

Improving Power Quality by DSTATCOM Based DQ Theory with Soft Computing Techniques

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Abstract: The development of non-linear loads at consumers has significantly impacted power supply systems. Since, the poor power quality has been found in the three-phase distribution system due to unbalanced loads, harmonic current, undesired voltage regulation, and extreme reactive power demand. To overcome this issue, Distributed STATicCOMPensator (DSTATCOM) is implemented. DSTATCOM is a shunt-connected Voltage Source Converter (VSC) that has been utilized in distribution networks to balance the bus voltage in terms of enhancing reactive power control and power factor. DSTATCOM can provide both rapid and continuous capacitive and inductive mode compensation. A rectified resistive and inductive load eliminates current harmonics in a three-phase power supply. The synchronous fundamental DQ frame is a time-domain approach developed from three-phase system space vector transformations has been designed using MATLAB/Simulink. The DQ theory is used to produce the reference signal for the Pulse Width Modulation (PWM) generator. In addition, a traditional Proportional Integral Derivative (PID) controller is designed and compared with proposed soft computing approaches such as Fuzzy-PID and Artificial Neural Network (ANN-PID) and compared accurate reference current determination for Direct Current (DC) bus through DC link. An Analytical explores the proposed control strategies given to establish superior outcomes. Finally, total harmonic distortion analysis should be taken for performance analysis of the proposed system with IEEE standards.

Keywords: DSTATCOM; synchronous reference frame; fuzzy-PID; artificial neural network-PID; power quality issues

1 Introduction

A Distributed STATicCOMPensator (DSTATCOM) is used to compensate for Q and unbalanced loads in the distribution system. It is a shunt device that produces an Alternate Current (AC) voltage, injected through a shunt transformer into the system. In the control of DSTATCOM, traditional control schemes such as Proportional Integral (PI) controller and Proportional Integral Derivative (PID) controller are used. Still,



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now, intelligent controllers such as Fuzzy Logic Controllers (FLC) and Artificial Neural Network (ANN) are employed as alternative linear and non-linear control strategies.

The performance of a three-phase, two-level, and four-switch DSTATCOM is evaluated by modified synchronous reference frame theory based control scheme [1]. Dynamic Voltage Restorer (DVR) was unable to correct for voltage sag as well as D-STATCOM. The ability to produce the rated current at nearly any network voltage, more excellent dynamic responsiveness and a comparatively small capacitor on the Direct Current (DC) link are all advantages of DSTATCOM.

This control technique maintains the constant DC-link voltage, balances the split capacitor's voltage, and generates switching pulses for the DSTATCOM's four insulated-gate bipolar transistor switches to achieve the desired objective. The Perturbation and Observation algorithm is used to track the maximum power point and regulate the output voltage of the solar photo voltaic system. By integrating neural network control in DSTATCOM [2], it is possible to minimize harmonic value while balancing currents and maintaining power supply quality. ANN controller generates gate pulses for DSTATCOM's Voltage source converters. DSTATCOM uses the least mean square algorithm combined with the ANN and PI controller algorithms [3]. The algorithms for current harmonics and the demand for Q correction are also discussed. For the computation of weights, learning management system adaptive online estimator approach created on a neural network was used to measure reference currents.

The Synchronous Reference Frame (SRF) based controlling of the DVR is responsible for successfully compensating balanced and unbalanced voltage sags [4]. The capacitor DC link voltage control technique of the DVR is linked to the SRF-based control for effective DVR functioning. FLC is intended to detect voltage sag in power line distribution and executes online DVR switching in response to the sagging presented in the line. Artificial Intelligence (AI) leads to reducing the complexity and size of a control system [5], as ANN is also an efficient AI technique that has found a lot of application in regulating power electronics systems. The enhanced DSTATCOM control method is based on the separation of active power and symmetrical voltage imaginary components [6]. It can extract the current reference components successfully even when the source voltage is distorted, and a PI controller is employed for the improved control method. Undesired variables are regulated and distribution system performance is enhanced by modifying the device control approach [7]. PQ reference theory produces reference signals to control DSTATCOM to increase the power quality. Using an interval type 2 FLC DSTATCOM [8] in the system dramatically decreases overall harmonic distortion, and the recursive, least square filter, aids in fine-tuning it to sharp levels. Also, lowering the current harmonic at the source side aids in a significant reduction in overall harmonic distortion.

Reactive power is created and provided to the AC system by increasing DSTATCOM's output voltage [9]. DSTATCOM's terminal voltage magnitude may be controlled by altering the metal oxide silicon field effect transistor (MOSFET) firing angle. The SRF control strategy requires a PI controller to regulate the DC link voltage [10]. The PI controller needs accurately calculated model values, which can be challenging to get, and it may not provide satisfactory results if parameters, loads, and other factors vary. The Fuzzy C-Means clustering technique [11] which is a fuzzy c-means clustering is a soft clustering method in which each data point is allocated a probability or likelihood score to belong to that cluster. It creates a suitable weight to regulate direct and quadrature axis currents of DSTATCOMs as described in the ANN controller. The method was built by predicting each cluster in the data for each cluster corresponding to a weight that relates directly to the area in the space of both outputs and inputs. If the system is linear, the PI controller may be tuned by the trial and error method [12]. This tuned method is used for sophisticated plants with higher orders, and specific tuning approaches must be used. Particle Swarm Optimization (PSO) is one of the approaches for tuning a PI controller that is accessible.

One of the forms of power quality issues is the harmonics problem [13]. A DSTATCOM controller based on discrete-time multilayer neural networks was described. The network weights were constantly adjusted

based on the closed-loop system's filtered error. A DSTATCOM provided shunt compensation in a classic series to reduce harmonics. The PSO is used to determine the optimal DSTATCOM controller gains, as well as the ANN is employed as an AI technique to control the DSTATCOM in real-time [14]. Compared to traditional control techniques, the developed ANN controller enables DSTATCOM with a robust tuning system [15]. It responds to various real-time voltage fluctuations in the distribution system with effective voltage profile improvement. Further DVR & DSTATCOM are used to reduce voltage sag or swell in distribution systems [16]. The DVR and DSTATCOM are linked in series and shunt with the line, injecting or absorbing reactive power to correct for voltage sags or swells in the distribution network and maintaining a smooth voltage level at the load end. Due to the expansion of disruptive loads in electric power networks, the challenge of evaluating power quality has become a critical need [17]. Unfortunately, identifying the origins of system disruption cannot always be accomplished by taking measures in a single metered portion of the electric network.

