JOURNAL OF SUSTAINABLE ENGINEERING AND TECHNOLOGY

Journal homepage: www.joset.com.ng

A Technical Review of the Basic Topologies and Control Strategies for DSTATCOM in Mitigating Power Quality Problems

Adamu Sa'idu [1, 2], Nasiru B. Kadandani[1], Bala Boyi Bukata[1]
[1] Department of Electrical Engineering, Faculty of Engineering, Bayero University, P. M. B. 3011, Kano, Nigeria
[2] Department of Electrical/Electronic Technology Education, School of Secondary Education (Technical), Federal College of Education (Technical) Bichi, P. M. B. 3473, Kano, Nigeria

ARTICLE INFO

Article History
Received: 28 Oct 2024
Accepted: 31 Dec 2024
Published: 18 April 2025

Corresponding Author:
Adamu Sa'idu
Bayero University, Kano
adamugiwa77@gmail.com

ABSTRACT

Power quality (PQ) problems in electric power systems signify an interesting field of study to researchers. The increased use of power electronics devices have led to improved system efficiency and performance, while conversely drawing nonlinear currents thereby creating signal disturbances in the power system network. The distribution static synchronous compensator (DSTATCOM) is one of the custom power devices used for mitigating power quality problems. This paper presents a technical review of the DSTATCOM employed for mitigation of such problems in the distribution corridor. The review intends to showcase a spectrum of DSTATCOM topologies and their associated control strategies for possible consideration by researchers and practitioners working in the area of PQ. Selection of a particular DSTATCOM design technique would depends on the type of the PQ problem that requires attention. The two major DSTATCOM topologies and their variants covered in this paper include power source topologies and inverter topologies, as presented under section 4. Lastly, this review on DSTATCOM portrayed its benefit to PQ stakeholders for enhancing quality of power at the distribution corridor.

Keywords: **:** *DSTATCOM · Power quality · Power distribution corridor · DSTATCOM topologies ·Control strategies*

1. Introduction

Power quality (PQ) problems are the main causes of reduced distribution system operational reliability and efficiency. As nonlinear and sensitive loads are increasingly being applied by assorted customers such as arc furnaces, medical and other computing and interfacing devices. Such devices have the tendency to inject or draw harmonic currents and voltages into and from the system, thereby polluting the power quality [1]. Additionally, due to unbalanced loads, the voltage waveforms of distribution systems are distorted, eventually impacting the customer's equipment operation [2]. Numerous PQ problems, such as harmonic distortions, poor power factor, noise, voltage sags, voltage swells, impulses, voltage unbalance, and voltage fluctuations have been reduced using custom power devices (CPD), for instance [3] which emphasized on the application of CPDs in correcting PQ problems. The CPDs are advanced techniques of mitigating power quality problems at the distribution level, developed in the advent of the Flexible alternating current transmission systems (FACTSs) devices typically used at the transmission level for enhancing system stability and transfer capacity of the transmission lines [4]. The basic idea of FACTs devices which is proposed in 1995 is to install the power electronic devices at the transmission side according to the power system grid to make the whole system electronically controllable [5]. FACTs devices are able to provide active and reactive power to the grid rapidly at the transmission side. The power compensation achieved by FACTs devices could adjust the voltage profile of the whole system and the power flow could be satisfactorily controlled. Generally, some of the first generation FACTs devices include tap changing and phase changing transformer, series capacitors and synchronous generators while Static Var Compensator (SVC) and Thyristor-Controlled Series Capacitor (TCSC) are some of the second generation FACTs devices as described in [5]. The CPDs have been identified to offer good practical solutions to power quality problems at the distribution corner [6]. The CPDs can be classified into: 1) Reconfiguration network comprising of static current limiter (SCL), static transformer switch (STS), solid state breaker (SSB), and uninterrupted power supply (UPS), and 2) Compensation network, typically involving the dynamic voltage restorer (DVR), distribution static compensator (DSTATCOM) and unified power quality conditioner (UPQC) normally connected to the system through the point of common coupling (PCC) either in series, parallel or both [7]. The DSTATCOM is a shunt device connected at the PCC ahead of a coupling reactance to compensate for voltage and provide reactive power support by injecting or absorbing reactive current. It has a very short response time to faults at higher capacitive reactive power and zero delay in the range of (<10ms), which goes proportional to the square of the voltage when compared to static VAR compensator (SVC) and takes about 40ms due thyristor switching [8]. Of all CPDs, DSTATCOM has played a significant role in curbing PQ problems as noted in [9]. DSTATCOM works in two control modes viz; the current controlled mode and the voltage controlled mode. In the current controlled mode, it is used to inject harmonic currents and compensate for reactive components, while it is used to regulate the voltage at PCC and provide reactive power support in the voltage controlled mode [10, 11]. Practically the configuration selected for the DSTATCOM depends on the power quality problem that needs to be mitigated [12, 13].

The main objective of this paper is to provide a technical review concerning the topologies and control strategies involved in DSTATCOM designs for controlling PQ problems for prospective system designers and researchers in the field. Additionally, an extensive literature survey was also conducted with the view of achieving this objective. The remaining part of the paper is arranged as follows: - Section 2 covers an overview of DSTATCOM and its major components. Principle of operation of DSTATCOM is presented in section 3. Basic DSTATCOM topologies are covered under Section 4. Section 5 describes basic control techniques used in DSTATCOM. Section 6 presents the literature survey on the application of DSTATCOM in solving PQ problems. Section 7 presents the challenges and constraints of DSTATCOM. The proposed future research trends for DSTATCOM are presented in Section 8. Finally conclusion is drawn in Section 9.

2. An Overview of Distribution Static Compensator (DSTATCOM)

2.1 Circuit Configuration

DSTATCOM is a shunt device configured as a voltage source converter (VSC) or as a current source converter (CSC), and can be used for voltage control and reactive power support at the PCC [14]. It may be used as an inductor to absorb excess energy when the source power potential is greater than the demand, or as a capacitor to inject deficient energy gap when the load side is greater than the supply side. There is no DSTATCOM action required when the supply is equal to demand i.e., when the system is in equilibrium [15]. This is demonstrated in Figure 1. The main components of DSTATCOM include: a VSC, a DC energy storage unit, an output ripple filter, a coupling transformer, and a control block [14].

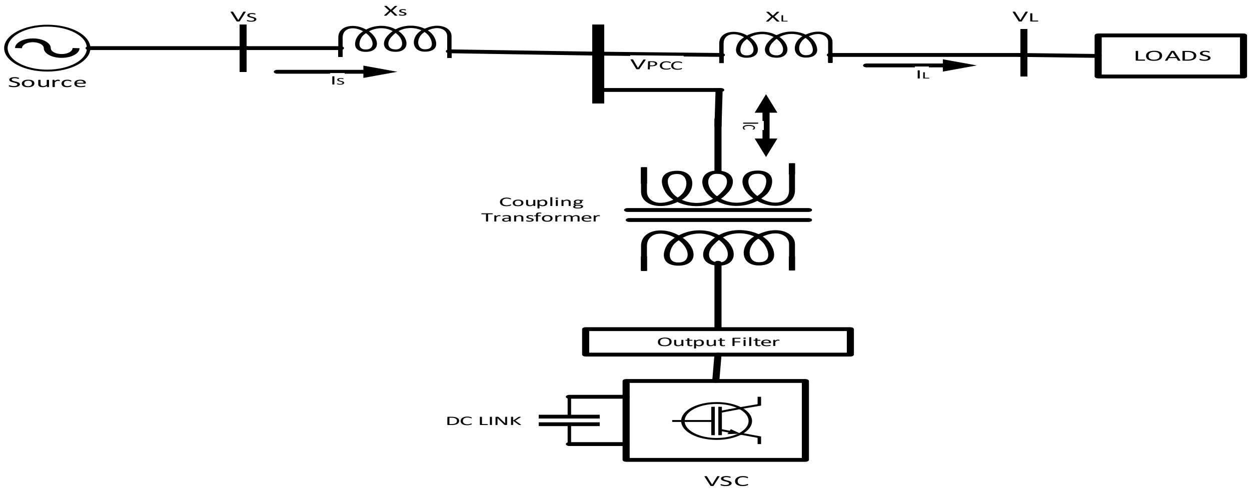

Figure 1. Schematic diagram of DSTATCOM [11]

