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Journal of Advanced Research in
Technology and Innovation Management

Journal homepage:
http://www.akademiabaru.com/submit/index.php/jartim/index
ISSN: 2811-4744

Efficient Power Quality Management: Control Algorithms and Configurations for DSTATCOM Application

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ABSTRACT

Power quality issues are a major problem that is faced by the distribution system nowadays as most of the consumer' electrical equipment is non-linear load. Non-linear load will cause a current harmonic issue to the distribution system where the presence of the harmonic will affect the power quality. Hence, by deploying DSTATCOM into distribution system, it can solve the issues as it can mitigate harmonic current distortion. This paper presents a review on various previous works on DSTATCOM system configuration and its control method. It is classified based on the supply and the load system which are single phase two-wire, three-phase three-wire, and three-phase four-wire systems. The control method for DSTATCOM is divided into two categories which are time domain and frequency domain.

Keywords:

Frequency domain; time domain; dstatcom; power quality

Received: 16 May 2022 **Revised: 7 Aug. 2022** **Accepted: 25 Aug. 2022** **Published: 28 Sept. 2022**

1. Introduction

Power quality issues is a major concern in distribution system as it impacts both consumer and the distribution system negatively if it is not taken care off. The increased use of power electronic components by consumers contributes to a rapid rise of power quality issues. Voltage swell, voltage sag, harmonic and noise are among the many examples of power quality issues that are faced by the distribution system [1-3].

Non-linear load is usually the main cause of power quality issues as it causes current harmonic distortion [4,5]. Harmonics in current flow affect the entire distribution system, right down to the connected loads [6]. Among the custom power device, distributor static synchronous compensator (DSTATCOM) is deemed the most suitable to mitigate the harmonic current distortion [7].

DSTATCOM is usually employed in distribution systems to address power quality issues. It plays a crucial role in maintaining the voltage across the Point of Common Coupling (PCC) [8]. It is used to solve voltage sags, surges, and to mitigate current-based power quality issues [9]. It is made up of

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https://doi.org/10.37934/jartim.4.1.114

three major components: a voltage source converter (VSC), a coupling reactor, and a controller [10]. Its performance relies heavily on its controller [11].

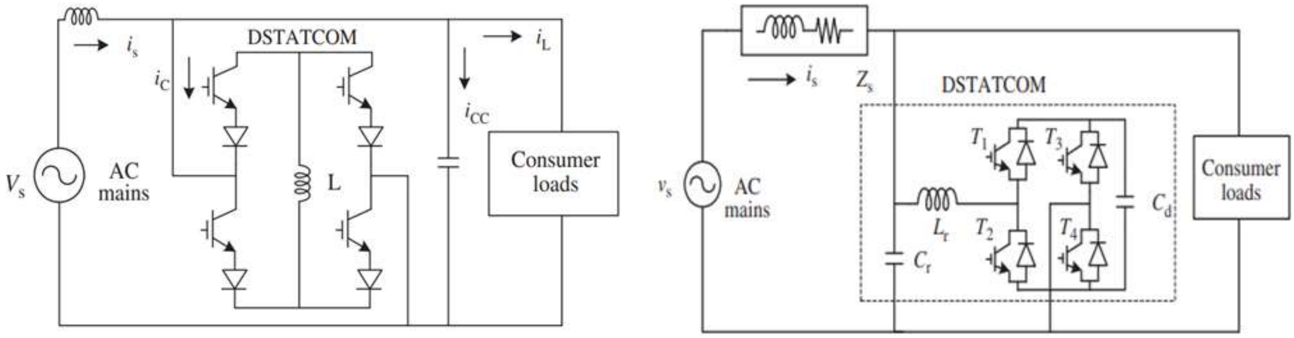
2. System Configuration

2.1 Classification of DSTATCOM

DSTATCOM can be categorized based on the type of power supply and/or load system they are designed for. These categories include single-phase two-wire, three-phase three-wire, and three-phase four-wire systems. In single-phase supply systems, various loads like residential appliances are connected. Three-phase loads like traction systems, furnaces, and adjustable speed drives (ASDs) require a neutral connection and are typically powered by three-wire supply systems. In contrast, three-phase four-wire supply networks are commonly used to distribute power to single-phase loads such as refrigerator. Therefore, DSTATCOM can be categorized as two-wire, three-wire, or four-wire DSTATCOM, depending on the type of supply system they are intended to compensate. This classification aligns with the various requirements of loads connected to this different supply system [12].