A new control mechanism for hybrid AC-DC microgrids, constructed on fuzzy control in D-STATCOM, is presented to minimize the unbalance voltage and solve the system's power quality problems. These problems arise from exposing the intended power system to unanticipated fluctuations, such as developing a three-phase fault or abrupt dynamic load fluctuations. This paper presents the DSTATCOM-based SRF/DQ theory using PID, Fuzzy-PID and ANN-PID controllers. The DSTATCOM-based SRF with the controllers has been analyzed using MATLAB/Simulink software. Also, a comparative analysis of the controller's Total harmonic distortion (THD) is illustrated.

2 System Configuration

A STATCOM is also called STATCON (STATicCONDenser). This is a FACTS device connected in parallel to the system (Shunt active filter) used to solve the power quality issues. A DSTATCOM is a VSC-based device with a V_s contained behind such a reactor. Because the V_s is derived from a DC link capacitor (C_{dc}), a DSTATCOM has relatively low P capabilities. However, connecting an appropriate energy storage device across the C_{dc} can enhance its P capability. The Q at the DSTATCOM terminals is proportional to the amplitude of the V_s . For instance, if the VSC's terminal voltage is higher than the AC voltage at the Point of Common Coupling (PCC), the DSTATCOM generates reactive current; similarly, if the amplitude of the V_s is less than the AC voltage, it absorbs Q. A DSTATCOM's response time is faster because of the quick switching times produced by the VSC's MOSFET. Since the Q from a DSTATCOM decreases linear with the AC voltage, it provides greater Q support at low AC voltages. This involves current and voltage quality, load unbalanced problems such as unbalanced current at the PCC, reactive components and harmonic distortion. The DSTATCOM comprises a three-phase controlled VSC, DC link capacitor and an inductor, as shown in Fig. 1.

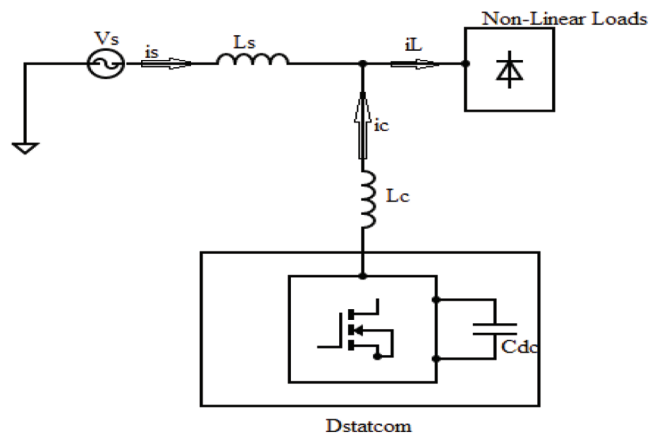


Figure 1: Schematic diagram of DSTATCOM

The capacitor acts as an active filter for stored energy. Due to the switching algorithm, energy can be transmitted from the C_{dc} to the inductor. The compensating principle of the DSTATCOM is constructed to compensate the current i_c from supply to the load. Because of this i_c , it eliminates the current harmonics and Q on the source side. Thus the source current (i_s) can be purely sinusoidal and in phase with source voltage (V_s).

2.1 SRF Control

The SRF control, commonly called DQ control, is primarily based on a reference frame transformation unit that converts the utility grid's current and voltage characteristics to a synchronously rotating reference frame. The Clarke and Park transformation procedures, which convert abc to and dq, are used to accomplish this transformation. The SRF control method is based on the current transformations in the d-q frame. Shunt Active Power Filter (APF) sensed the source voltage (V_a, V_b, V_c). The PCC current (I_a, I_b, I_c) and the injected V_a, V_b, V_c are in phase. These voltages and source current can be converted into D-Q, shown in Fig. 2. The below equations can give a better understanding of the operating controller.

$$V_{ED}^* = V_D^* - I_D, V_{EQ} = V_Q - I_Q \quad (1)$$

$$V_{EQ}^* = V_Q^* - I_Q, V_{ED} = V_Q - I_Q \quad (2)$$

where, the DQ axes are represented revolving with an angular velocity equal to, the same as the phase voltages and currents. V_{ED} and V_{EQ} are the representation of rotating reference frame to a three-phase (abc) signal. The shunt APF signals are given to the PID controller to generate control signals, converted to the ABC domain for switching signals in PWM. It again provides the pulse to the shunt APF converter by synchronized decision.

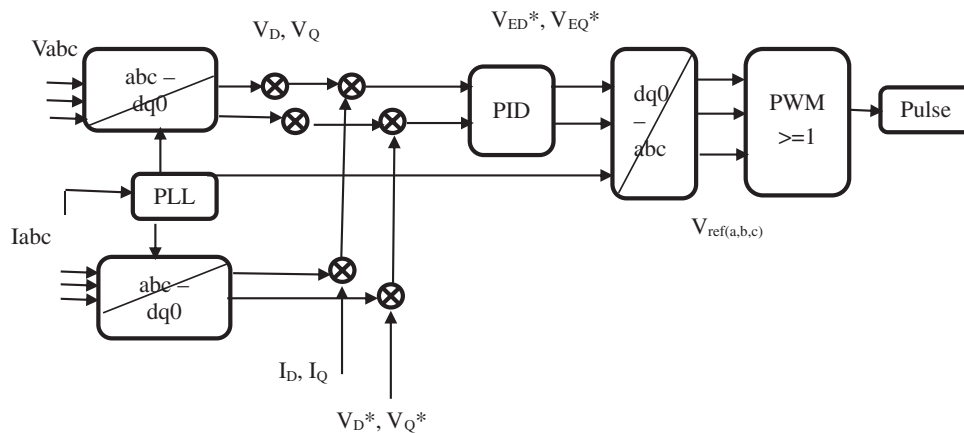


Figure 2: SRF control

The current components are generated in α - β coordinates using transformation angle θ . These can be transfers α - β to d - q frame is called the park's transformation.

$$\begin{bmatrix} i_a \\ i_b \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

SRF control extracts the DC component of i_d and i_q ; further, the dc components are extraction of i_{ddc} and i_{qdc} are transformed into an α - β frame, known as reverse park's transformation.

$$\begin{bmatrix} i_{\alpha dc} \\ i_{\beta dc} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} i_{ddc} \\ i_{qdc} \end{bmatrix} \quad (4)$$

The current transformation is obtained as i_{abc} . The compensation of 'Q' can be provided as it is zero to calculate the reference source current i_{refabc} .

