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Voltage Profile Improvement using DSTATCOM Based on Artificial Intelligence Techniques

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ABSTRACT The demand for electric power has recently increased as a result of an increase in residential and industrial facilities that may contain sensitive nonlinear loads that require high power quality (PQ) on the distribution system to avoid malfunction. The improvement of voltage profiles with appropriate voltage harmonic distortion is a major PQ problem. It should be monitored to keep it within reasonable limits. The distribution static synchronous compensator (DSTATCOM) is used with an established control strategy to boost the voltage profile. DSTATCOM control is developed in this study using artificial intelligence (AI) and the artificial neural network (ANN), which is focused on optimum values found by particle swarm optimization (PSO). The simulation results demonstrated that DSTATCOM's proposed control strategy for improving the voltage profile on the distribution system is superior and stable. The MATLAB/Simulink software package was used to validate the performance.

KEYWORDS: Artificial Neural Networks, DSTATCOM, PI controller, Power Quality, Voltage Profile

1. INTRODUCTION

The rapid rise in electrical power consumption has resulted in the increased usage of renewable energy sources (RES) and distributed generation (DG) in the electrical grid. When new energy resources enter the grid and different types of loads, such as nonlinear loads, different difficulties develop in current, voltage, and/or frequency, causing instrument error and malfunction, which is referred to as power quality (PQ) difficulties [1].

Several researches have been conducted on PQ difficulties, utilizing the benefits of major advancements in power electronics technology, resulting in a network transition from traditional to smart. PQ can also be defined as electrical limitations that allow a piece of equipment to work properly and at a high level of performance. Poor PQ, according to these definitions, has a negative impact on the electrical network's dependability and stability, as well as sensitive loads linked to the distribution bus's end user. PQ is concerned with three key factors: voltage, current, and frequency, all of which should be kept within acceptable ranges [2].

PQ issues in the network are produced by a variety of factors, including the connection of nonlinear loads, such as big motors in industrial applications, power electronics devices, switching capacitor banks, and the addition of new electrical resources to the grid. Indeed, these disturbances have an impact on the distribution system's performance and operation, as well as sensitive equipment. The smart grid (SG) technology opens up a lot of possibilities for resolving PQ issues. Flexible alternating current transmission systems (FACTS), a family of power electronics technologies, complement SG systems and offers answers to PQ issues. The distribution static synchronous compensator (DSTATCOM), which is a shunt device attached to the distribution bus, is one application of the FACTs family. Voltage var control is one of the most important parts of a power system, hence voltage var optimization (VVO) is the key SG application that improves power system security and efficiency. Artificial intelligence (AI) development is now playing a major role in the optimization of power system concerns, particularly in SG [3].

Several PQ studies have focused on enhancing and increasing the electrical grid's dependability and stability. These studies focus on challenges such as voltage profile improvement in power systems, imbalance circumstances in systems caused by unbalanced loading and load change, symmetrical and unsymmetrical failures, actual and reactive power losses due to harmonic distortion, and low power factor (PF). To address these PQ difficulties, several FACTs devices are used. Different DSTATCOM control techniques are susceptible to non-ideal supply conditions and load fluctuations, necessitating careful controller design tuning for each individual insulator. In addition, the cost of the system rises as a result of the employment of specialized equipment like the LCL filter. Other DSTATCOM control systems in the literature required extensive control facilities and controllers, as well as supplemental components like active filters. In addition, the controller may require additional delay time due to the analogue-to-digital conversion [4-5].

On the other hand, new proposed control techniques for DSTATCOM have been implemented, such as an adaline-based algorithm and a direct method that is based primarily on output voltage position and magnitude control. Although these strategies have been confirmed as effective for managing DSTATCOM, they are more complicated and costly than previous procedures. DSTATCOM analyzes and implements various control techniques using various mathematical theories and physical models. The dynamic system equations are simplified using instantaneous power theory, rotating reference frame (dq0), stationary reference frame, instantaneous reactive power (IRP), and Park's transformation [6-7].

FACTS devices and smart controls that are compatible with renewable energy supplies have been the subject of extensive research. Existing RES and DGs in the electricity system provide unique issues, particularly when these resources have a high penetration rate. To meet these issues, SG technology is required to manage the grid's power flow. The power created or absorbed by FACTS devices, as well as the power created or absorbed by RES. Using SG technology improves the power system's dependability and stability, even when the number of RES connected to the distribution bus is high. Many studies have been completed on optimization approaches for various PQ concerns in power systems. A comparison of meta-heuristic approaches such as GA, PSO, differential evolution (DE), harmony search (HS), and seeker optimization algorithm (SOA) is included in these papers [8-13]. As a result of the literature research, there are significant obstacles in utilizing AI techniques to tune DSTATCOM's PI controller. This paper proposes the use of ANNs as a strategy for tweaking the DSTATCOM controller, whose controller constants are best determined using PSO [14-17].

This work offers an AI methodology, specifically PSO and ANN, that is employed in the DSTATCOM design controller to improve the voltage profile on distribution electrical power systems. DSTATCOM settings and design are introduced in part II. The proposed system's mathematical model is described in Section III. The created AI methodologies and proposed optimization strategy for developing the developed controller for DSTATCOM are discussed in detail in section IV. The methodology is presented in Section V, which includes a description of a real-world distribution system as a case study. Section VI shows the simulation findings for the proposed scenarios in this study, as well as a full discussion of all outcomes for voltage events such as sag and swell. Finally, section VII summarizes the suggested approach's performance, efficiency, and superiority.