DSTATCOM can compensate a bus voltage or a line current depending on the power quality problem. It can also compensate for active power disturbances by adjusting the angle, between DSTATCOM voltage and the system voltage [16, 17]. The active and reactive power injected or absorbed by the DSTATCOM can be calculated using equations (1) and (2) respectively.

$$P = \frac{V_{pcc}V_c}{X_{coupling}} \sin\delta \quad (1)$$

$$Q = \frac{V_{pcc}^2}{X_{coupling}} - \frac{V_{pcc}V_c}{X_{coupling}} \cos\delta \quad (2)$$

where P is the active power, Q represents the reactive power of DSTATCOM, V_{pcc} is the system voltage at PCC, V_c is the DSTATCOM voltage, and δ is the system transfer angle.

2.2 Components of the DSTATCOM Described

The various components of DSTATCOM include voltage source converter (VSC), DC bus capacitor and coupling transformer and ripple filter as shown in Figure 1. The VSC converts a dc voltage into a three-phase ac voltage and synchronized with PCC through a tie reactor and capacitor. The transformer is used to match the inverter output to the line voltage [18, 19]. The important components are described in the following subsections.

2.2.1 Voltage Source Converter

The VSC allows bidirectional power flow and realized using devices such as insulated gate bipolar transistors (IGBT) and metal oxide field effect transistors (MOSFET). The switching of these devices is based on pulse-width modulation (PWM) technique [20]. In addition to switching devices, VSC also has components like dc bus capacitor and interfacing inductor [21, 22]. The minimum dc bus voltage should be greater than twice the peak value of the phase voltage of the system. The value of dc capacitor depends on the instantaneous energy available to the DSTATCOM during transients [23]. The dc bus capacitor may also be used with two split sections having equal or unequal values [24]. The dc capacitor C_{dc} and dc bus voltage V_{dc} are calculated as

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \quad (3)$$

$$C_{dc} = \frac{6aVIt}{[V_{dc}^2 - V_{dc1}^2]} \quad (4)$$

where m is the modulation index; V_{LL} is the AC line voltage; a is the overloading factor; V is the phase voltage; I is the phase current; V_{dc1} is the phase voltage; t is the time by which the dc bus voltage is to be recovered.

2.2.2 Transformer

Unbalanced and nonlinear loads in distribution system cause problems of excessive neutral current. Transformers are used for neutral current compensation. Its effectiveness for compensating the neutral current depends on the system impedance and location of the compensator [25]. Transformers are used either in nonisolated condition for compensating the neutral current only or for providing isolation of the VSC along with neutral current compensation. The transformer topologies commonly used with DSTATCOM are zig-zag, star/delta, T-connected, and star/hexagon.

2.2.3 Ripple Filter

A first-order high-pass filter tuned at half the switching frequency is used to filter the high-frequency noise from the voltage at the PCC [26]. It consists of a series resistance R_f in series with the capacitor C_f [27, 28]. The time constant of the filter should be very small compared to the fundamental time period (T):

$$R_f C_f \ll \frac{T}{10} \tag{5}$$

2.2.4 AC Inductor

For reducing ripple in compensating currents, the tuned values of interfacing inductors are connected at the AC output of VSC [29]. The AC inductance L_f of VSC depends on the ripple current $i_{cr,p-p}$, switching frequency f_s, and DC bus voltage V_{dc} and its value is given as:

$$L_f = \frac{\sqrt{3} m V_{dc}}{12 a f_s i_{cr,p-p}} \tag{6}$$

where m is the modulation index and a is the overloading factor.

3. Principle of Operation of DSTATCOM

DSTATCOM is capable of compensating either bus voltage or line current. It can operate in two modes based on the parameter it regulates. DSTATCOM can be operated either as voltage control mode (VCM) or current control mode (CCM). In the VCM, it can make the bus voltage to be smoothly oscillating, irrespective of the unbalance and voltage distortion in the supply side or line current. In the CCM, it can force the source side currents to be smoothly oscillating. The performance of DSTATCOM is directly related to the design of power circuit components (such as DC – bus energy storage device, output filters and types of inverter), control algorithms used to estimate the compensation signals with less calculation, switching scheme to generate the switching pulses and stability of designed control algorithms [30].

Although the STATCOM has been applied for PQ improvement at the transmission corridor, DSTATCOM which is known for its size advantage, cost effectiveness, high bandwidth and load balancing capabilities has promptly taken over this role from the STATCOM at the distribution corner [17]. The contention that whether the DSTATCOM could resist additional pressure due to variability of loads characterizing distribution system also remains. This argument can be overcome by optimizing the DSTATCOM controller through computational intelligence.

The operating principle of DSTATCOM in voltage quality mitigation is to regulate the bus voltage by generating or absorbing the reactive power. Therefore, the DSTATCOM operates either as an inductor or as a capacitor based on the magnitude of the bus voltage. If the bus voltage (V_B) magnitude is greater than the rated system voltage (V_D) then the DSTATCOM acts as an inductor absorbing the reactive power from the rated system whereas if the bus voltage magnitude (V_B) is lower than the rated system voltage (V_D) then the DSTATCOM acts as a capacitor generating the reactive power to the system as depicted in Figure 2. The transition from capacitive to inductive mode is achieved by shifting the angle δ from zero to a positive value. The active power is transferred from the DC capacitor to the utility grid and causes a voltage drop in the DC – link. Again the transition from inductive to capacitive mode is obtained by shifting the angle δ from zero to a negative value. The active power is transferred from the utility grid to the DC capacitor and this causes a voltage rise in the DC – link [18].

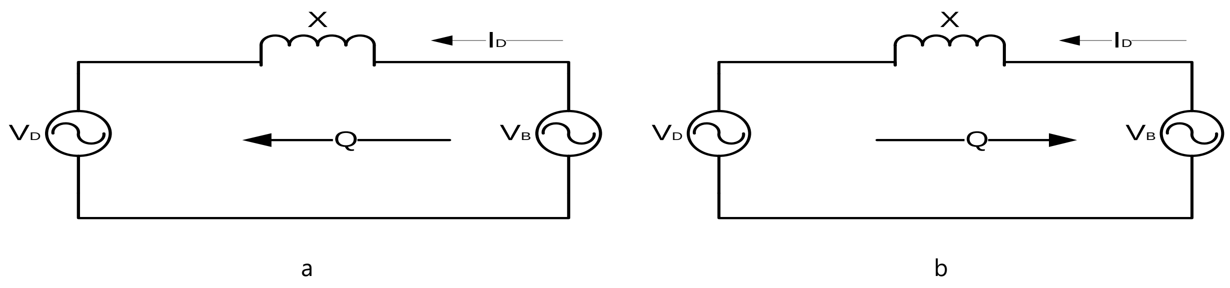

Figure 2. Operational principle of DSTATCOM (a) absorption (b) generation [18]

4. Basic Topologies of DSTATCOM

DSTATCOM topologies can be classified based on the application into three – phase three – wire (3P3W) and three – phase four – wire (3P4W) distribution systems. Further topological classification can be based on the use of transformer for isolation and neutral current compensation, number of switching devices, type of converter, etc. Figure 3 depicts the topological classification of DSTATCOM. The classification of DSTATCOM topologies is detailed in [31]. In topological diagrams the unbalanced/nonlinear loads as well as supply source are not shown, only the converter topologies and transformer configurations are included for the sake of clarity.