3 Control Strategies

The function of DSTATCOM needs an AC supply to require real power (P) to the load and losses. So, the switching DSTATCOM is used to decide i_{refabc} by the load current component, which is extracted from SRF and the losses can be estimated using PID, Fuzzy-PID and ANN-PID control the DC link voltage (V_{dc}).

3.1 PID Control to Maintain the V_{dc}

A controller in a control system is a technique that attempts to reduce the difference between a system's actual value (i.e., the process variable) and its desired value (i.e., the setpoint). All sophisticated control systems require controllers; these are critical points of control technique. The second-order active reference current is compared with reference V_{dc}^* and sensed V_{dc} is a voltage error in nth sample $V_{dc(error,n)}$, which is expressed below,

$$V_{dc(error,n)} = V_{dc(n)}^* - V_{dc(n)} \quad (5)$$

$V_{dc(error,n)}$, which is progressed in PID control, the output $I_{out(n)}$ in the n^{th} sample,

$$I_{out(n)} = I_{out(n-1)} + K_{pdc}(V_{dc(error,n)} - V_{dc(error,(n-1))}) + K_{ids}(V_{dc(error,n)}) + K_{ddc}(V_{dc(error,n)}/dt) \quad (6)$$

where K_{pdc} , K_{ids} , and K_{ddc} are 1, 0.5 and 0.001 are the gains of the PID controller. The PID controller's output is considered the current loss component of the DSTATCOM. This can be added to the d-axis of the current.

3.2 Fuzzy-PID Control to Maintain the V_{dc}

A Fuzzy-PID is used to regulate V_{dc} in DSTATCOM. The fuzzy rules are consequences of the knowledge of the system's behavior, whereas mathematical modeling is needed to incorporate into the system. Capacitor voltage (V_c) and reference voltage (V_{dref}) are compared. Fuzzy control has the input variables like error (e) and change in error (Δe), which is taken from V_c . the n^{th} sampling of the system time is expressed below,

$$e(n) = \alpha(V_{dc}(n) - V_{dref}) \quad (7)$$

$$\Delta e(n) = \beta(e(n) - e(n-1)) \quad (8)$$

where α and β are the scaling factors of the input.

$$I_{adj}(n) = I_{adj}(n-1) + \gamma \cdot \Delta I_{adj}(n) \quad (9)$$

Then the ΔI_{adj} is the output of the change in adjusting the current, I_{adj} is the actual adjusting current and γ scaling factor of the output. The I_{adj} is supplied to the converter loss, and it will include the peak value of the i_{refabc} . The fuzzy control adds appropriate rules that narrate the input variables to the output model. Here, the inputs and output were selected to the triangle type Membership Functions (MF). This arranged MF can be combined with (e) and (Δe), each seven MFs are applied, where the error MFs are NL, NM, NS, Z, PS, PM and PL are negative large, negative medium, negative small, zero, positive small, positive medium and positive large respectively. Then the Δe are negative high (NH), negative moderate (NM), negative low (NL), zero (Z), positive low (PL), positive moderate (PM) and positive high (PH). And the output MFs

are zero (Ze), low (L), average (A) and Positive (P). In this way, time can be reduced. The input membership functions are shown in Fig. 3.