2. DSTATCOM CONFIGURATION AND DESIGN

The circuit diagram of the equivalent model of DSTATCOM is shown in Fig.1 [6].

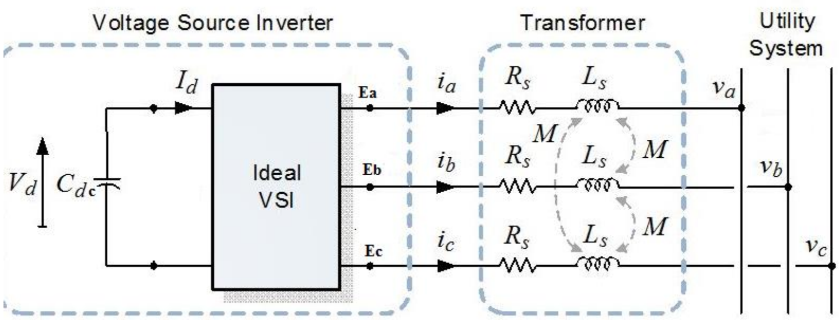

Figure 1. Equivalent model of DSTATCOM.

Where:

R_s and L_s: are 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 voltage source converter (VSC) is the main electrical component of DSTATCOM, transforms dc to ac voltage. In this investigation, the following forms of VSC were used:

1. A gate turn-off thyristor is utilized to create a square wave 48-step voltage waveform of four three-level inverters; however, specific interconnection transformers are utilized to eliminate harmonics from the output voltage waveform.
2. This inverter uses isolated gate bipolar transistors and employs PWM to convert DC input voltage to AC output voltage sinusoidal waveform (IGBT).

DSTATCOM's operation is divided into three modes:

1. Mode 1: when the output voltage Vout amplitude is larger than the utility bus voltage Vac, current flows from the converter to the AC side of the power system via reactance, and the DSTATCOM injects reactive power into the AC side of the power system.
2. Mode 2: when the voltage at the utility bus is less than the amplitude of Vout, current flows from the AC side of the power system to the converter, and DSTATCOM absorbs reactive power from the AC power system.
3. Mode 3: there is no reactive power exchange between DSTATCOM and the power system when the output voltage V_{out} amplitude equals the voltage amplitude at the AC side of the power system; in this situation, DSTATCOM is in a floating condition.

The PI controller is used to control the function of DSTATCOM to inject the required reactive current to the load. Figure 2 shows the simplified scheme of control strategy of DSTATCOM [8].

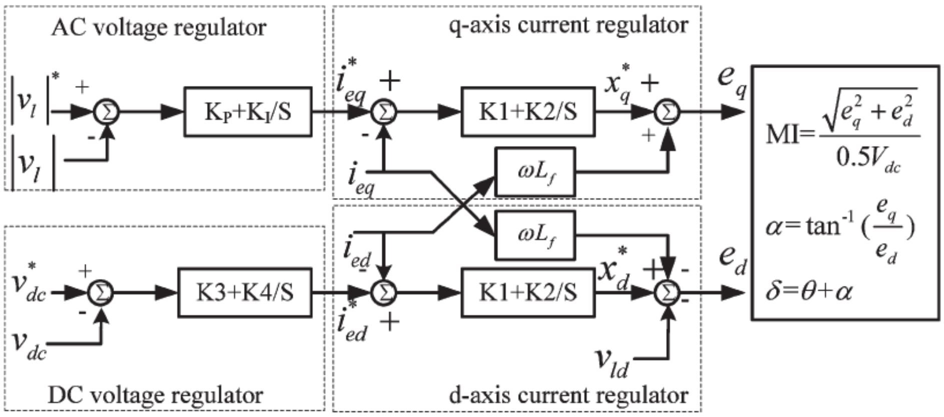

Figure 2. Control strategy scheme of DSTATCOM

PWM controls the output voltages for VSI based on the modulation index (MI) and phase angle between the inverter voltage and line voltage. DSTATCOM's PI controller is in charge of generating/absorbing the desired reactive power at the power system's common coupling point [11]. The purpose of this type of control is to keep the voltage magnitude at PCC constant throughout system disruptions. The controller input in Figure 3 is an error signal, which is the difference between the RMS reference voltage (1pu) and the RMS value of the observed terminal voltage. To minimize the error to zero, the PI controller processes the error signal and generates the needed drive angle [15].

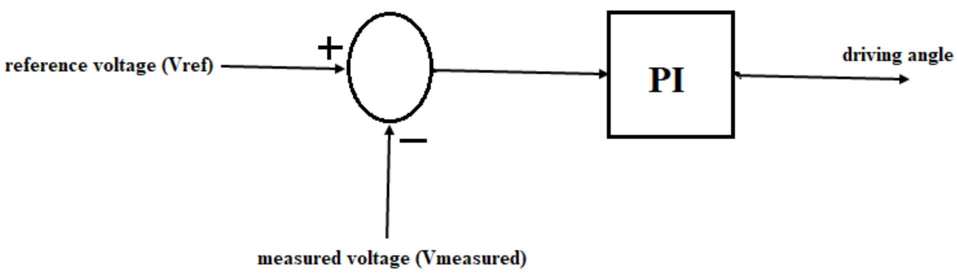

Figure 3. Direct PI control of DSTATCOM

3. MATHEMATICAL MODEL OF PROPOSED DSTATCOM

Because DSTATCOM has a nonlinear operation structure, the control strategy of DSTATCOM is studied using simplified mathematical formulas. The configuration parameters of DSTATCOM connected to the power grid are illustrated in Figure 4 [8].