2.1.1 Single-Phase Two-Wire DSTATCOM

Two-wire DSTATCOM circuits utilize two distinct converter topologies: a current source converter (CSC) bridge that employs inductive energy storage elements, and a voltage source converter (VSC) bridge that utilizes capacitive DC bus energy storage components. The arrangement of a two-wire DSTATCOM with a CSC topology is illustrated in Figure 1.



(a) (b)

Fig. 1. (a) Configuration of Two-Wire DSTATCOM with CSC (b) Configuration of Two-Wire DSTATCOM with VSC [13]

2.1.2 Three-Phase Three-Wire DSTATCOM

Three-phase three-wire DSTATCOMs are utilized in three-phase three-wire distribution systems to improve power quality by compensating the consumer's load [10]. In these systems, it is essential that the total current flowing through the three legs of the DSTATCOM is balanced and adds up to zero [14]. However, it is not feasible to compensate for zero sequence current that may exist in the load, nor is it possible to eliminate any DC flowing from the load into the source. As a result, the source current may be affected. Figure 2 presents the configuration of a three-wire DSTATCOM.

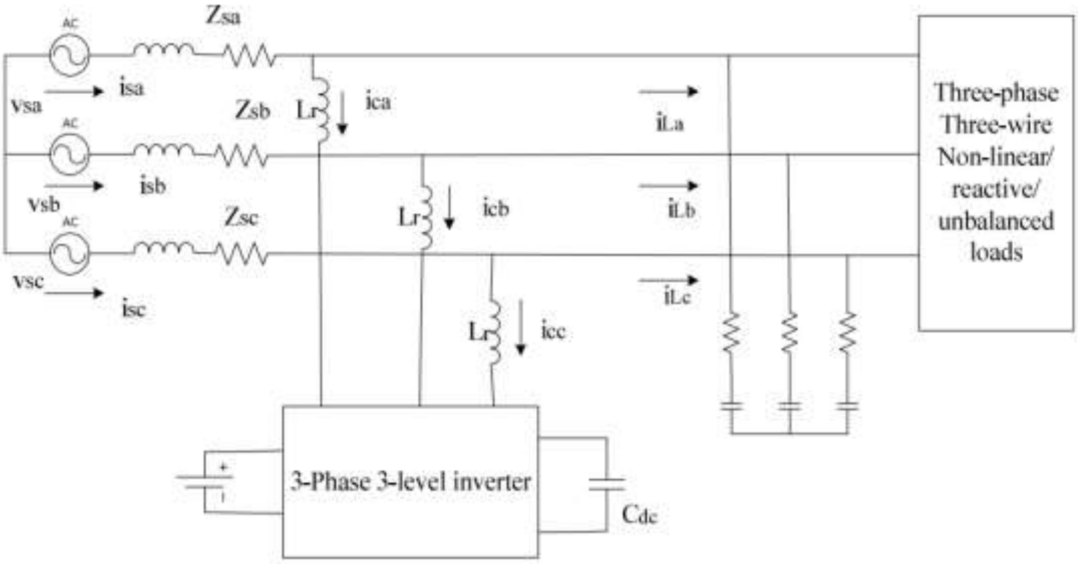


Fig. 2. Configuration of Three-Phase Three-Wire DSTATCOM [10]