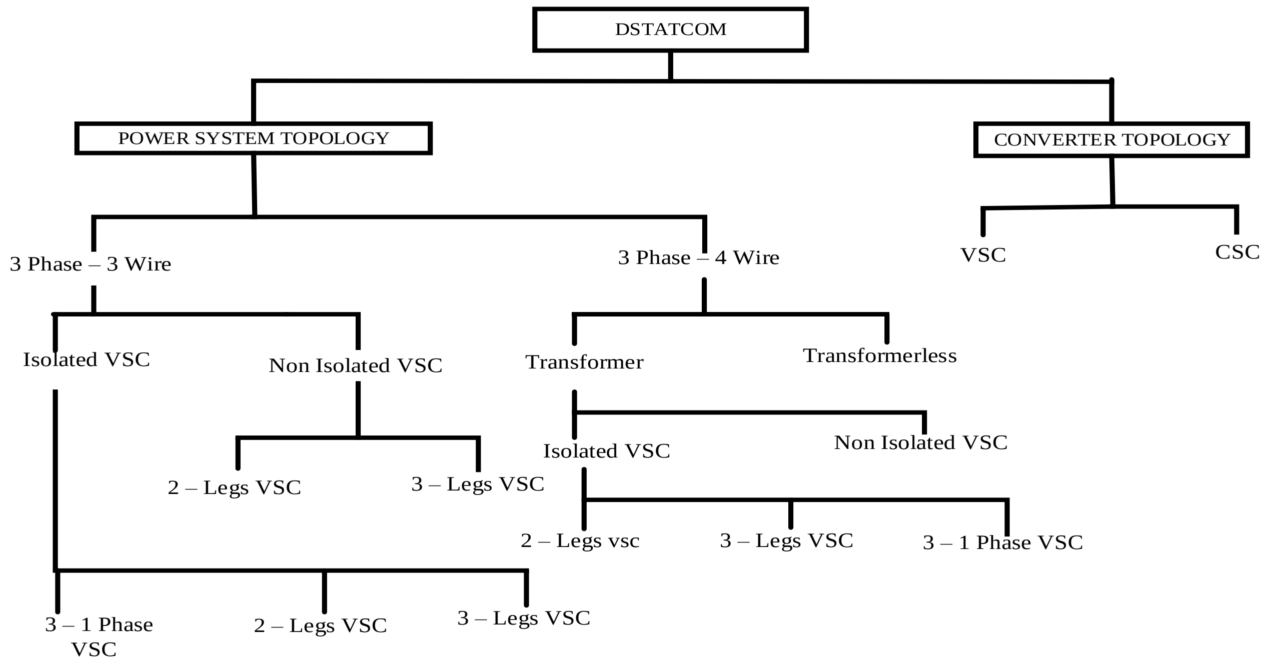

Figure 3. Topological classification of DSTATCOM

4.1 Three Phase - Three Wire (3P-3W) DSTATCOM

The 3P – 3W DSTATCOMs are used for reactive power compensation, harmonic elimination, PQ improvement and load balancing in 3P – 3W distribution system. The topologies for three-phase three-wire DSTATCOMs include isolated VSC and nonisolated VSC-based DSTATCOM as detailed in [31]. Three – leg VSC-based isolated topology of 3P – 3W DSTATCOM using star/delta transformer is shown in Figure 4.

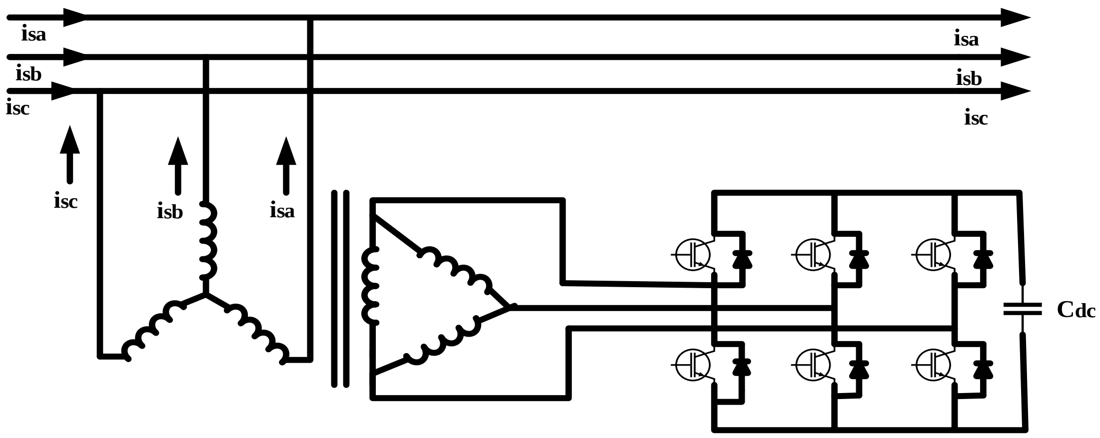

Figure 4. Isolated 3P – 3W 3 legs VSC based DSTATCOM topology [29]

4.2 Three Phase - Four Wire (3P – 4W) DSTATCOM

The 3P – 4W DSTATCOM is used in 3P – 4W distribution system to filter load current to meet out the specifications for the utility connection [32, 33]. This can be used to cancel the effect of poor load power factor (PF) such that source current has near unity PF, and provide harmonic compensation in loads, as well as compensate for unbalanced loads, cancel DC offset in loads and improve PQ. The three phase – four wire DSTATCOM topologies are mainly classified into two categories, with transformers and without transformers. Important topologies of 3P – 4W DSTATCOM are extensively discussed in [31]. The isolated three-legged VSC based having a DC bus with Star/Delta transformer is used as 3P – 4W DSTATCOM portrayed in Figure 5.

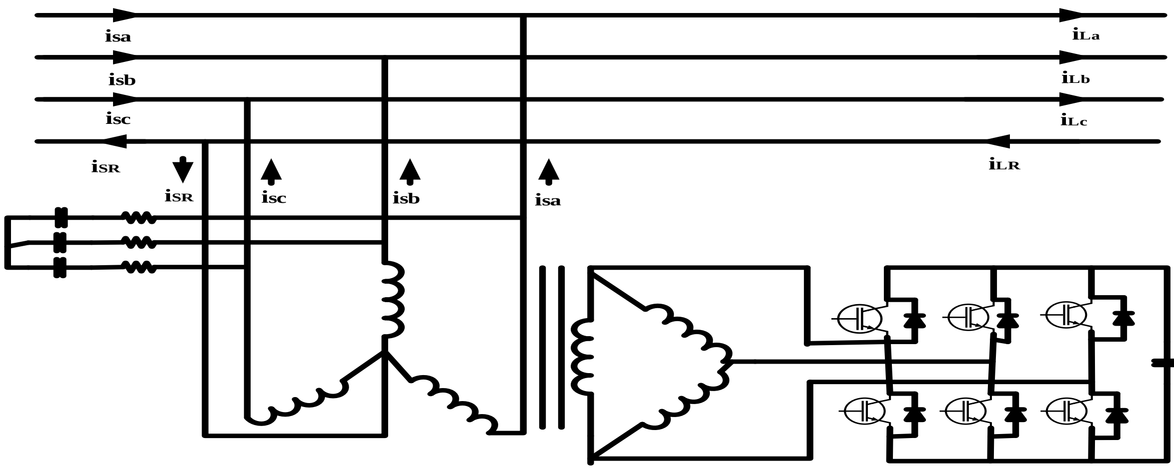

Figure 5. Isolated 3P – 4W 3 legs VSC based DSTATCOM topology [29]

5. Basic Control Techniques used in DSTATCOM

Solving PQ problems such as transients, flicker and undervoltage or overvoltage may be achieved through conventional use of capacitor banks, recloser circuit breakers or surge arresters at some specific locations. However, for the steady state operation of the system which faces the threats of major problems like sag, swell, interruption, imbalance and harmonic distortions, it is critical to stack the DSTATCOM with a strong structure that would account for the nonlinear dynamics arising from customer's loads. The performance of the system will improved by introducing DSTATCOM to intervene in both transient and steady state network operations. The steady-state is one at which tougher PQ disturbances like sags, interruption and harmonic distortions tend to maximize network attacks. However, the boring costs of PQ problems are becoming unbearable to the customers, utilities and other stakeholders in the power sector. Hence, search for more cost effective and robust DSTATCOM controllers capable of providing the required ride through for the future grid soon escalated. The efficiency of a DSTATCOM control algorithm depends upon its effectiveness in extracting the reference current signals [34]. Figure 6 describes a single line diagram of power system with control arrangement connected at PCC through DSTATCOM.