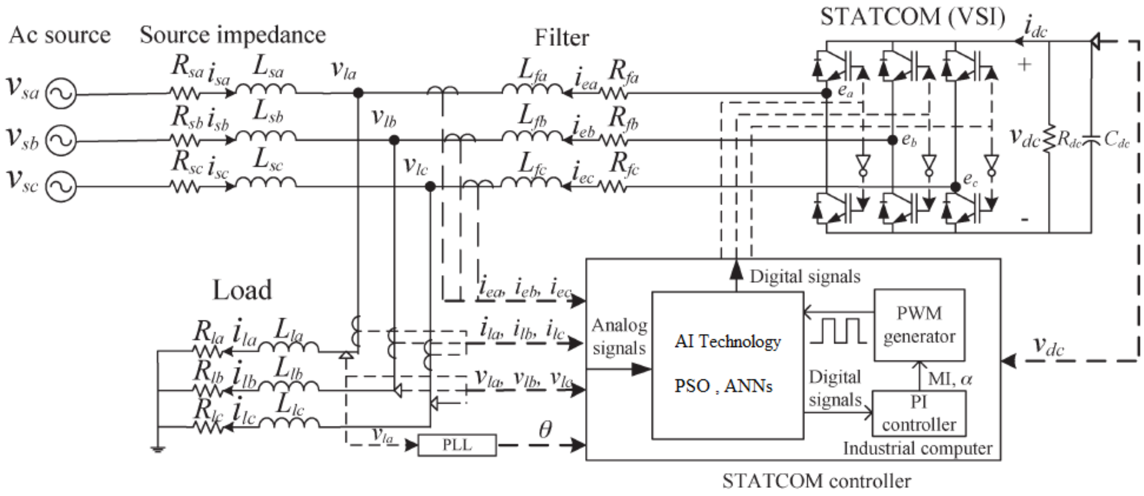

Figure 4. DSTATCOM Configuration connected on power system.

The inverter voltage magnitude Vc and the angle difference between the bus voltage and the inverter output voltage govern the actual and reactive power of DSTATCOM. Equations (1) and (2), respectively, explain DSTATCOM's active and reactive power compensation [10]:

$$P = \frac{V_{Pcc} V_c \sin\alpha}{X} \tag{1}$$

$$Q = \frac{V_{Pcc}(V_{Pcc} - V_c \cos\alpha)}{X} \tag{2}$$

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's controller is based on the system's dynamic equations and is constructed with the assumption that the system is linear [8].

4. DSTATCOM DESIGN

The equations of the mathematical model of the specified system [11] to be used to calculate DSTATCOM components, which include:

4.1 DESIGN DC BUS VOLTAGE

Current compensation can be determined using the following equation if the voltage DC link is sufficient.

$$V_{dc\,min} > \sqrt{2}V_{L-L(rms)} = \sqrt{2}\,\sqrt{3}V_{L-N(rms)} \tag{3}$$

4.2 DESIGN DC BUS CAPACITOR

The C_{dc} can be calculated using the energy conservation principle:

$$\frac{1}{2}\mathrm{C_{dc}}[\mathrm{V_{dc}}^2 - \mathrm{V_{dc1}}^2] = 3\ \mathrm{k\ a\ V\ I\ t} \tag{4}$$

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

4.3 DESIGN AC INTERFACING INDUCTOR

The following equation determines which filter to use based on the ripple current icr-pp, switching frequency fs, and DC bus voltage V dc:

$$L_f = \frac{\sqrt{3}\,m\,V_{dc}}{12\,a\,f_s\,i_{cr-pp}} \tag{5}$$

Where *m* is modulation index.

4.4 DESIGN PASSIVE HIGH PASS RIPPLE FILTERS

To eliminate the high frequency noise from the voltage waveform at PCC in the power system the high pass filter is needed to do that, it could be calculated by the following formula:

$$R_r C_r = \frac{T_s}{10} \tag{6}$$

5. ARTIFICIAL INTELLIGENCE AND OPTIMIZATION TECHNIQUES

5.1 PARTICLE SWARM OPTIMIZATION

PSO is a social and cooperative behavior-inspired heuristic search optimization approach. The approach is linked to the primary components. The first is influenced by personal behavior (P_{best}), while the second is influenced by social experience (G_{best}). These two pieces [14] determine how the particle's position in search space is updated. The technique's fundamental equations are as follows:

$$V_{i,j}^{k+1} = w \times V_{i,j}^{k} + c_1 \times r_1 \times \left(P_{besti,j}^{k} - X_{i,j}^{k}\right)(15) + c_2 \times r_2 \times \left(G_{besti,j}^{k} - X_{i,j}^{k}\right) \quad (7)$$

$$X_{i,j}^{k+1} = X_{i,j}^{k} + V_{i,j}^{k+1} \quad (8)$$

Where $P_{besti,j}^{k}$ represent personal best jth component of ith individual, whereas G_{bestj}^{k} represents jth component of the best individual of population up to iteration k. The PSO search mechanism is multidimensional search space. The considered steps of PSO technique is shown in the following flowchart.