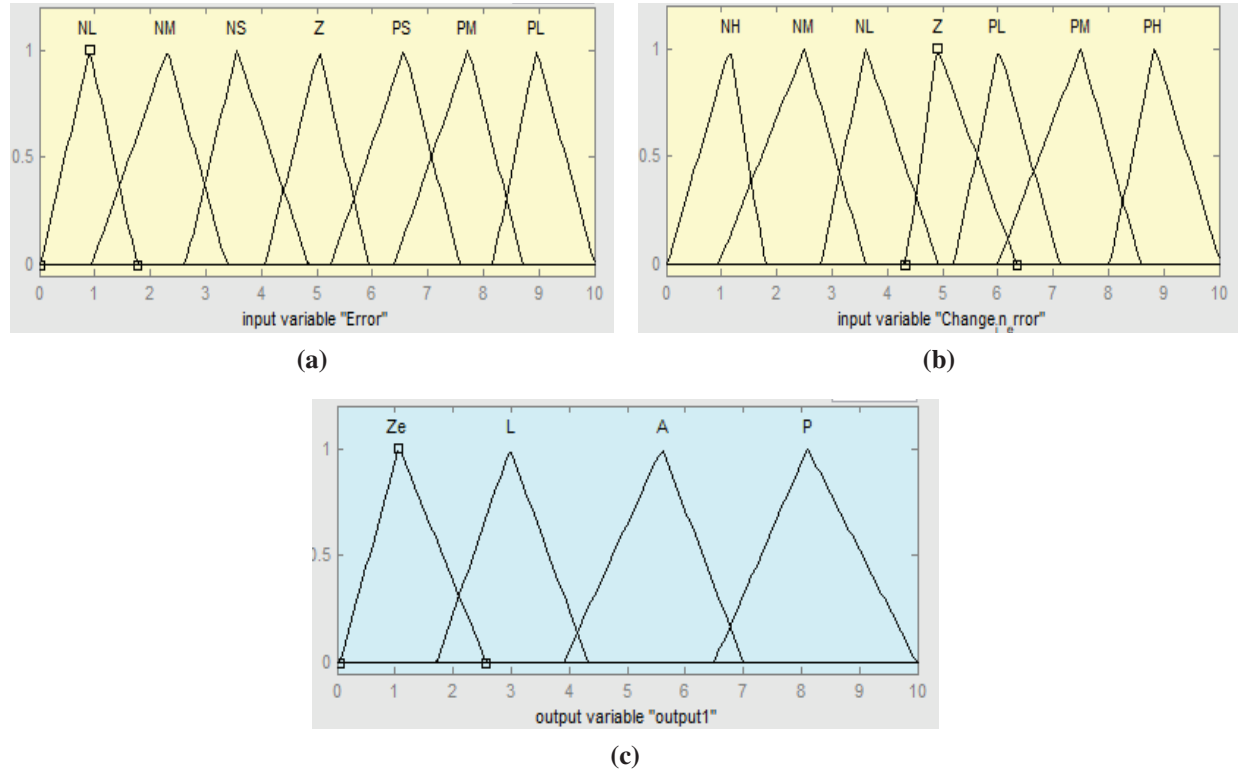


Figure 3: MFs of the fuzzy control (a) input variable 1, (b) input variable 2 and (c) output variable

The input MFs can ensure that the converter output voltage with the 49 rules is derived, as shown in Tab. 1.

Table 1: Rules for the fuzzy control

		Δe					
e	NH	NM	NL	Z	PL	PM	PH
NL	P	P	P	A	Z	L	Z
NM	P	P	A	Z	Z	Z	L
NS	P	A	L	Z	Z	L	L
Z	A	L	L	Z	L	L	A
PS	L	L	Z	Z	L	A	P
PM	L	Z	Z	Z	A	P	P
PL	Z	L	Z	A	P	P	P

Then the attained values from fuzzy can be given to the PID control. It can be further tuned the required value to the DSTATCOM.

3.3 ANN-PID Control to Maintain the V_{dc}

In this ANN control, the data can be trained with initial inputs and targets from the presented system, as shown in Fig. 4. The input and output data were taken from the simulated DSTATCOM design with SRF control. The gained data can be imported to the input and targets in the nf tool. The data can be trained from the model of DSTATCOM implementation, which has been trained from the multi SRF technique.

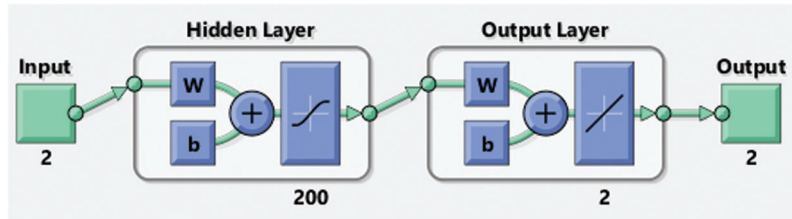


Figure 4: ANN tool for ANN control

Then select the samples in matrix rows. After that, validation and test data should be checked with 15% of 1810 samples of 2 inputs and 200 hidden layers of the neurons with two output layers. Finally, train the system.

The load can sense the reference current. Then the waveform can be expressed by Fourier analysis,

$$f(t) = \sum_{n=1,2,\dots,N} [X_n \cos(n\omega t) + Y_n \sin(n\omega t)] \quad (10)$$

where X_n and Y_n are the n^{th} harmonics component of cos and sin amplitude,

$$f(t) = W^T \bullet X(t), \quad (11)$$

The sample singles are arranged with a uniform rate (Δt). W^T is the weighting vector. $k\Delta t$ is the discrete-time, $k = 1, 2, \dots$. $X(t)$ is the model signal and $f(t)$ is the actual signal. Then inserted data can be estimated make to upgrade the weights. Hence, the estimated signal $f_{esti}(t)$ can converge to the optimum. The neurons taking the W^T are given by

$$\text{Where, } W^T = [X1, X2, \dots, X_N] X(t) = \begin{bmatrix} \cos \omega t \\ \sin \omega t \\ \dots \\ \dots \\ \dots \\ \cos N\omega t \\ \sin N\omega t \end{bmatrix}$$

Here the error $e(k)$ can be expressed as,

$$e(k) = f(t) - f_{esti}(t) \quad (12)$$

The attained weight is used as the next iteration $W_{(k+1)}$ to minimize the (k) . Likewise, the iteration can be processed until the actual signal can be attained from estimated signals. Then the estimated signal can be given to the PID control to tune the gained values further to regulate the V_{dc} of the DSTATCOM.

4 Simulation Model of DSTATCOM System

The simulation of the DSTATCOM system is designed using MATLAB/Simulink in the Simscape platform, which is shown in Fig. 5. This simulation can be configured with a three-phase source, DSTATCOM, Controllers and load. The Non-linear load is considered the load consisting of the universal bridge, resistance (R) and inductance (L) integrated into series and parallel with each phase. The three-