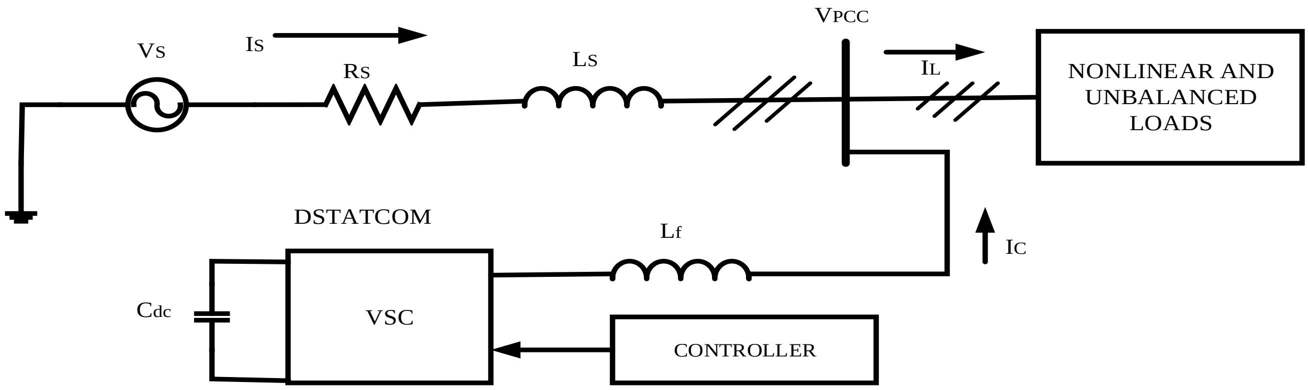

Figure 6. DSTATCOM control arrangement at PCC [34]

Many conventional control techniques such as synchronous reference frame (SRF), instantaneous reactive power theory (IRPT), symmetrical component theory, average unit power factor, hybrid least mean square - least mean fourth (LMS - LMF) and leaky LMS current control have been studied in [35] which uses filters to obtain the reference current signals from the load currents. Phase locked loops (PLL) have also been used to extract the reference current signals. However, intelligent techniques such as PI controller, PID controller, model predictive control, sliding mode control, artificial neural networks, Fuzzy logic control have gained prominence for the control of DSTATCOM. They provide good transient response than the conventional controls as the parameters are automatically adjusted according to the system dynamics [36] and are easy to implement with basic mathematical operations.

An overview of the various traditional as well as intelligent control strategies applied to DSTATCOM for improving power quality and their underestimating difficulties are presented in the following subheadings.

5.1 Instantaneous Reactive Power (IRP) Theory

Instantaneous reactive power theory has been initially proposed by Akagi in 1983 [37]. The hypothesis is based on the conversion of three-phase quantities to two-phase quantities in $\alpha - \beta$ frame and the estimate of instantaneous active and reactive power in this frame [38]. Figure 7 shows a building block of this theory. In IRP method real and reactive power components are required. By utilizing Clarke transformation, 3-stage signals are changed to 2-stage segments, and these 2-stage current and voltage segments are utilized to appraise PQ segments. This proposed algorithm has three phase load currents and three phase load voltages coupled at the point of common coupling. IRP theory having high computational complexity as it requires complex transformation and also dealing with the power components has the disadvantages of delay in computation due to low pass filter (LPF) used for filtering power signals. It also uses voltage signals to compute instantaneous active and reactive powers if any variations in supply voltage causes inaccurate measurements [38].

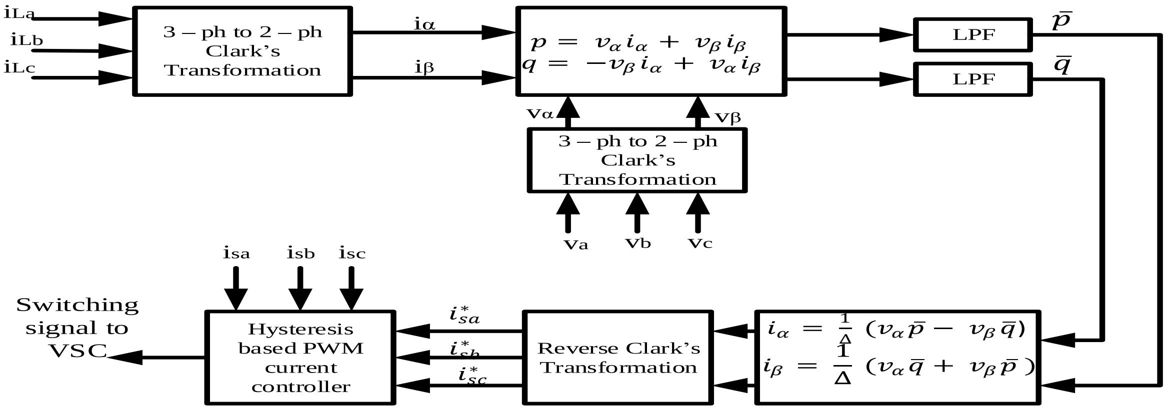

Figure 7. Basic building blocks of IRP theory [38]

5.2 Synchronous Reference Frame (SRF) Theory

Synchronous reference frame theory is used in three phase systems, which is one of the most popular PLL methods but it does not supply the individual values of phase, frequency and amplitude. The main purpose of this method is to identify the voltage amplitude and frequency at a point of common coupling between the inverter. SRF theory is based on the transformation of currents in a synchronously rotating d-q frame as described in Figure 8. Voltage signals are proposed by a PLL to generate unit voltage templates (sine and cosine signals) [38]. This control technique is based on the extraction of the current component in phase with the unit voltage template. The reference source current used to decide the switching of DSTATCOM has two components. The main drawbacks of this method are the generation of voltage templates i.e. sine and cosine terms which is very crucial and PLL is involved in the generation of templates. The operation of PLL is slow and also imposes some amounts of delay in computation, effect of delay due to LPF used for filtering signals in d- q frame, mathematical computations are more and not suitable for 3P - 4W system.