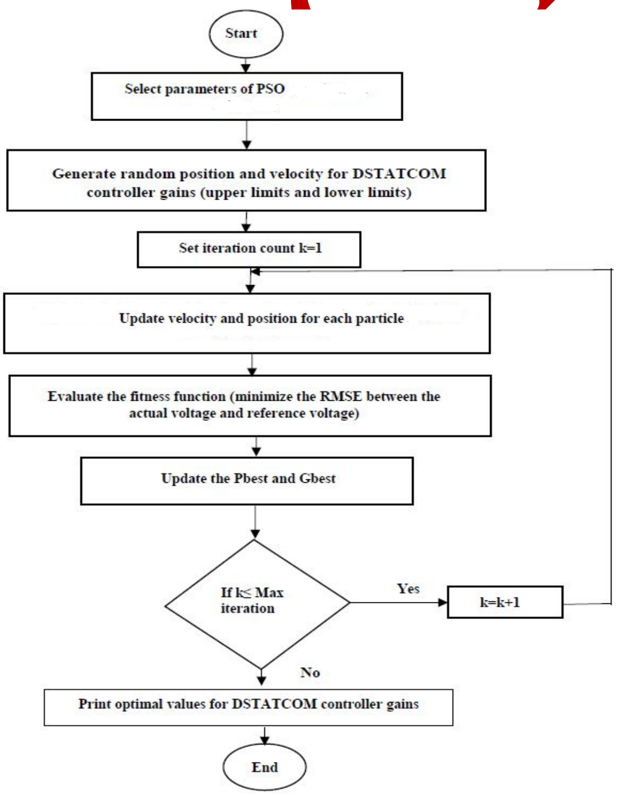

Figure 5. Flowchart of PSO algorithm

5.2 ARTIFICIAL NEURAL NETWORKS (ANNS)

forward-thinking DSTATCOM's controller is tuned in real time based on the voltage level of the distribution bus using ANN. The basic design of an ANN feed forward is shown in Figure 6, which consists of three layers: input, hidden, and output. Each layer's node (neurons) is linked to the following layer's node. The number of input nodes in the input layer corresponds to the number of system inputs, and the number of output nodes in the output layer corresponds to the number of system outputs. The number of hidden nodes in the middle layer is usually equal to the sum of the system's input and output nodes. Because both overfitting and underfitting have an impact on training results [15-16], the number of hidden nodes is critical.

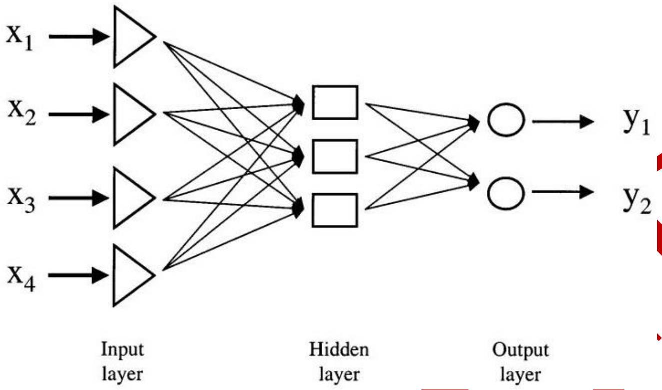

Figure 6. Basic neural network structure

The training procedure of the feed forward ANN used in this study is according to the mean square error of output criterion, which can be defined by

$$J = \sum_{1}^{N} e(i)^2 \qquad (9)$$

Where N is the output neurons number, and $e(i)$ is instantaneous error between the actual and estimated value of the output.

The value of each neuron in the output layer (y_j) is given in terms of the input values x_i as shown in the following equation

$$y_j = \tanh(\sum w_{ij}\, x_i + b_j) \qquad (10)$$

6. CASE STUDY

The work is tested on a live network using data provided by the Jerusalem District Electricity Company (JDECO). The network is for the West Bank's Abu Mashaal zone. Due to industrial nonlinear loads, the voltage on this network falls below the standard level (11kV) on the distribution bus. Figure 7 shows a single line diagram of the provided radial network.