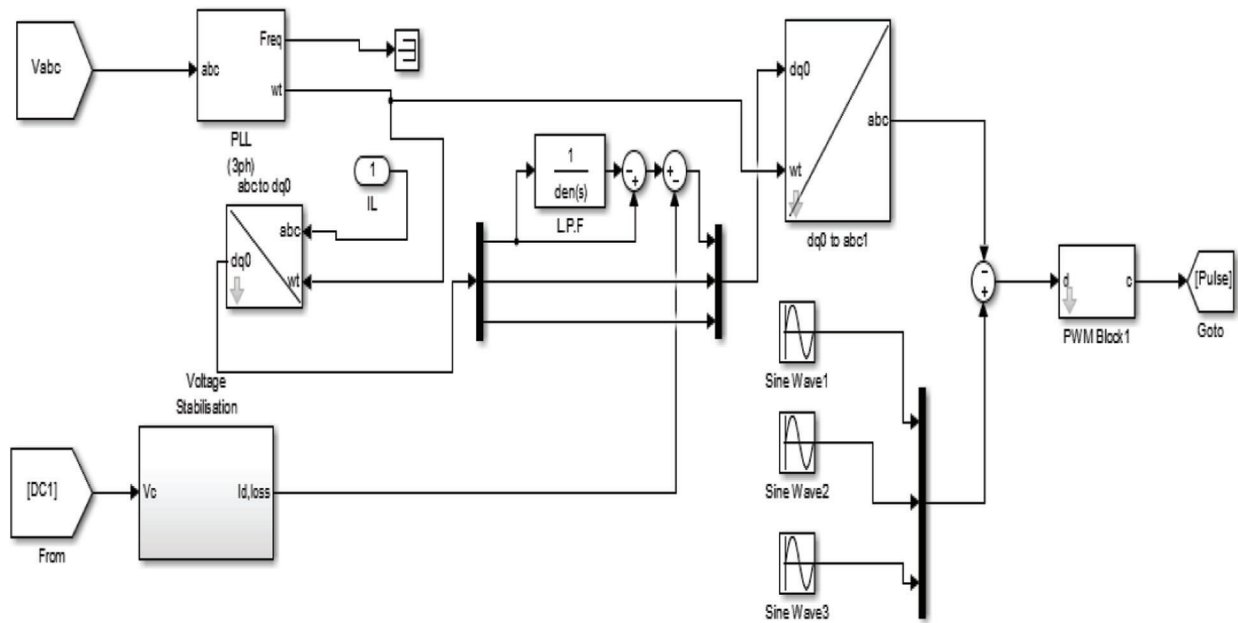


Figure 6: Simulation diagram of SRF control

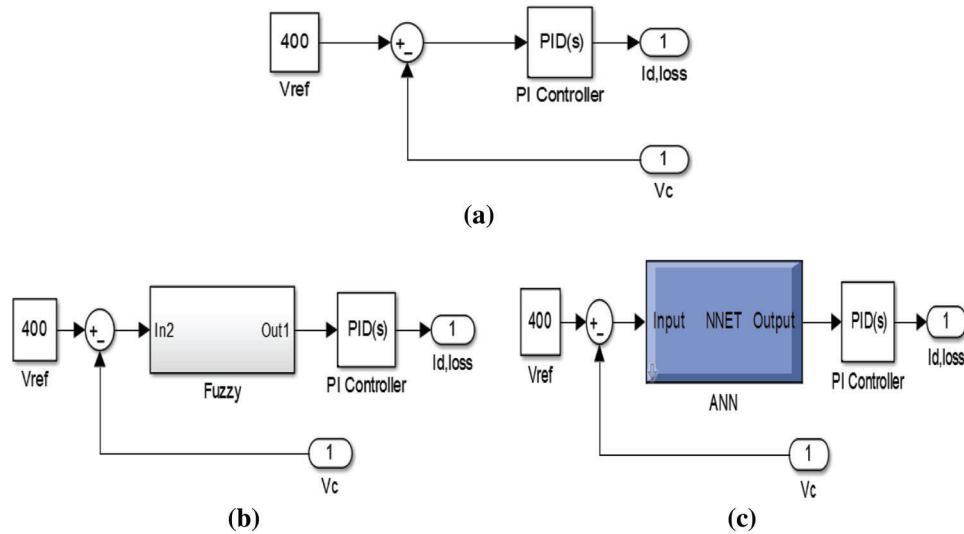


Figure 7: Simulation blocks of controllers (a) PID, (b) Fuzzy-PID, (c) ANN-PID

Fig. 8 illustrates the V_s and I_s , which means without compensation. The V_s and I_s are 300 V and 11 A, respectively. At the fault period, the V_s and I_s can be unbalanced. So the voltage can be decreased from 300 to 250 V and the current is unbalanced from 11 to 60 A. Fig. 9 shows the received accurate results in voltage and current waveform magnitude.

The voltage is decreased and the current is increased due to the inductive nature of the load, which receives a significant amount of power from the supply side. Also, the system's P is increased from 5.7 to 12 kW and Q is decreased from 3.2 to -10 kVAR at 0.4 to 0.6 s because of the unbalances.