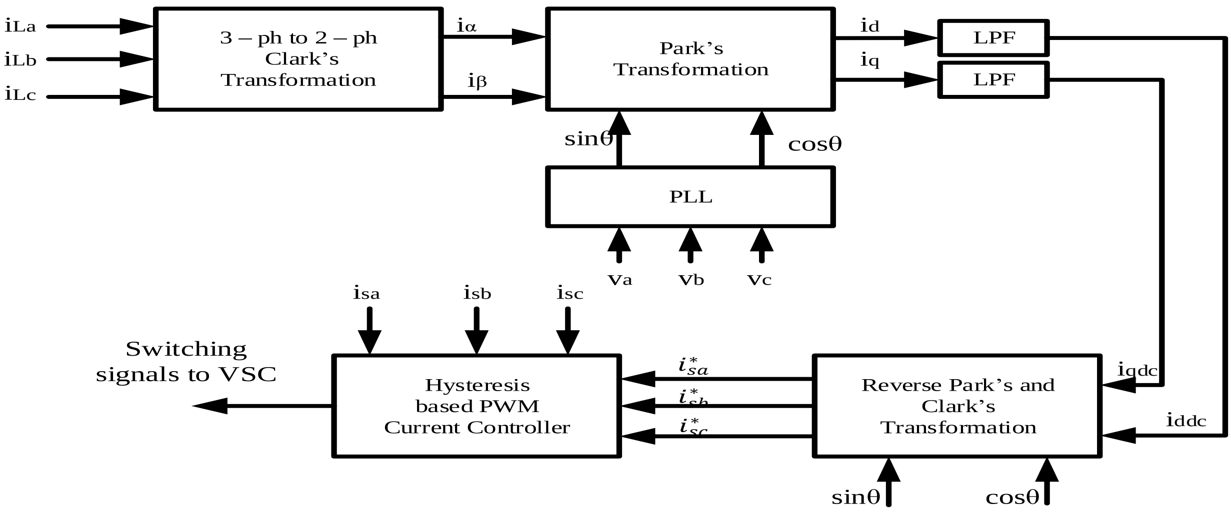

Figure 8. Basic building blocks of SRF theory [38]

5.3 Symmetrical Component Theory

This control algorithm is based on prime objective to obtain the balanced source currents for which the positive sequence voltage and currents are considered [39]. Therefore the reference source currents can be considered as:

$$i_{sa} + i_{sb} + i_{sc} = 0 \quad (7)$$

Implementation of this control technique is explained by the block diagram in Figure 9. The power generated from the source is constant and equal to the dc value of the load power. The average load power is computed using filter. The reference currents as well as sensed currents and voltages are shown in the block diagram. The switching signals generated are used for control of VSC. This technique fails under non-ideal source voltage condition such as unbalanced and distorted source voltage conditions with linear as well as non-linear loads [39].

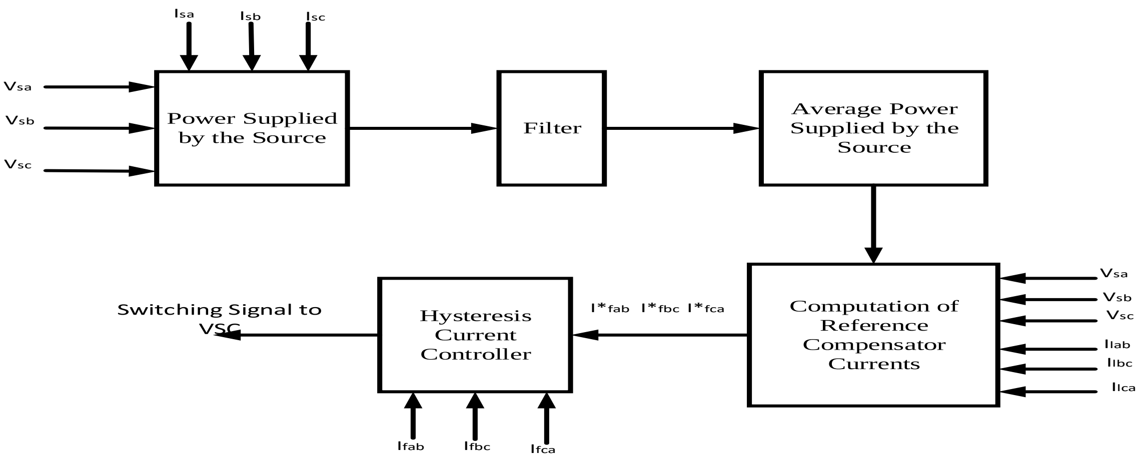

Figure 9. Basic block diagram of symmetrical component theory [39]

5.4 Average Unit Power Factor (AUPF) Theory

In this algorithm, the source must supply the sinusoidal currents in phase with the voltages. The relation between source currents, voltages and average load power is given by the following relation [40]:

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sb} \end{bmatrix} = \frac{P_{lav}}{V^2} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \tag{8}$$

where

$$P_{lav} = \frac{1}{T} \int (v_{sa} i_{La} + v_{sb} i_{Lb} + v_{sc} i_{Lc}) dt \tag{9}$$

$$V^2 = \frac{1}{T} \int (v_{sa} v_{sa} + v_{sb} v_{sb} + v_{sc} v_{sc}) dt \tag{10}$$

The compensator currents are derived as $i_c = i_l - i_s$

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} - \frac{P_{lav}}{V^2} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{11}$$

The compensator reference currents are compared with actual compensator currents and passed through the hysteresis band controller which generates gate pulses for VSC of the DSTATCOM [41].

5.5 Proportional-Integral (PI) Controller

This technique is used to estimate losses over the DC bus voltage of the DSTATCOM [42]. The reference DC bus voltage V_{dc}^* is compared to the sensed DC bus voltage V_{dc} of the DSTATCOM and produces voltage error, which is expressed in the nth sampling as

$$V_{dcl(n)} = V_{dc(n)}^* - V_{dc(n)} \tag{12}$$

The error voltage signal $V_{dcl(n)}$ is processed in a PI controller and the output at the nth sampling is expressed as

$$I_{p(n)} = I_{p(n-1)} + K_{pdc}\left[V_{dcl(n)} - V_{dcl(n-1)}\right] + K_{idc}V_{dcl(n)} \tag{13}$$

where K_{pdc} and K_{idc} are the proportional and integral gains of the PI controller respectively.

The output of PI controller is added with average real power for controlling DSTATCOM using PQ theory. In SRF theory, the output of PI regulator is added with the d-axis component of current signal and in adaline control it is added with equivalent source currents [43]. In [44], authors applied genetic algorithm to the optimization of PI coefficients in DSTATCOM non-linear controller for regulating DC voltage and proposed new PI coefficients. It is based only on measurements of the voltage $V_{dc(n)}$ at the load point. The voltage error signal $V_{dcl(n)}$ is obtained by comparing the measured voltage $V_{dc(n)}$ with a reference voltage $V^*_{dc(n)}$. The angle δ is used in the PWM generator as the phase angle of the sinusoidal control signal. The modulating angle δ is applied to the PWM generators in phase A. The angles of phases B and C are shifted 120 and 240 degrees, respectively.

5.6 PID Controller

PID controller is a three term scheme whose design is coordinated through the action of each of its terms. Ease of implementation and user friendly features makes it popular in industrial applications. On the other hand, as a linear controller, the PID control performance tends to deteriorate when subjected to a nonlinear process with constantly changing operating conditions and model parameters. However, some literature has reported the PID application to reinforcement learning scheme for studying the control performance of the DSTATCOM [45]. Consider the general feedback system with a PID controller and DSTATCOM in which the output of the PID controller is given by

$$u(t) = K_p e(t) + \frac{1}{K_i}\int_0^t e(t)\,dt + K_d\frac{de(t)}{dt} \tag{14}$$

where $u(t)$ is the controller output, K_p is the proportional gain, K_i is the integral gain, K_d is the derivative time and $e(t)$ is the error between the reference voltage and the observed voltage which is given by

$$e = V_{ref} - V_{in} \tag{15}$$

5.7 Model Predictive Control (MPC)

MPC was better known in petrochemical industry applications. It is now gaining fast popularity into other sectors as advanced control technique. Its unique features of low control update rates, handling actuator constraints and the ability to deal with complex control systems makes it suitable for online applications. In PQ prediction, the current DSTATCOM outputs are subjected to some reference signal values based on past inputs in order to calculate the future outputs. For this reason, any waveform anomaly would have been anticipated and corrected before any disturbance occurs to the customer's device [46]. MPC is a very popular current control algorithm for controlling power quality problems and also having fast-transient response. In addition to this, DSTATCOM is also used to maintain the load voltage at 1p.u during voltage swells/sags. In current control using conventional MPC, the difference between the reference and actual DSTATCOM currents is produced as a cost function (current error). MPC based DSTATCOM is used to compensate for the current related power quality problems such as harmonic, reactive, and neutral currents and also to maintain a constant voltage across each flying capacitor [35]. MPC algorithm is easy in implementation, providing good dynamic and steady-state response, and constraints can be easily added to the cost function. Two additional constraints included in the cost function using weighting factors are its main challenging issue. The schematic diagram for the MPC model for controlling the values of DSTATCOM currents is shown in figure 10.