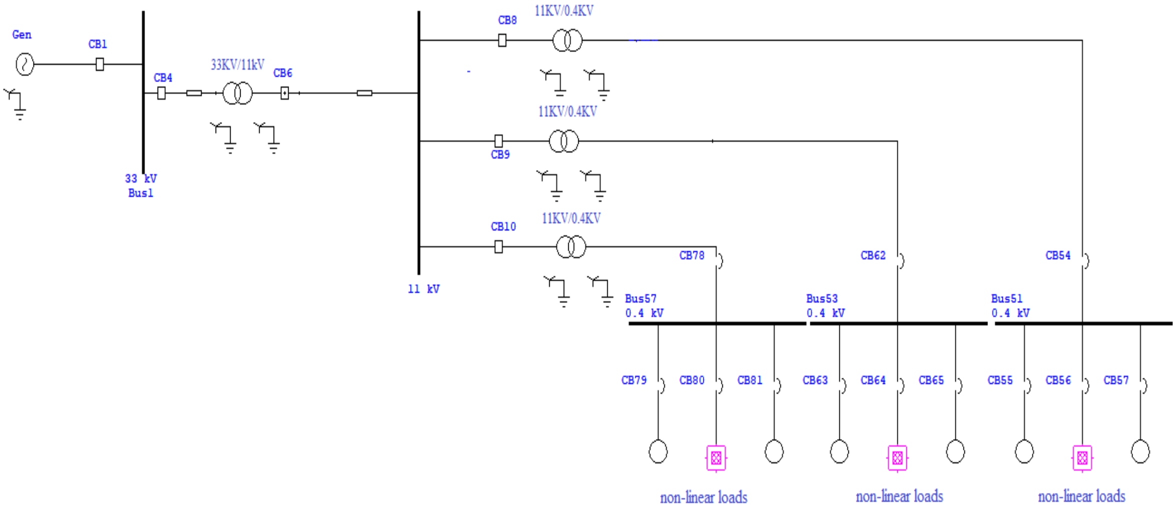

Figure 7. Single line diagram for radial network

Description of the system configuration is summarized in Table 1.

Table 1. Description of proposed distribution feeder

Parameter	Value
3 phase ac source	V_{rm}=11kV, f=50Hz
Line impedance	L_s=3.851mH, R_s=0.211Ω
Distribution transformers	33kV/11kV, 11kV/0.4kV

The rated load connected on the end user of distribution system is 1MVA, Table 2 summarize the calculation values of DSTATCOM configuration.

Table 2. Values of DSTATCOM configuration

Parameter	Value
I_{rms}	1443.3A
V_{dc}	15556.3V
C_{dc}	16.665mF
L_f	31.42μH
C_r	1.8mF
R_r	0.0027Ω

7. TUNING DSTATCOM CONTROLLER USING ANNS AND PSO

7.1 EMPLOY PSO FOR OPTIMUM VALUE OF CONTROLLER

The PSO method is used to determine the best DSTACOM controller gains (Vac regulator, Vdc regulator, and current regulator and PLL regulator). The goal is to reduce the root mean square error (RMSE) between the actual measured voltage and the reference voltage as much as possible (1pu). The following equations represent the objective function:

$$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n}(V_i - V_{ref})^2\right)^{\frac{1}{2}} \quad (11)$$

$$J = \min[RMSE] \quad (12)$$

Where:

J: fitness function

$RMSE$: Root mean square error

V_i: actual voltage

V_{ref}: reference voltage(1pu)

n: number of samples

7.2 EMPLOY ANNS FOR CONTROL DSTATCOM

The usage of ANN as an AI tool for controlling DSTATCOM is presented. Because ANN controllers can proficiently learn the unknown continuously altering environment and act accordingly, they have become a wide subject of interest among researchers in a wide range of fields. The PSO findings were analyzed for a wide range of sag and swell occurrences (0.7-1.3), with roughly 70% of these data being used as a data foundation for the ANN training procedure. The output of the ANNs are then used to control DSTATCOM in real time. The ANN learning process is created in MATLAB with the help of the toolbox neural network.

In order to apply the ANNs algorithm for learning and discover the optimum optimal value of controllers gains according to disturbance voltage level, eight networks are defined in MATLAB code for this study, as shown in Table 4.

Table 3. Define networks in ANN algorithm

ANNs	Controller gain
Network1	$V_{ac}(k_p)$
Network2	$V_{ac}(k_i)$
Network3	$V_{dc}(k_p)$
Network4	$V_{dc}(k_i)$
Network5	$i(k_p)$
Network6	$i(k_i)$
Network7	$PLL(k_p)$
Network8	$PPL(k_i)$

7.3 DESIGNING AND PROGRAMMING ANNS

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.

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

Figure 8 describes the Basic flowchart for designing ANN Model.

