077	0.0417802	0.028721			
DAM21	DAM22	FEAL 1X50	0.084	0.0455784	0.031332			
DAM22	DAM23	FEAL 1X50	0.087	0.0472062	0.032451			
DAM23	DAM24	FEAL 1X50	0.068	0.0368968	0.025364			
DAM24	DAM25	FEAL 1X50	0.07	0.037982	0.02611			
DAM25	DAM26	FEAL 1X50	0.083	0.0450358	0.030959			
DAM26	DAM27	FEAL 1X50	0.087	0.0472062	0.032451			
DAM27	DAM28	FEAL 1X50	0.073	0.0396098	0.027229			
DAM28	DAM29	FEAL 1X50	0.08	0.043408	0.02984			
DAM29	DAM30	FEAL 1X50	0.091	0.0493766	0.033943			
DAM30	DAM31	FEAL 1X50	0.07	0.037982	0.02611			
DAM30	DAM30-1	FEAL 1X50	0.095	0.051547	0.035435			
DAM30-1	DAM30-2	FEAL 1X50	0.093	0.0504618	0.034689			
DAM30-2	DAM30-3	FEAL 1X50	0.093	0.0504618	0.034689			
DAM30-3	DAM30-4	FEAL 1X50	0.089	0.0482914	0.033197			
DAM30-4	DAM30-5	FEAL 1X50	0.035	0.018991	0.013055			
DAM30-5	DAM30-6	FEAL 1X50	0.038	0.0206188	0.014174	1	250 KVA	
DAM31	DAM32	FEAL 1X50	0.077	0.0417802	0.028721			
DAM32	DAM33	FEAL 1X50	0.079	0.0428654	0.029467			
DAM33	DAM34	FEAL 1X50	0.065	0.035269	0.024245			

Figure B.3: Der Abu Mshaal Data Feeder

Appendix C

Optimum values of controller gains for swell and sag voltage events

1. *DSTATCOM Controller Gains For Swell Events Using PSO*
2. *DSTATCOM Controller Gains For Sag Events Using PSO*

APPENDIX C. OPTIMUM VALUES OF CONTROLLER GAINS FOR SWELL AND SAG VOLTAGE

Table C.1: DSTATCOM Controller Gains For Swell Events Using PSO

Event	Vac(kp)	Vac(ki)	Vdc(kp)	Vdc(ki)	i(kp)	i(ki)	PLL(kp)	PLL(ki)	error%
1.30pu	10	10	10	20	2.75	415	1170	3000	4.0009
1.295pu	0.834	3100	5.73	18.8	5	1050	1290	2310	2.960
1.29pu	10	3500	1e-4	20	5	4.08e2	1.42e3	1.11e2	3.599
1.285pu	10	10	10	20	4.97	1.06e3	1.42e3	3000	4.440
1.28pu	2.48	10	1e-4	1.72e1	4.71	1e2	1500	10	3.517
1.275pu	7.57	3500	0.46	0.92e-1	5	1500	1.25e3	1.91e3	4.880
1.27pu	3.19	3270	10	20	5	100	1.23e3	5.77e2	3.440
1.265pu	1e-2	2.55e3	10	20	5	1.17e2	1.26e3	10	4.997
1.26pu	10	3500	10	1e-2	5	1.10e2	1500	10	4.339
1.255pu	10	3500	1e-4	1e-2	5	1500	1.25e3	10	3.950
1.25pu	7.43	3500	1e-4	1.23e1	2.17	1500	1500	10	4.580
1.245pu	4.35	4.71e2	3.97	20	2.50	0.44e2	1.33e3	1.57e3	7.553
1.24pu	4.15	4.31e2	3.57	20	3.57	4.39e2	1e3	1.27e3	3.353
1.235pu	2.26	3.31e2	2.97	20	2.40	3.36e2	1.02e3	1.57e3	5.335
1.23pu	6.79	4.61e2	10	3.44	5	2.51e2	1.27e3	2.84e3	4.813
1.225pu	4.14	3.50e3	5.02	3.53	5	1.78e2	1.42e3	8.26e2	6.487
1.22pu	4.13	3500	5.02	3.53	5	1.76e2	1.22e3	8.48e2	3.990
1.215pu	1e-2	3500	10	20	5	100	1.17e3	10	3.915
1.21pu	1e-2	3500	10	20	5	100	1.27e3	10	4.451
1.205pu	10	10	3.61	1e-2	5	1500	1.31e3	2.70e2	4.640
1.20pu	3.82	1.98e2	6.22	1.55e1	2.05	4.36e2	1.38e3	2.64e3	5.457
1.195pu	1e1	3500	1e-4	1e-2	5	1500	1.37e4	10	3.852
1.19pu	10	3500	1e-4	1e-2	5	1500	1.36e3	10	7.709
1.185pu	4.33	1.31e2	589	1.2	4.59	6.24e2	1.32e3	2.52e3	7.604
1.18pu	8.54	2.19e3	2.25	1.71e1	3.38	6.93e2	1.27e3	1.27e3	7.227
1.175pu	8.54	2.19e3	2.25	1.71e1	3.38	6.93e2	1.27e3	1.27e3	7.227
1.17pu	2.41	2.83e3	1.89	4.85e-1	3.71	3.09e2	1.43e3	2.96e3	9.651
1.165pu	10	10	5.49	1.06e1	5	8.68e2	1.50e3	1.19e3	4.543
1.16pu	10	10	5.49	1.06e1	5	8.68e2	1.50e3	1.19e3	4.543
1.155pu	10	3500	1e-4	2e1	5	1500	1.50e3	10	7.137
1.15pu	10	10	1e1	1e-2	5	1.28e3	1.50e3	3000	8.866
1.145pu	10	10	1e-4	1e-2	1	1500	1.5e3	10	6.974
1.14pu	1e-2	3500	1e-4	1e-2	5	100	1.26e3	3000	5.774
1.135pu	10	3500	1e-4	2e1	5	1500	1.50e3	10	4.436
1.13pu	1.28	2.3e3	3.11	1.81e1	4.25	8.3e2	7.32e1	2e4	9.989
1.125pu	4.13	1.06e3	7.19	1.96	4	1.07e3	1.22e3	1.5e3	5.646
1.12pu	10	3500	1e-4	1e-2	5	9.74e2	1.50e3	5.58e2	7.713
1.115pu	10	2.77e2	1e1	1.01e1	3.49	100	1.50e3	3000	7.620
1.11pu	5.02	7.37e2	5.18	1.02e1	2.83	100	1.24e3	2.479e3	6.403
1.105pu	4.33	2.05e3	4	1.25e1	3.91	8.4e2	1.81e3	1.18e3	7.569
1.10pu	10	10	10	20	5	1500	1.8e3	3000	5.925