2.1.3 Three-Phase Four-Wire DSTATCOM

Three-phase four-wire DSTATCOM are employed in three-phase four-wire distribution systems to enhance power quality. In addition to adjusting the power quality of the supply current, other DSTATCOM topologies designed for three-phase four-wire systems also compensate for neutral current. Compared to three-phase three-wire DSTATCOMs, these systems have a lower number of power electronic switches. In Figure 3, a diagram is presented depicting the three-phase voltages (Vsa, Vsb, and Vsc) and their corresponding currents (Isa, Isb, and Isc) in connection with an unbalanced, non-linear load. Reactive currents are represented as iLa, iLb, and iLc. To ensure optimal performance, the selection of the interface inductor and the design of the DC bus capacitor are critical. These choices are influenced by the energy storage requirements during transient situations, considering factors such as switching frequency and ripple current. These considerations play a role in achieving efficient operation and providing the necessary compensation for power quality issues within the DSTATCOM system [15].

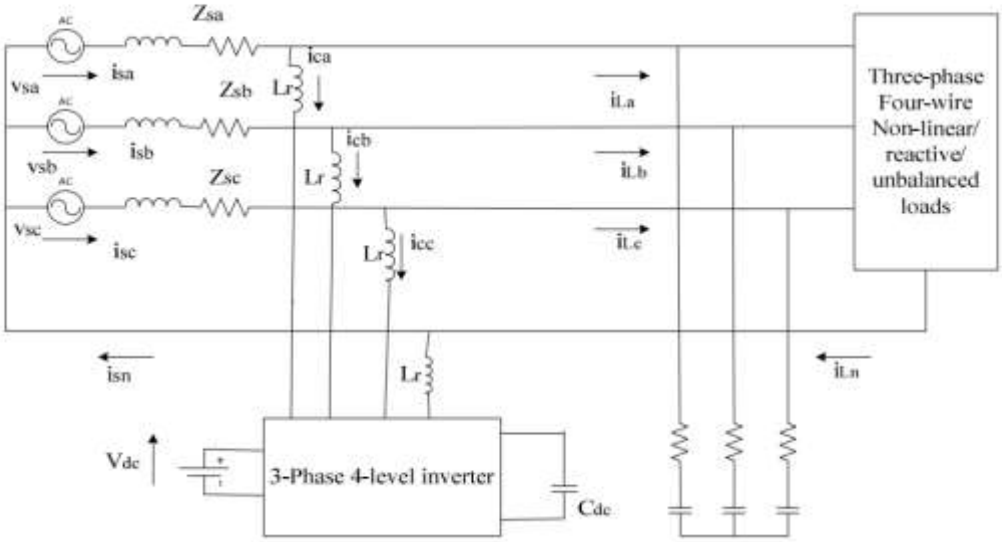


Fig. 3. Configuration of Three-Phase Four-Wire DSTATCOM

3. Control Algorithm

The primary objective of a DSTATCOM control algorithm is to determine the desired reference currents by utilizing feedback signals. These reference currents, combined with the measured currents, are subsequently employed in Pulse Width Modulation (PWM) current controllers. The PWM current controllers generate PWM gating signals for the switching devices, usually IGBTs (Insulated Gate Bipolar Transistors), used in the Voltage Source Converter (VSC) when it operates as a DSTATCOM. Accurate calculation of the reference currents is crucial for the effective regulation of DSTATCOMs. To approximate these signals, various control algorithms can be employed. These control algorithms play a vital role in determining the appropriate reference currents, which in turn help in achieving the desired compensation and power quality improvement provided by the DSTATCOM. Performance of DSTATCOM relies heavily on its controller, so it is important to find the best controller to optimize its performance. Several control methods, categorized as time domain control algorithms and frequency domain control algorithms, have been published in the literature for the control of DSTATCOM [13,16]. Table 1 shows the control algorithm that is discusses in this paper.