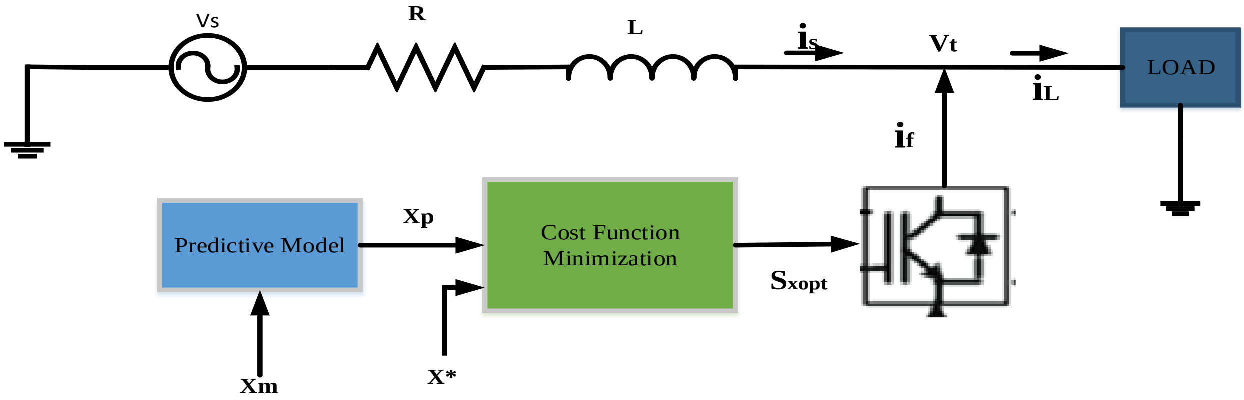

Figure 10. Schematic diagram of MPC controlled DSTATCOM [46]

5.8 Sliding Mode Controller (SMC)

SMC is applied in the current control of the DSTATCOM, to regulate the voltage and also compensated the harmonics in load currents. The SMC technique is based on the development of a discontinuous control signal that drives the system states to the desired values again in [35]. To achieve this, two steps are required; the design of sliding surfaces that, when the scheme is in the sliding condition, follow the references correctly, and the design of a control law that guarantees the continuation of the sliding modes in the system. The three supply currents are sinusoidal and in phase with the supply voltages thereby unity power factor is achieved. In normal operations, due to its robustness properties, sliding mode controllers have two major design difficulties in the design of a control technique. The system is highly nonlinear and the performance of the system depends strongly on the knowledge of the loads nearby the DSTATCOM. SMC is capable of harmonic elimination of source current and successfully verified by the IEEE-519 standard [47]. Due to resonance problems and fixed compensation in the filters, custom power devices are now available for mitigating power quality concerns. The in-phase components of unit vectors are calculated from the PCC voltages (V_a, V_b and V_c) The direct amplitude of PCC is estimated as,

$$V_t = \sqrt{2(V_a^2 + V_b^2 + V_c^2)/3} \tag{16}$$

The in-phase components of unit templates are computed as

$$u_{sap} = \frac{V_a}{V_t}, u_{sbp} = \frac{V_b}{V_t} \ and \ u_{scp} = \frac{V_c}{V_t} \tag{17}$$

5.9 Artificial Neural Network (ANN)

ANN is artificial intelligent nonlinear controllers based on the popular black box concept of input – output relationships. They are equipped with the set of training algorithms which improves their learning capacity to perform as closely as possible the set of fixed weights and bias terms. Despite the wide range of applicability, ANN exhibits a large permutation of training parameters which causes snag during feed forward time – series forecasting. This increases the sensitivity of the network to a number of choices like size of training sets. Nevertheless, its application of DSTATCOM to power quality control has been reported in [46]. It is magnificent to reiterate that this controller is only good for small perturbations. Figure 11 shows the block diagram of ANN controlled DSTATCOM which is used to improve the performance of the system under various operating conditions such as overloaded, faulty condition, and various power quality problems. ANN based DSTATCOM gives the fast dynamic response and accurate result as compared to other control methods such as PI controller, PID controller, MPC etc.

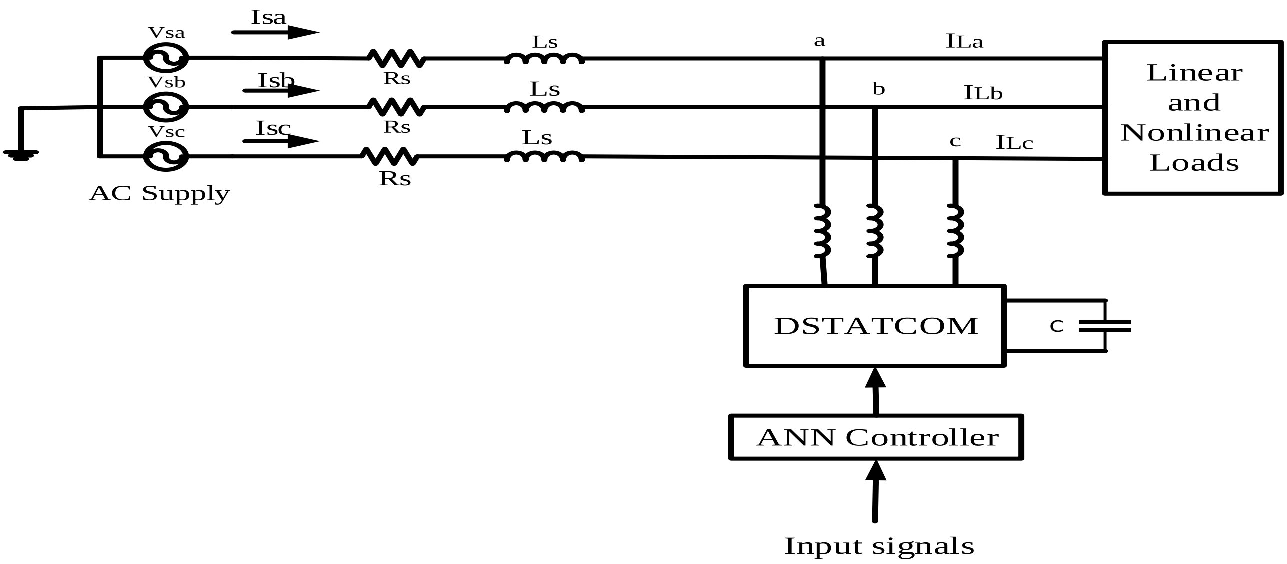

Figure 11. Block diagram of ANN controlled DSTATCOM [48]

5.10 Fuzzy Logic Control (FLC)

FLC is an aspect of computational intelligence which was first introduce as fuzzy set theory by Lotfi Zadeh in 1965 [46]. It was later applied by Mamdani to motor control in 1974. Since then FLC has found significant application in various engineering capacity including power industry. The ability to deal with complex and nonlinear systems gives it a room over loads of conventional methods. Various types of fuzzy controllers have been successfully developed for the DSTATCOM to solve PQ problems. The major drawback with this kind of controller is based on manual tuning, except for the neuro – fuzzy breed which has a self – tuning mechanism [36]. This can be overcome by automatic classification of PQ problems using convolutional neural network and supplementary fuzzy logic to control the signal fed to the DSTATCOM. A 3MVA

DSTATCOM controller based on fuzzy logic is proposed which is used for improvement of the PQ and to stabilize the distribution power system [45] which is shown in Figure 12. When the voltage sag and load variations at grid end occurs, the DSTATCOM controller is evaluated.