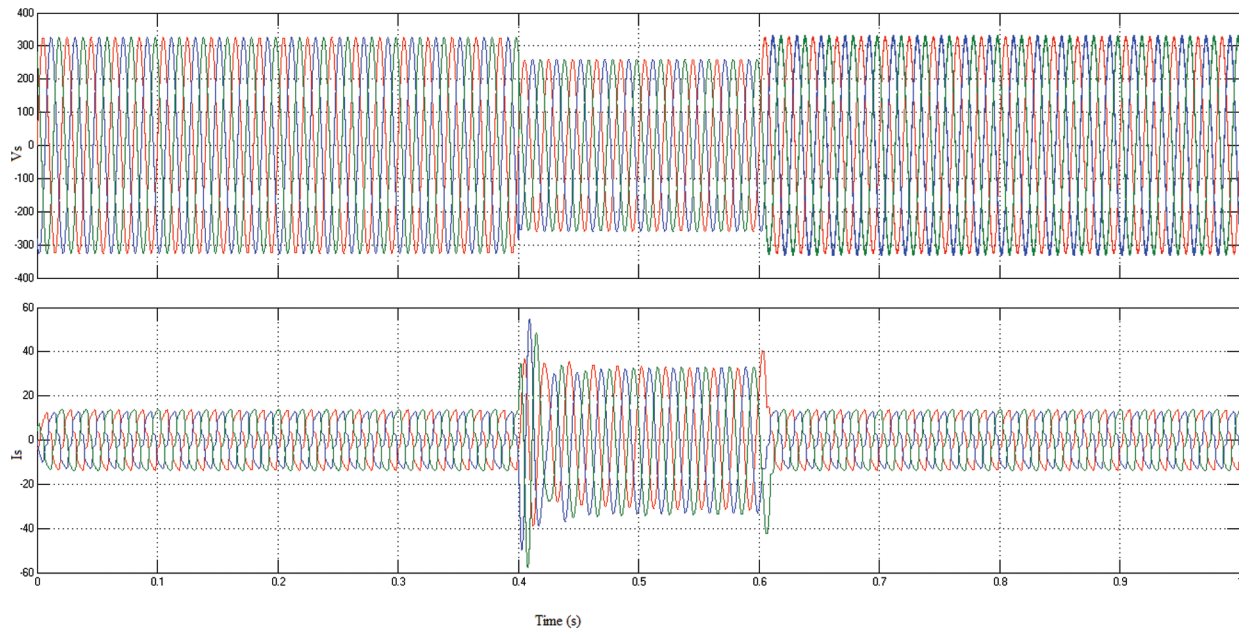


Figure 8: V_s and I_s of the DSTATCOM based SRF

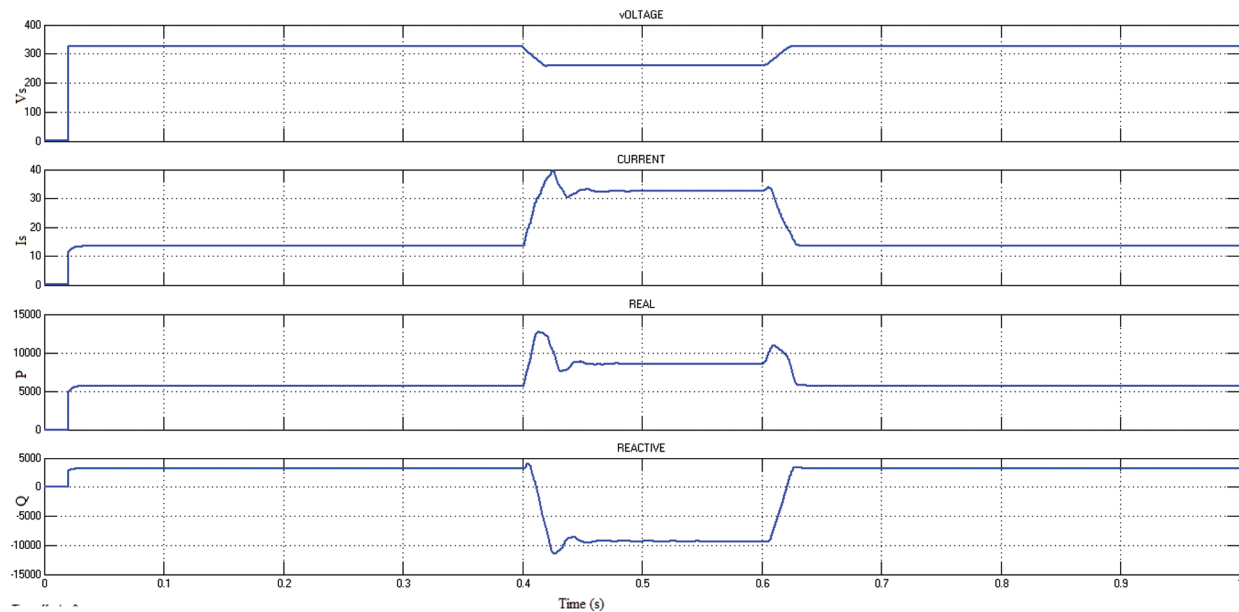


Figure 9: P and Q of the DSTATCOM based SRF without compensation

The dynamics are displayed in reverse order after 0.6 s. I_L waveforms show a delay in compensating. The Low Pass Filter (LPF) causes this delay used to filter power signals. An LPF has a cut-off frequency that determines which frequencies are allowed to pass and which are filtered. A signal component would pass if its frequency is less than the cut-off frequency, or it would be filtered. These filters are employed to reduce circuit noise. When a sound is sent via LPF, most of the noise is eliminated, leaving a clean sound. Furthermore, SRF theory-based PID computes instantaneous P and Q using voltage signals. Any

voltage distortion or unbalance will consequence in an incorrect computation of $i_{ref,abc}$ should only include the true fundamental frequency component of the current of the load.

Fig. 10 shows that the DSTATCOM-based SRF uses PID control; this waveform represents the V_L , I_L , P and Q. At 0.4 s, the load was raised from 300 to 350 V, and the unbalance was introduced at 0.4 s. This waveform shows the compensation of the voltage and current due to the injection of Q by the DSTATCOM. In compensation, P is 5.5 to 7 kW with a slight peak at 0.45 s; Q is 2.4 to 1.6 kVAR at 0.4 to 0.6 s.

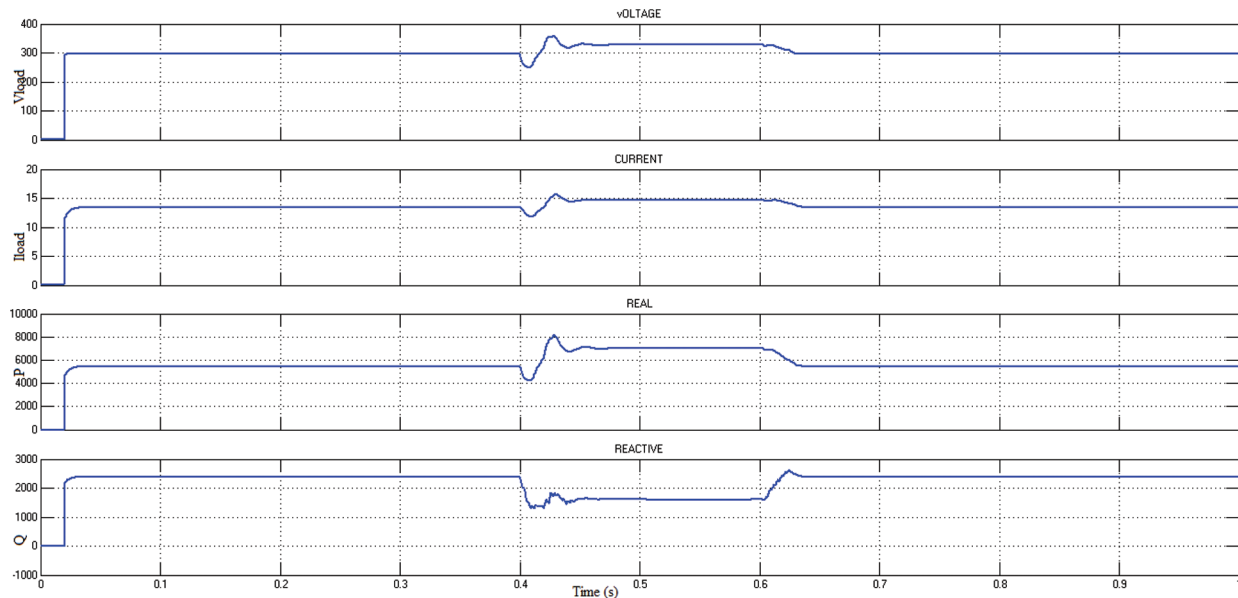


Figure 10: Waveform of DSTATCOM based SRF using PID

After that, a Fuzzy-PID controller is proposed to control the unbalances. Simultaneous load adjustments and imbalanced circumstances are simulated as in the preceding scenario. The extracted reference current waveform shows the influence of delay caused by the LPF utilized in the DQ frame signal filtering. The development of voltage is essential in calculating $i_{ref,abc}$.