APPENDIX C. OPTIMUM VALUES OF CONTROLLER GAINS FOR SWELL AND SAG VOLTAGE

Table C.2: DSTATCOM Controller Gains For Sag Events Using PSO

Event	Vac(kp)	Vac(ki)	Vdc(kp)	Vdc(ki)	i(kp)	i(ki)	PLL(kp)	PLL(ki)	error%
0.9pu	1e-2	10	1e-4	1e-2	1	1e2	2.1e2	2.38e1	9.989
0.895pu	1e1	1.22e3	1e1	1e-2	1	1.5e3	9.2e2	2.77e3	8.144
0.89pu	4.93	3.47e3	2.65	1.87e1	9.9e-1	1.86e2	2.21e2	1.06e3	9.760
0.885pu	4.86	2.45e3	9.13	8.08	1.92	1.21e3	9.77e2	2.01e3	8.311
0.88pu	4.86	2.45e3	9.13	8.08	1.92	1.21e3	9.77e2	2.01e3	8.311
0.875pu	10	3500	2.75	1.39e1	1	1500	9.95e2	10	9.856
0.87pu	1e-2	3500	10	20	1	100	9.45e2	10	9.656
0.865pu	10	1.18e3	10	1e-2	1	1e2	9.35e2	3000	6.93
0.86pu	1e-2	3500	10	20	1	1500	9.75e2	10	7.004
0.855pu	9.9	2.05e3	2.87	9.65	4.14	4.01e2	9.72e2	2.18e3	9.784
0.85pu	1e-2	3500	10	1.67	1	1.17e3	9.88e2	3000	9.552
0.8455pu	1e-2	10	1e-4	1e-2	1	100	1.03e3	10	6.781
0.84pu	10	2.02e3	10	20	1	1500	1.08e3	10	7.775
0.835pu	10	2.02e3	10	20	1	1500	1.08e3	10	7.775
0.83pu	8.97	3500	10	20	1	1500	9.36e2	9.36e2	8.5223
0.825pu	8.97	3500	10	20	1	1500	9.36e2	9.36e2	8.5223
0.82pu	1e-2	10	10	1e-2	1	100	9.72e2	3000	6.480
0.815pu	1e-2	10	10	1e-2	1	100	9.72e2	3000	6.4808
0.81pu	7.16	2670	10	1.68e1	2.61	1.28e3	1000	1.1e3	8.310
0.805pu	7.16	2670	10	1.68e1	2.61	1.28e3	1000	1.1e3	8.310
0.80pu	10	3500	1e-4	20	5	7.01e2	1.13e3	3.24e2	9.141
0.795pu	10	2900	1e-4	20	1	100	4.46e1	3000	7.376
0.79pu	10	2900	1e-4	20	1	100	4.46e1	3000	7.376
0.785pu	10	2900	1e-4	20	1	100	4.46e1	3000	7.376
0.78pu	10	2900	1e-4	20	1	100	4.46e1	3000	7.376
0.775pu	10	3500	10	20	1	1500	4.29e1	3000	7.059
0.77pu	10	2630	1e-4	1e-2	1	1500	10	1.37e2	0.641
0.765pu	10	2630	1e-4	1e-2	1	1500	10	1.37e2	0.641
0.76pu	10	3500	1e-4	1e-2	1	100	10	3.26e2	0.555
0.755pu	10	10	10	6.28	1	100	4.4e1	3000	4.833
0.75pu	10	3500	1e-4	20	1	1.37e3	6.59e2	10	9.171
0.745pu	10	10	10	1e-2	1	100	6.71e1	3000	6.041
0.74pu	10	1930	7.14	2.66	1	100	7.47e2	10	2.146
0.735pu	10	1.06e3	10	1e-2	1	1e2	7.30e2	3000	0.251
0.73pu	10	1.06e3	10	1e-2	1	1e2	7.30e2	3000	0.251
0.725pu	10	3500	10	20	1	100	7.30e1	3000	0.184
0.72pu	9.02	6.99e2	1e-4	20	1	8.82e2	10	1.23e2	7.697
0.715pu	1e-2	3500	10	20	1	8.01e2	10	10	0.812
0.71pu	10	10	1e-4	20	1	100	7.61e2	10	9.209
0.705pu	10	3500	10	3.99	1	100	6.71e2	10	8.134
0.70pu	10	10	1e-4	20	1	100	4.55e1	10	0.999