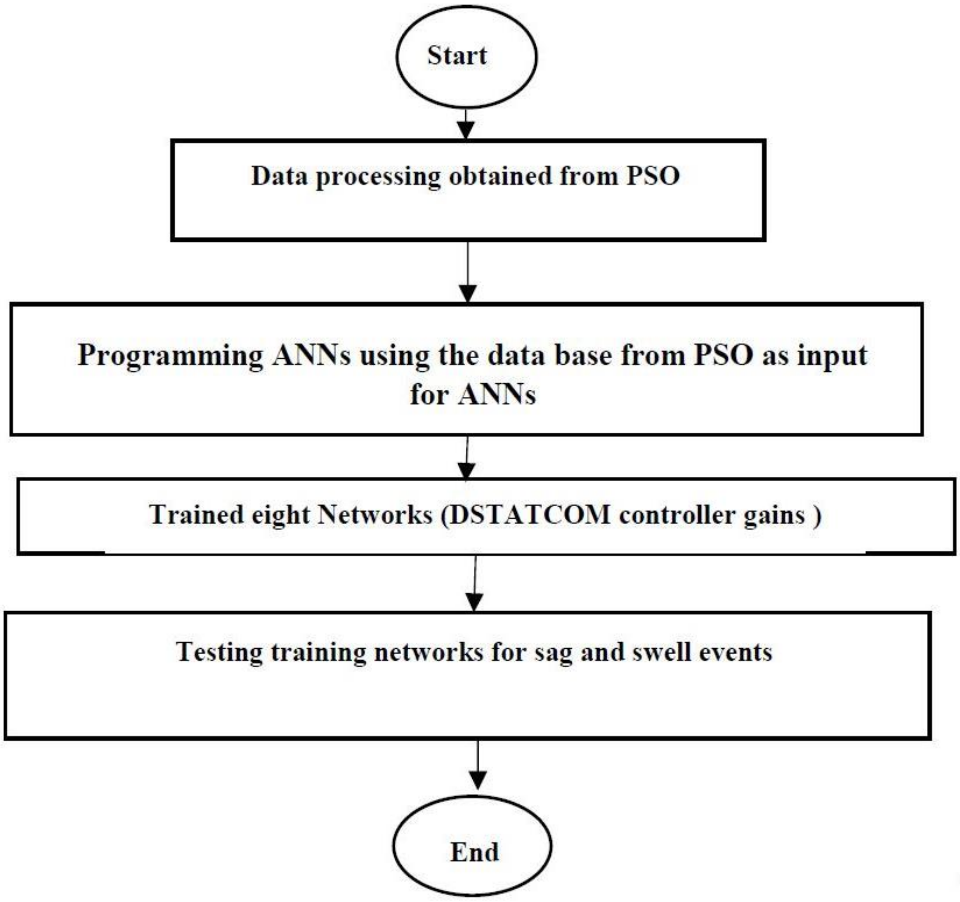

Figure 8. Basic flowchart for designing ANNs model

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 4. Values for controller gains is applied to ANNs in training phase. ANN logarithm is used for practice the controller and select the gains constants according to activations elements. The controller constants are used as inputs to train the eight controller constants networks.

8. RESULTS DISCUSSION

The ANN logarithm is used to test the controller and choose its gains constants based on the activation's elements. Nearly 70% of the data obtained through PSO is used in the algorithm. The findings and controller gains for extreme swell and extreme sag using DSTATCOM's created controller are shown in Table 5.

Table 5. Voltage profile improvement using developed DSTATCOM controller

Event	Voltage profile improvement	THD%
Extreme swell (1.3pu)	1.02pu	3.26
Extreme sag (0.7pu)	1.07pu	9.23

The effect of DSTATCOM on enhancing the voltage profile of the system at the PCC during a voltage swell event with an acceptable range is shown in Figure 9.

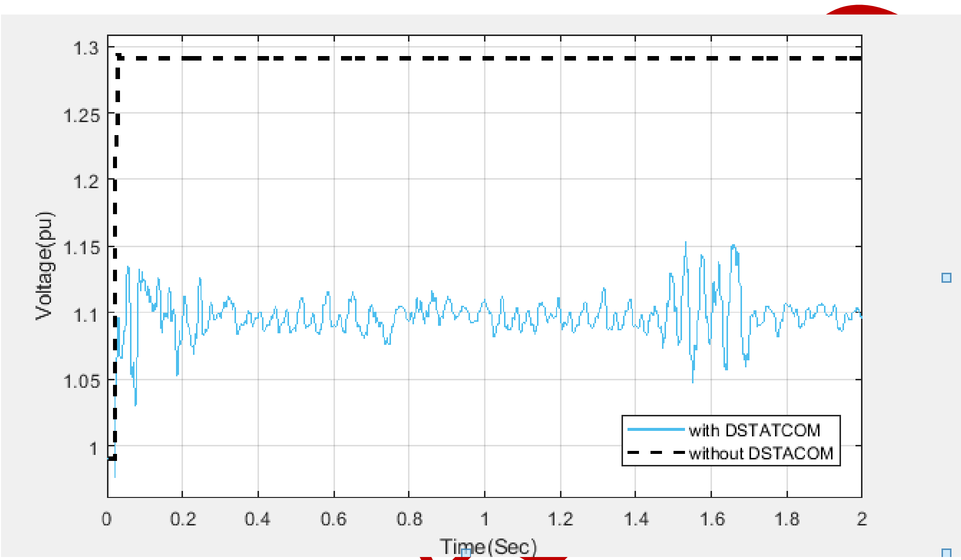

Figure 9. Effect of DSTATCOM on Voltage profile during extreme swell event.

DSTATCOM's effect on enhancing the voltage profile of the system at the PCC during a voltage sag event with an acceptable range is shown in Figure 10.