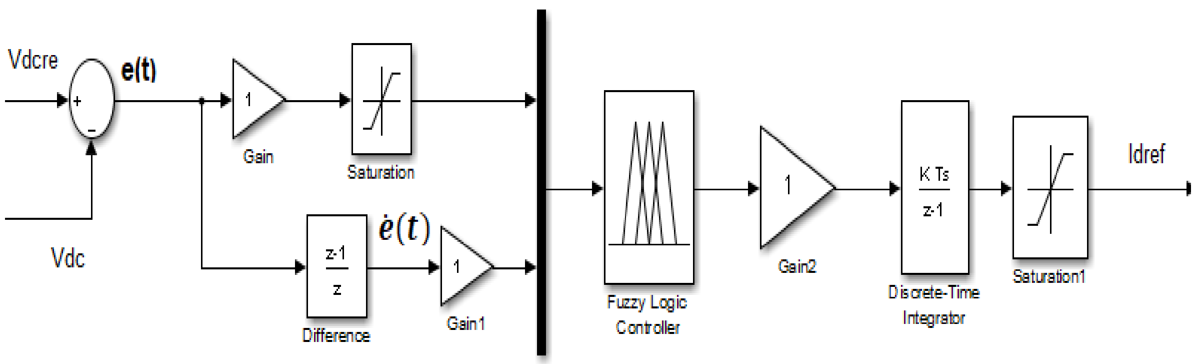

Figure 12. Block diagram of FLC based controlled DSTATCOM [45]

Therefore, FLC control strategy is proposed in this work because of its ability to improve dynamic response and hence improves power quality. The requirement of a mathematical model is also eliminated as this controller uses only linguistic variables. In the DSTATCOM, a voltage source converter which is voltage controlled (VC-VSC) and 3-phase IGBTs based are used. The control algorithm uses supervisory FLCs. The fuzzy controlled DSTATCOM has the lowest overshoot and fastest dynamic response during the initial system transient period. Performances of the various control strategies reviewed are compared and described in Table 1. In addition, the fuzzy controlled DSTATCOM has the ability to improve the voltage dynamic response more at PCC by providing less overshoot and faster settling time compared to other DSTATCOM control strategies [45]. Comparative study of control techniques presented in Table 1 is greatly helpful for selection of these techniques for specific application.

Table 1. Performance comparison of various DSTATCOM control strategies

S/N	Characteristics	IRP	SRF	SC	AUPF	PI	PID	MPC	SMC	ANN	FLC
1	Reactive power compensation	Partial	Good	Excellent	Excellent	Partial	Good	Better	Good	Good	Excellent
2	Harmonic mitigation	Good	Good	Better	Average	Good	Better	Excellent	Better	Good	Excellent
3	Load balancing	Excellent	Average	Excellent	Good	Good	Good	Good	Excellent	Excellent	Excellent
4	Neutral current elimination	Excellent	Good	Good	Good	Average	Partial	Good	Good	Good	Better
5	Computational complexity	High	Average	Simpler	High	Average	Average	High	High	Simpler	Simpler

6. Literature Survey on the Application of DSTATCOM

The concept of custom power devices was first introduced by Hingorani in 1995 [48], and since that time, several researches has been conducted in studying DSTATCOM and looking at expanding its applications and developing strong control strategies to improve its performance in mitigating various power quality problems. In this section, literature survey of some of the researches conducted to mitigate various PQ issues using DSTATCOM to make an image of the research gaps that have been studied over time.

The work reported in [49] studied (E-STATCOM) which is STATCOM integrated with the battery energy storage (BES) system. PI controller has been suggested in controlling the operation of E-STATCOM connected at a weak point of the ring system of Mosul city. Some types of disturbances have been simulated in the system. The results show improvements in the transient and dynamic stability of the power system by keeping the reactive power constant during the disturbances and decreasing the active power oscillation during and after these disturbances. Adding E-STATCOM causes THD of the bus voltage to be within IEEE-519 standards. The response time was very short about two cycles.

In order to improve the power quality, [50] studied the effectiveness of applying a DVR and DSTATCOM to improve the voltage unbalance problem in urban and rural feeders containing rooftop PVs. A stochastic analysis was executed by Monte Carlo to test their effectiveness for PV and load rating and location in the system. A control algorithm and converter topology is suggested for the DVR and DSTATCOM based on the pole-shift technology developed to control the voltage in the output of the DVR and DSTATCOM converters. Through simulation, DSTATCOM has been shown to have better overall results compared to DVR. These devices also succeeded in reducing the voltage imbalance to less than the standard limits.

Researchers in [51] conducted a research using the variational technique to find an optimal size and location of DSTATCOM for radial distribution systems in order to reduce the amount of loss incurred in the system and to improve its voltage profile. The research was conducted using MATLAB software associated with the IEEE of 33-bus system. The DSTATCOM distribution of the radial distribution network was compared using the voltage stability index and the power loss index with the result of two other researches. The results showed a significant reduction in losses and an improvement in the voltages profile and the size of DSTATCOM obtained by the proposed method is lower than reported in these two researches.

The application of a soft computing technique namely differential evolution to realize harmonic elimination PWM (HE-PWM) for direct control of the DSTATCOM was studied in [52]. The method was compared with phase-shifted PWM (PS-PWM) using PLECS and MATLAB program. The analysis revealed that a coupling inductor about 2 to 3 times bigger is needed for PS-PWM to perform a harmonic like HE-PWM at the same switching frequency. The low-order harmonics have been successfully eliminated. Moreover, the HE-PWM direct control has a very fast dynamic response.

Also, researchers in [53] proposed DSTATCOM that uses inductors as energy storage through a matrix converter applying MPC technique. DSTATCOM provided load compensation without the use of electrolytic capacitors (which have some failures). It was established that the proposed compensator has a longer expected service life and greater reliability compared to VSI-based compensators. The simulation results showed that inductors instead of capacitor elements achieved good compensation for reactive power.

Research presented in [39], proposed a design for a high-powered new model DSTATCOM that uses an isolated–dual converter topology. Transformer paralleling has been achieved by coupled inductors based on a single magnetic core. Grid currents were controlled using linear quadrature optimization control to reduce the steady-state error and improve the transient response. DC vector voltages stay stable, and the delivered currents are shared equally between the two isolated VSCs. The feasibility of the suggested design was investigated through a practical experiment and concluded that it is unnecessary to oversize the converters' power ratings.

Report presented in [40] studied the estimation of the voltage imbalance related to the suppliers and consumers in the distribution system by using a time domain strategy. Based on this assessment, the DSTATCOM based 3p4w is allowed to compensate for the voltage unbalances of the negative and zero sequences caused by the consumers only. The performance of the proposed algorithm that controls DSTATCOM has been verified to compensate for consumer-induced voltage imbalance through various types of scenarios that power networks commonly encounter such as single phase fault, imbalanced static resistive load, the start of a big induction motor, and switching of capacitor bank.

In an attempt to mitigate the power quality problems, the work reported in [42] designed DSTATCOM with a 4-wire inductor-capacitor-inductor (LCL) filter to compensate for the neutral current, balance the load, compensate for the reactive power, and eliminate the harmonics. The LCL filter design was introduced for high ripple attenuation by integrating two resonance damping technologies viz; active damping and passive damping. Both methods have been shown to effectively address the resonance phenomenon caused by the LCL filter while maintaining the connecting point voltages, as well as the THD at less than 3% for nonlinear and unbalanced loads.

In [54], researchers have studied an integrated controlling scheme based on the second-order super twisting control algorithm and sliding mode control for the DSTATCOM converter. The algorithm of super twisting along with standard SMC has been used to remove the chattering effect which is the drawback of SMC while keeping its other features such as faster response time, robustness, and insensitivity to load variation. The simulation results showed that the proposed control can effectively detect and mitigate voltage sags and swells and compensate for the active and reactive power through a short time and that the THD in all simulation cases is less than 5%.