Fig. 11 presents the magnitude of the voltage, current, P and Q. This waveform differs from the unbalances by using a PID controller, because, this Fuzzy-PID is pretty more accurate. The magnitude of the voltage and current can be balanced due to the injection of Q at corresponding ranges of 300 V and 13.5 A.

The ANN-PID extractor has the benefit of requiring less computing effort, making implementation of this approach considerably simpler. Furthermore, ANN-PID has intrinsic linearity which is the models having non-linear parameters, but they can be converted into linear regression models with the appropriate transformation that enables it to a quick solution. Fig. 12 depicts DSTATCOM's utilizing ANN-PID.

It can be seen that DSTATCOM with SRF-based ANN-PID is sufficient to meet load fluctuations within a one sine wave. Using this technique, the unbalance load voltage is compensated from 250 to 310 V at 0.4–0.6 s. Likewise, the load current also compensated from 60 to 11 A at 0.4–0.6 s. Here the injection of Q is 2.4 to 2.2 kVAR. In this technique, the Q injection is low than in other techniques, which shows that the voltage and current are balanced and maintain the power quality, which leads to a unity power factor. If

the power factor is lesser than one, then the load current will be higher and so the unity power factor is maintained. It also prevents transformers, motors, and other electrical components from overheating. The unity power factor develops even though there is no phase shift across voltage and current or when they are both in the same phase. When the power factor is one, the primary power source is doing beneficial work. In this situation, no electricity is being wasted. Shallow losses occur at the unity power factor. Whereas the system can be stable at the unity power factor, due to power quality issues, the system may unbalance, which is explained above, which leads to 0.8 PF.