Table 1
DSTATCOM control algorithm

Time Domain	Frequency Domain
Synchronous reference frame (SRF) theory	Kalman filter-based control algorithm
Instantaneous reactive power theory (IRPT)	Wavelet transformation theory
Harmonic reference theory	Fast Fourier transform theory (FFT)

3.1 Time Domain

3.1.1 Synchronous reference frame (SRF) theory

The Synchronous Reference Frame (SRF) theory is introduced as a controller for DSTATCOM [10]. The Synchronous Reference Frame (SRF) theory is frequently employed in three-phase systems and is a commonly used Phase-Locked Loop (PLL) approach. However, it does not provide detailed information about the phase, frequency, and amplitude of the signals. The main goal of this technique is to calculate the voltage amplitude and frequency at the point of common connection (PCC) within the inverter. By using the SRF theory, the DSTATCOM control system can synchronize with the grid voltage and accurately determine the reference signals for compensation. Although the SRF technique may not provide specific details regarding phase angles or waveform distortion, it plays a vital role in ensuring synchronization and regulating the voltage amplitude and frequency at the PCC. This allows DSTATCOM to effectively inject or absorb reactive power and mitigate power quality issues in the system. The fundamental concept of SRF theory involves modifying currents in a d-q frame that rotates synchronously [17]. To generate unit voltage templates, a PLL suggests voltage signals in the form of sine and cosine signals [18]. The measured current signal is first transformed into a d-q frame and then subjected to filtering. The filtered currents are then fed into the hysteresis current controller for switching and generation, following additional filtering [19]. Figure 4 illustrates the SRF controller configuration. The mathematical transformation equations for converting the currents from α-β coordinates to d-q coordinates using Park's transformation and the transformation angle θ are depicted in Eq. (1) [20].

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{1}$$

As demonstrated in Eq. (2)., the DC components i_{ddc} and i_{qdc} are recovered with the use of a low pass filter and then turned back into coordinates using reverse Park's transformation.

$$\begin{bmatrix} i_{\alpha dc} \\ i_{\beta dc} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{ddc} \\ i_{qdc} \end{bmatrix} \tag{2}$$

To acquire three-phase reference source currents in ab coordinates, Eq. (3) shows how these currents are changed.

$$\begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 0 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{\alpha dc} \\ i_{\beta dc} \end{bmatrix} \tag{3}$$

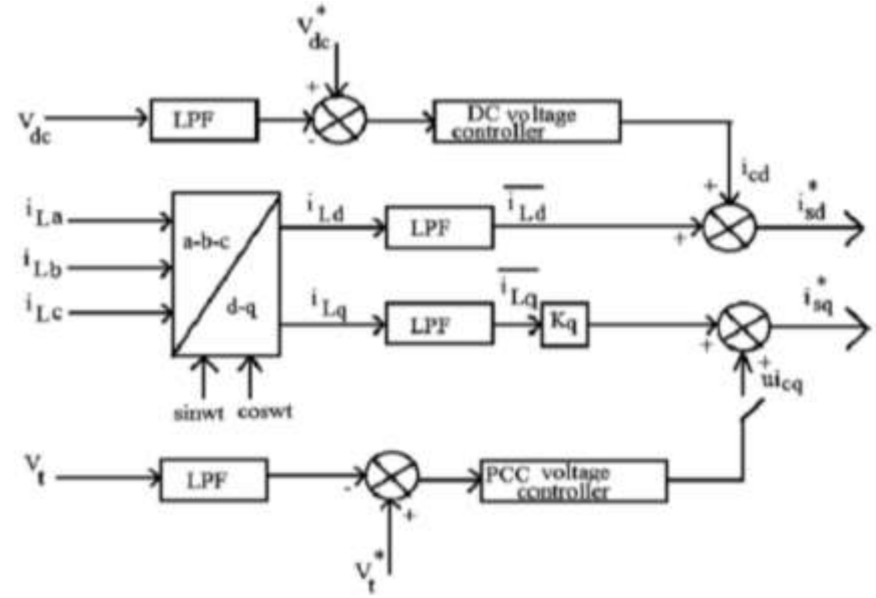


Fig. 4. SRF Controller [10]

3.1.2 Instantaneous reactive power theory (IRPT)

The Instantaneous Reactive Power Theory (IRPT) is introduced as a controller for DSTATCOM [10]. The control of the DSTATCOM involves the utilization of IRPT or p-q theory to calculate the necessary compensation current [21]. Clark's transformation is employed to transform the measured three-phase Point of Common Coupling (PCC) voltages and load currents into the α-β-o axis. This transformation facilitates the application of appropriate control techniques for the DSTATCOM. To ensure that the zero-sequence component of the voltage at the PCC does not contribute to the source power, the source should also not provide any zero-sequence active power [17]. Figure 5 shows the configuration of the IRPT controller.