Also, the work reported in [55] aimed at finding an optimal placement and sizing of the DSTATCOM in a radial distribution system with 78 buses in Ethiopia to minimize losses and improve stability and profile of voltage using the improved bacterial foraging search algorithm (IBFA). The results showed considerable improvement by IBFA in reducing power loss, voltage profile, and stability as compared with the results of the conventional BFA and the scenario of the base case.

Another work in [56] proposed a new design to modify DSTATCOM with a current controller for micro grid applications. The modified design is incorporated into the system to accurately deal with balanced, unbalanced, and excursion loads for both inductive and nonlinear loads. Also, it handled the stability problems of the MG at fault-caused islanding incidents. The simulation results showed the superiority of the proposed design in improving the power factor, voltages at PCC, source current and reduction of harmonics currents, besides the stability operation at islanding is maintained compared with conventional DSTATCOM.

The work presented in [57] proposed a novel control algorithm for a DSTATCOM to handle voltage regulation using self- excited induction generator (SEIG) based wind energy conversion systems. An enhanced PLL based on current synchronous detection (CSD) algorithm is proposed to estimate the individual phase voltages, and filter the SEIG voltage from harmonics by moving average filter, DC offset by delayed signal cancellation, and the frequency deviation. The proposed algorithm has been checked under nonlinear and linear load conditions. The results clearly showed the effectiveness and the superiority of the proposed algorithm compared second- order generalized integrator-based CSD control algorithm [57].

Table 2 summarizes some recent performances of DSTATCOM in terms of converter topologies, control methods and objectives based on the literature surveyed. DSTATCOM has two working modes, single mode and dual mode. In single mode, the topology of 3P – 3W is used to mitigate PQ problems based on voltage; while to mitigate PQ problems based on current, the topology of 3P – 4W is used. It can also use the last topology to mitigate PQ problems related to voltage if DSTATCOM works in dual mode, so that it combines the functions of the two topologies in one scenario and reduces the cost [58]. The implementation of the selective harmonic elimination PWM method on multilevel converters provides high-quality output voltage waveform and accurate control of the harmonic output voltage while keeping the switching frequency of the semiconductors at a low level in comparison to other modulation techniques [59].

Table 2. Performance of DSTATCOM based on topology and control methods

S/N	Design Objective	Converter Topology	Control Method	Modulation Strategy
1	Voltage regulation	single phase	Phase space	PWM
2	Current harmonics and neutral current mitigation	3p4w-2L-VSC	Symmetrical component	Hysteresis-based PWM
3	Reactive power, current harmonics load balance, voltage regulation	3p4w-2L-VSC	SRF	SPWM
4	Voltage regulation, neutral current, current unbalance	3p4w-2L-VSC	IRP	Hysteresis-based PWM
5	Load compensation, harmonics, voltage regulation	3ph3w-2L-VSC	Back propagation	SPWM
6	Load compensation, power factor correction, voltage regulation	3ph3w-2L-VSC	LMS based ADALINE	Hysteresis-based PWM
7	Reactive power	3ph4w-5L-VSC	SMC	Hysteresis-based PWM
8	Load compensation, harmonics, voltage regulation	3ph3w-2L-VSC	ANN based anti Hebbian	PWM
9	Voltage flicker	3ph3w-2L-VSC	Intelligent FLC	PWM
10	Voltage sag, reduced harmonic, DC voltage, load current	3ph3w-2L-CSC	Fuzzy-PI	PWM

It is very useful to employ artificial intelligence techniques because it provides adaptivity for the DSTATCOM working during various disturbances, unlike traditional controllers (such as PI) whose performance deteriorates greatly at large disturbances or changing network parameters [60].

7. Challenges and Constrains

It is clear from the reviewed literature that most of the methods employed to tackle the menaces of PQ problems using DSTATCOM are implemented based on manual tuning. The techniques however do not provide the control unification required for a single controller diversification to offer unrestricted multiple solutions [61]. Limited voltage regulation range, limited control capabilities, harmonic distortion, cost and complexity of DSTATCOM, stability and control, grid synchronization, power quality monitoring as well as maintenance and repair are some of DSTATCOM difficulties that need proper attention [62]. Other challenges that need to be addressed in order to solve the projected complexities of future distribution system are hinted below.

7.1 Feeder Impedance Resistivity

With suitable control scheme, DSTATCOM performance in current control mode (CCM) is independent of feeder impedance whereas voltage control mode (VCM) operation is largely affected by the feeder impedance. Voltage regulation performance will be better when feeder impedance is inductive and degrades as feeder impedance becomes resistive. Moreover, in a distribution system where feeder impedance is mainly resistive, DSTATCOM has limited voltage compensation bandwidth [63].

7.2 DSTATCOM Power Rating

Power rating is an important issue related to DSTATCOM control. In CCM, DSTATCOM needs to be rated for maximum RMS reactive and harmonic load current. However, high reactive current is required to mitigate the voltage disturbances using DSTATCOM. This increases the rating of VSI, which makes it more bulky and results in higher current rating of IGBT switches [64]. Additionally, it causes excessive heating losses in the IGBT switches and the feeder.

7.3 Load Voltage Changes

Also, loads perform satisfactorily for permissible range of supply voltages and DSTATCOM should be operated in CCM to mitigate current related PQ problems. However, load can change at any time due to disturbances, and it is more important to maintain constant voltage at the load terminal than to continue working in CCM [65]. But maintaining load at 1.0pu always results in exchange of reactive power with the source even for nominal supply voltage.

7.4 DSTATCOM Operating in both CCM and VCM

Due to the same circuit configuration, a DSTATCOM operating in CCM can also be operated in VCM without any extra circuitry. However, several issues need to be addressed to utilize DSTATCOM for both current and voltage related enhancement, since the requirements of both operating modes are different [66].

8. Future Research Trends

The DSTATCOM is very much effective for improvement of both voltage and current related PQ problems such as harmonic elimination, load balancing, voltage regulation, power factor correction and neutral current compensation in distribution system. However, the present day cost of DSTATCOM is on higher side which is main hurdle for its implementation in the power system. Therefore, it is highly desirable to carry out extensive research to reduce the cost of DSTATCOM without affecting the efficiency and effectiveness in PQ improvement capability.

Integration with renewable energy sources, cybersecurity, electric vehicle charging, more advanced control strategies, high – temperature operation and modular and scalable designs are some of the crucial areas that need to be properly researched into and squarely addressed for the widespread adoption and effective operation of DSTATCOM in the future

9. Conclusion

In this paper a comprehensive literature review on DSTATCOM is carried out. The paper presents a detailed survey on the various topics of DSTATCOM used for PQ improvement in distribution system. Topologies used in both 3P – 3W and 3P – 4W distribution system were analyzed systematically and performance of DSTATCOM of different control methods was presented in Table 2. The control techniques such as IRP, SRF, SC, PI, PID, SMC, ANN, AUPF, MPC and FLC were briefly analyzed and their performances presented. Finally, at the end of paper existing challenges as well as future trends for further research to enhance the performance and suitability of DSTATCOM for specific purpose was presented.

According to the developed review, it can be concluded that DSTATCOM is an effective tool for PQ improvement in distribution system. The commonly used control techniques for DSTATCOM are SRF, IRP, SC, PI, PID, SMC, ANN, AUPF, MPC and FLC. A comparative study presented would help the users in selecting the particular topology and control technique of DSTATCOM that suits a specific application. It is hoped that this review on DSTATCOM will be beneficial to the users, designers, manufacturers, researchers and power engineers for enhancing the quality of power in the distribution system.

Acknowledgement

The authors wish to use this opportunity to extend their warmth appreciation to the Tertiary Education Trust Fund (TETFUND) Nigeria for its contribution to this effort.

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