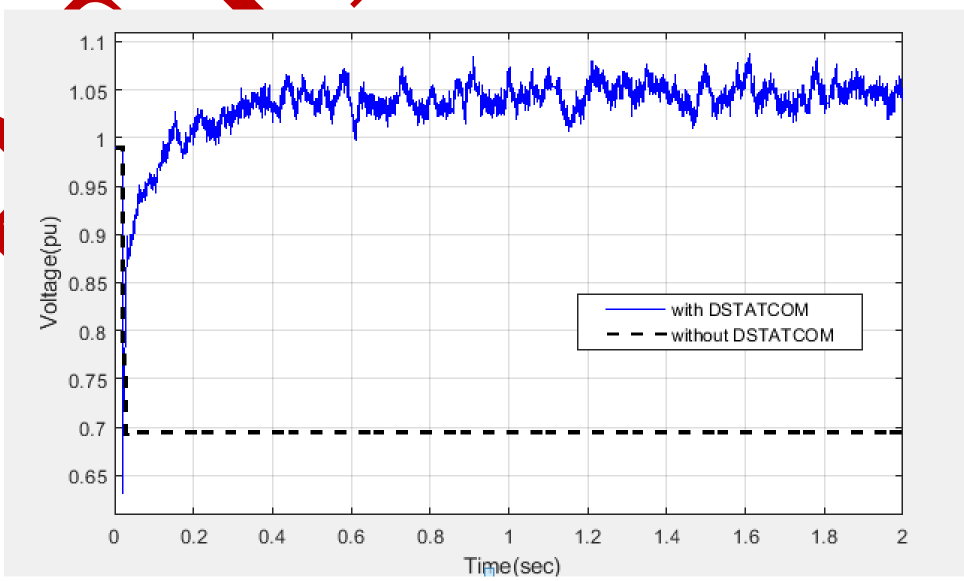

Figure 10. Voltage profile improvement for extreme sag event.

The technique that has been proposed is the use of ANN with PSO to regulate DSTATCOM for voltage profile improvement on distribution systems with the purpose of real-time control rather than traditional off-line control is an effective methodology. The controller was also tested for optimizing the voltage profile for continuous extreme sag and extreme swell, and the findings showed that the created controller was both resilient and efficient, as shown in Figs. 11 and 12 for rms and phase voltage, respectively.

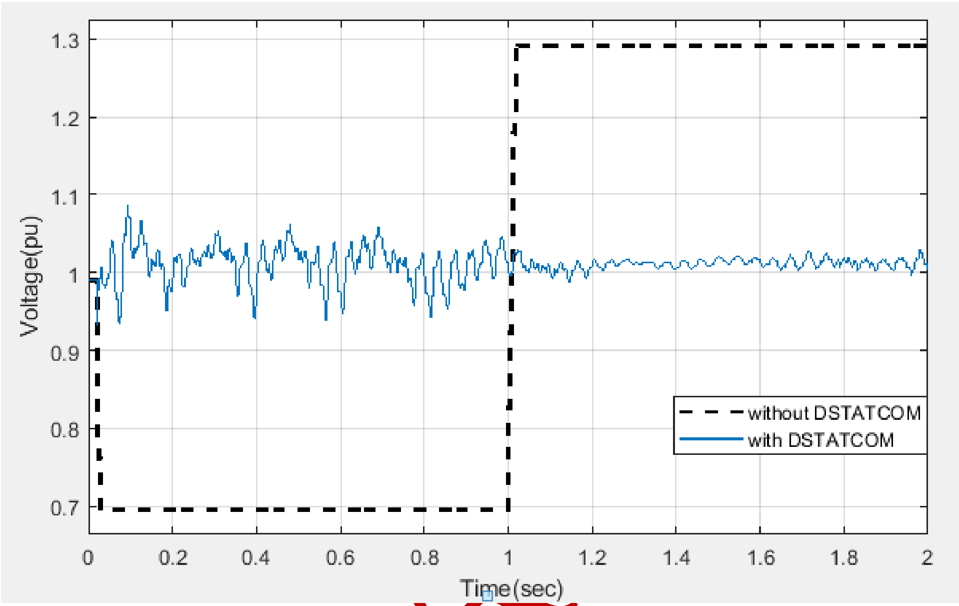

Figure 11. Effect of developed DSTATCOM controller using AI on rms voltage profile

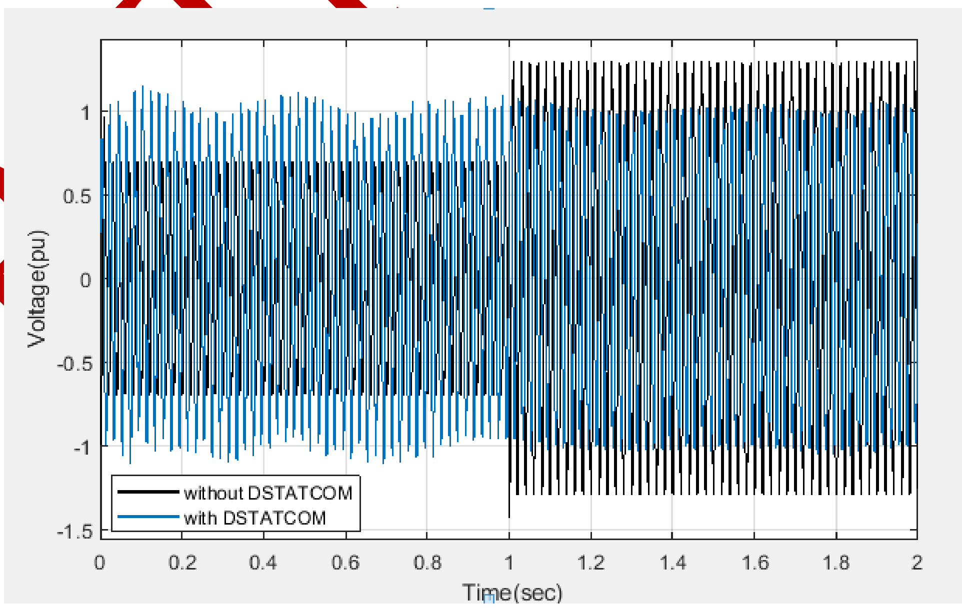

Figure 12. Effect of developed DSTATCOM controller using AI on instantaneous voltage profile