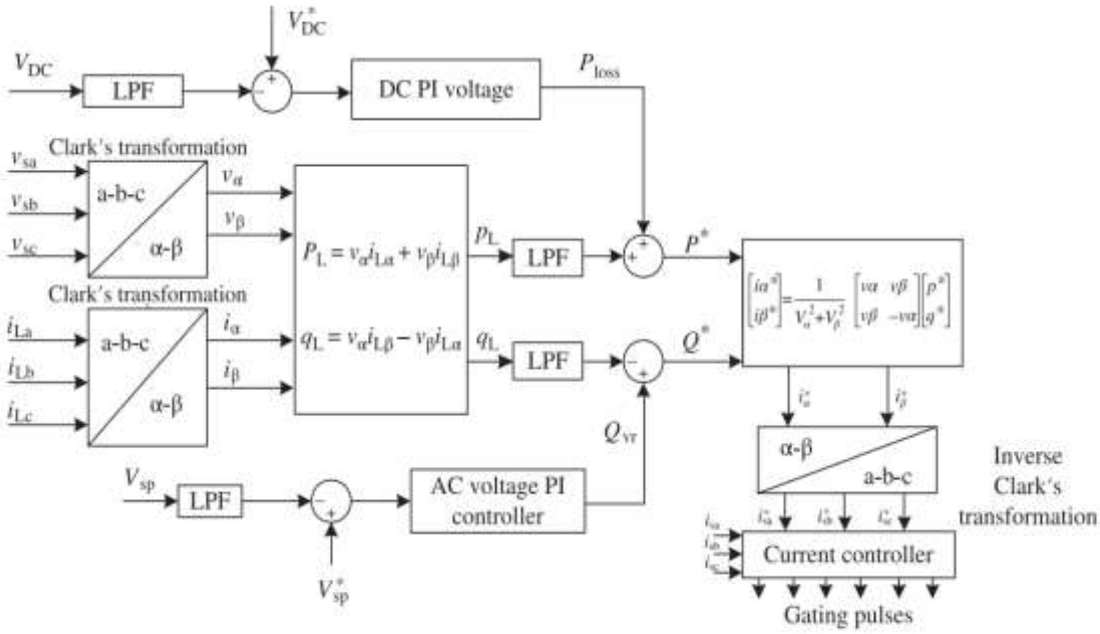


Fig. 5. IRPT Controller [13]

In this method, the three-phase load currents, and three-phase voltages at the PCC are processed using the Clarke transformation. By applying this transformation, both the real and reactive powers can be determined based on these two quantities. This allows for a quick identification of the sign changes resulting from the Clarke transformation and facilitates the analysis of reference current values [22]. Eq. (4) shows how to calculate the voltage of the system [23,24].

$$
\begin{aligned}
v_a &= V_m \sin(wt) \\
v_b &= V_m \sin(wt - 120) \\
v_c &= V_m \sin(wt - 240)
\end{aligned}
\tag{4}
$$

The load current is calculated as in Eq. (5).

$$
\begin{aligned}
i_{La} &= \sum I_{Lan} \sin\{n(wt) - \theta_{an}\} \\
i_{Lb} &= \sum I_{Lbn} \sin\{n(wt - 120) - \theta_{bn}\} \\
i_{Lc} &= \sum I_{Lcn} \sin\{n(wt - 240) - \theta_{cn}\}
\end{aligned}
\tag{5}
$$

Eq. (6) shows how to convert the phasors into α-β coordinates

$$
\begin{aligned}
\begin{bmatrix} v_a \\ v_b \end{bmatrix} &= \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \\
\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} &= \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}
\end{aligned}
\tag{6}
$$