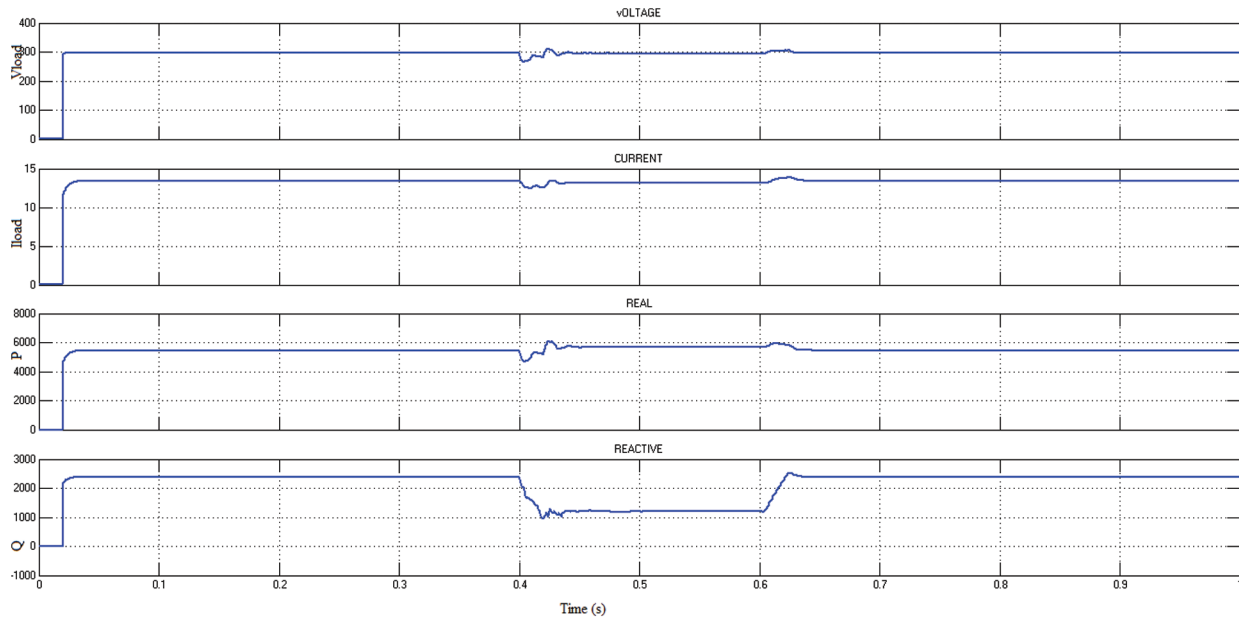


Figure 11: Waveform of DSTATCOM based SRF using Fuzzy-PID controller

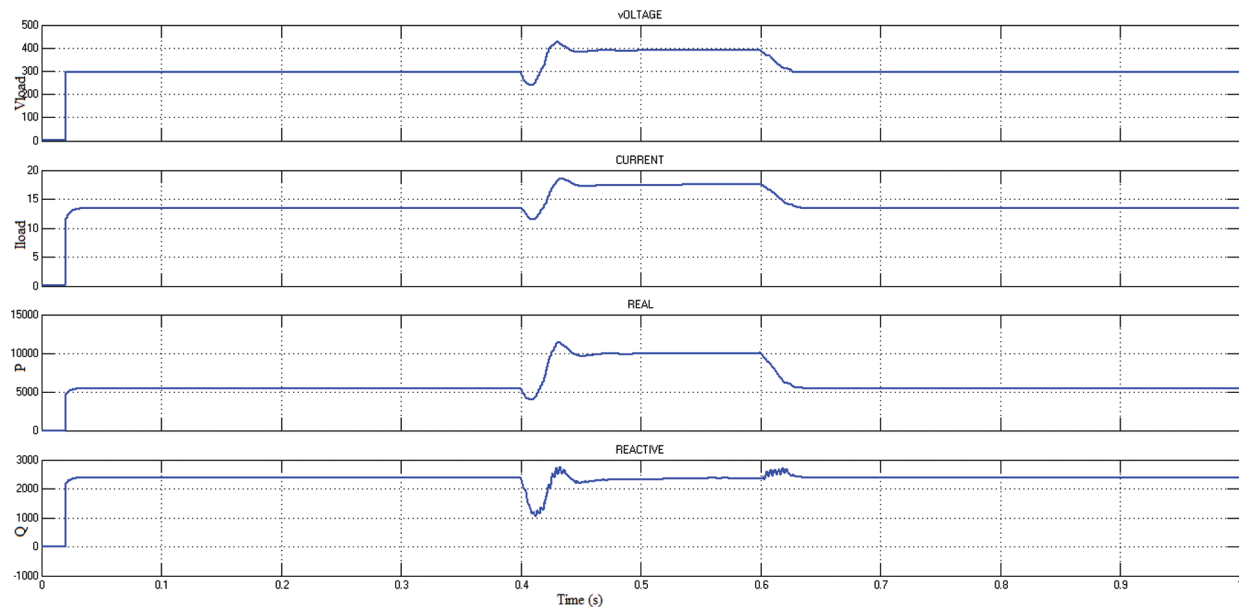


Figure 12: Waveform of DSTATCOM based SRF using ANN-PID controller

Fig. 13 shows that the power factor, the first waveform represents that the without compensated unbalanced system's PF is 0.8, mainly at the fault time the PF is further reduced. After compensation of the unbalanced load, PF is 1 and still 1 PF at 0.4 to 0.6 s. Comparative THD analysis of the DSTATCOM-based SRF using various controllers.

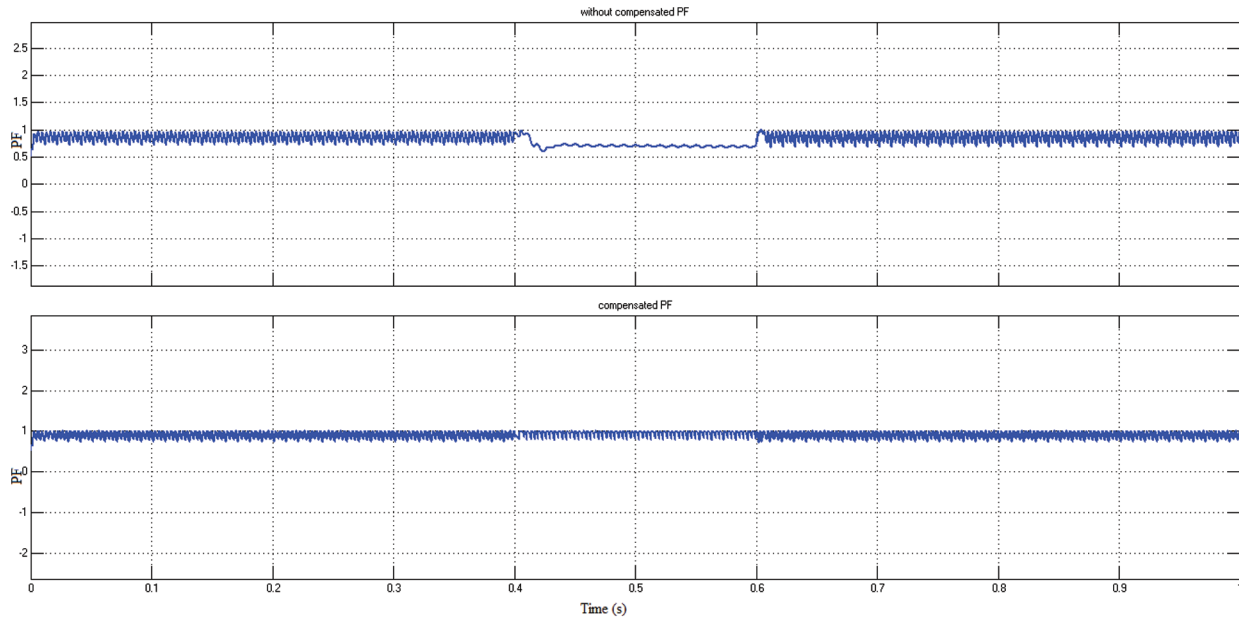


Figure 13: PF of the presented model

Total harmonic distortion (THD) is a measurement that indicates the voltage or current distortion caused by harmonics in the signal. It is defined as the ratio of the total of all harmonic components' powers to the fundamental frequency's power. Fig. 14 illustrates the THD analysis of the DSTATCOM-based SRF using soft computing techniques. The waveform shows that ANN-PID control has low harmonics, among other methods. PID control has more THD%, which is a conventional technique.

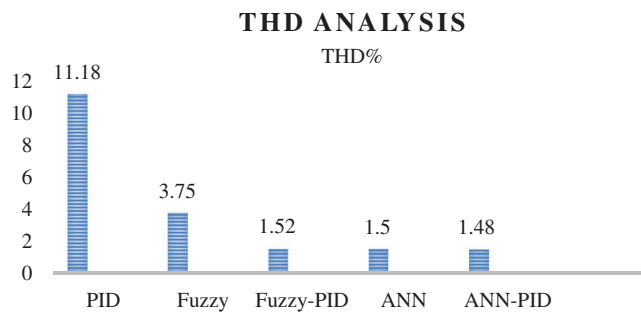


Figure 14: Comparative analysis of THD%

6 Conclusions

Improving power quality is essential because of the increasing use of electronic devices more vulnerable to electrical interference. This article recommended implementing DSTATCOM to enhance power quality in the distribution system. The SRF control, which is time domain-based, is presented here. Furthermore, soft

computing approaches such as Fuzzy-PID and ANN-PID are proposed to improve power quality concerns. The proposed controllers are compared to classic PID, Fuzzy, and ANN controllers. The proposed system is simulated in MATLAB/Simulink, demonstrating that the DSTATCOM-based SRF has a rapid reaction and precise load adjustment utilizing Fuzzy-PID and ANN-PID controllers. It is observed that DSTATCOM-based SRF with ANN-PID control offers THD of 1.48%. To overcome the complexity of the presented system, the future scope of this work is to mitigate the power quality issue using Genetic Algorithm (GA)-PID control and metaheuristic optimization techniques for more effectiveness.

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