9. CONCLUSION

The results demonstrated the value of AI in DSTATCOM controller design, as the voltage profile is improved in real time during voltage events such as sag and swell. The PSO is used to find the best DSTATCOM controller gains, and then the ANN is utilized as an AI methodology to control DSTATCOM in real time. The effectiveness of employing ANN as an AI methodology to tune the PI controller of DSTATCOM in order to optimize the voltage profile on the distribution system was demonstrated in this study. The importance of AI approaches such as ANN was confirmed by the DSTATCOM with built controller. Using this designed controller, the power system's stability and dependability may be improved, and the network can become smart.

When compared to conventional control techniques, the developed controller using ANN enables DSTATCOM with a robust tuning system because it responds to various real-time voltage disturbances that may occur in the distribution system with efficient voltage profile augmentation. The simulation results showed that the suggested strategy for controlling DSTATCOM to improve the voltage profile on the distribution system is effective.

REFERENCES

[1] Z. Saafin, F. Zaro, M. Jawadeh, "Voltage Profile Improvement Using DSTATCOM Based on Artificial Intelligent Techniques," *IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT)*, pp.773-778, 2019.

[2] A. Sharaf, F. Gandoman, "A switched hybrid filter-DVS/green plug for smart grid nonlinear loads," *Smart Energy Grid Engineering (SEGE)*, pp.1-6, 2015.

[3] T. Short, "Distribution reliability and power quality," United States: Crc Press, 2005.

[4] F. Zaro, M. Abido, "Real-Time Detection and Classification of Power Quality Problems Based on Wavelet Transform," *Jordan Journal of Electrical Engineering*, vol. 5, no. 4, pp. 222-242, 2019.

[5] O. Ipinnimo, S. Chowdhury, S.P. Chowdhury, J. Mitra, "A review of voltage dip mitigation techniques with distributed generation in electricity networks," *Electric Power Systems Research*, vol.103, pp. 28-36, 2013.

[6] A. Rana, I. Trivedi, C. Vasoya, M. Pandya, S. Gohil, P. Saradva, "Application of D-STATCOM for power quality improvement in distribution line," *International Conference on Computation of Power, Energy Information and Commuincation, Chennai*, pp. 719-725, 2016.

[7] S. Bhim, R. Sabha, V. Pankajkumar, "An implementation of double-frequency oscillation cancellation technique in control of DSTATCOM," *International Transactions on Electrical Energy Systems*, vol. 24, no. 6, pp. 796-807, 2013.

[8] C. Liu, Y. Hsu, "Design of a self-tuning PI controller for a STATCOM using particle swarm optimization," *IEEE Transactions on industrial Electronics*, vol. 57, no. 2, pp. 702-715, 2010.

[9] P. Kamaraj, T. Thamizharasu, "Voltage regulation of soft switched interleaved boost converter using fuzzy proportional integral controller," *Journal of Energy Systems*, vol. 4, no. 4, pp. 145-160, 2020.

[10] S. Alqam, F. Zaro, "Power Quality Detection and Classification Using S-Transform and Rule-Based Decision Tree," *International Journal of Electrical and Electronic Engineering & Telecommunications*, vol. 8, no. 1, pp. 45-50, 2019.

[11] M. Labeeb, B. Lathika, "Design and analysis of DSTATCOM using SRFT and ANN-fuzzy based control for power quality improvement," *IEEE Recent Advances in Intelligent Computational Systems, Trivandrum, Kerala*, pp. 274-279, 2011.

[12] A. Nabisha, X. Joseph, "Power Quality Enriched Wind Energy System using DSTATCOM based on PID-ANN Controller," *American-Eurasian Journal of Scientific Research*, vol. 12, no. 5, pp. 271-284, 2017.

[13] Babaei M, Jafari-Marandi M, Abdelwahed S, Smith B. A simulated Annealing-based optimal design of STATCOM under unbalanced conditions and faults. *Power and Energy Conference at Illinois (PECI)*, pp. 1-5, 2017.

[14] F. Zaro, "True Multi-Objective Optimal Power Flow in a Deregulated Environment Using Intelligent Technique," *Journal of Engineering Research and Technology*, vol. 3, no. 4, pp. 110-118, 2017.

[15] S. Panda, N. Padhy, "Comparison of particle swarm optimization and genetic algorithm for FACTS-based controller design," *Applied soft computing*, vol. 8, no. 4, pp. 1418-1427, 2008.

[16] E. Beşikçi, O. Arslan, O. Turan, A. Ölçer, "An artificial neural network-based decision support system for energy efficient ship operations," *Computers & Operations Research*, vol. 66, pp. 393-401, 2016.

[17] S. Samadianfard, S. Jarhan, H. S. Nahand, "Application of support vector regression integrated with firefly optimization algorithm for predicting global solar radiation," *Journal of Energy Systems*, vol. 2, no. 4, pp. 180-189, 2018.