Where α and β axes are the orthogonal coordinate. On a three-phase circuit, the usual instantaneous power can be defined as in Eq. (7).

$$p = v_a i_a + v_b i_b \tag{7}$$

The instantaneous reactive power can be defined as in Eq. (8).

$$q = -v_\beta i_\alpha + v_\alpha i_\beta \tag{8}$$

The instantaneous and reactive power in matric is shown on Eq. (9).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{9}$$

The α-β current is shown on Eq. (10).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{10}$$

Where Δ= $v_a^2 + v_b^2$

The reference source currents i*sα and i*sβ in α-β coordinate are shown in Eq. (11).

$$\begin{bmatrix} i^*{}_{s\alpha} \\ i^*{}_{s\beta} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ 0 \end{bmatrix} \tag{11}$$

Eq. (12) shows how this current is transformed in a-b-c quantities to find the reference current [25].

$$\begin{bmatrix} i^*{}_{sa} \\ i^*{}_{sb} \\ i^*{}_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{vmatrix} \frac{1}{\sqrt{2}} & 1 & 0 \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{vmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \tag{12}$$

3.1.3 Harmonic reference theory

Harmonic reference theory is discussed as DSTATCOM control algorithm [26]. Figure 6 illustrates the basic configuration of the Active Power Filter (APF) based on Instantaneous Harmonic Power Theory commonly employed for calculating compensating currents in DSTATCOM. The Instantaneous Harmonic Power Theory is utilized to control the compensating currents in the system. The reference compensating powers are generated based on the actual values of voltage and currents, which are then separated into active and reactive powers. These powers are passed through a Low-Pass Filter (LPF) and compared with the power loss. Subsequently, the generated harmonic power is transformed into the $\alpha\beta0$ coordinate system. This transformed signal is compared with the filter current, and the resulting signal is fed into the hysteresis controller of the DSTATCOM, generating gate pulses. While various methods are available for generating control signals, the simplicity of the instantaneous harmonic reference theory makes the design more accessible. Generally, when the load is nonlinear, the real and imaginary powers can be decomposed into average and oscillating components.

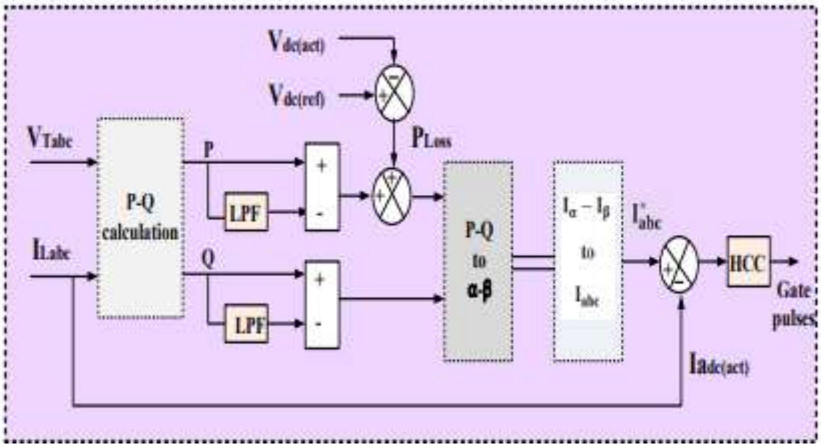


Fig. 6. Harmonic reference theory [26]

3.2 Frequency Domain

3.2.1 Kalman filter-based least mean square control algorithm

A DSTATCOM algorithm combining the least mean square (LMS) and Kalman filtering (KF) [27] is proposed. LMS algorithms are gaining attention due to their adaptability. These algorithms continuously update their parameters based on the current error input. LMS algorithms find applications in various areas such as wireless communications, and harmonic cancellation. Among different types of LMS algorithms, the fixed step size LMS algorithm is preferred for its speed, simplicity, adaptability, and hardware implementation. However, it has a limitation in that the learning rate parameter may not be optimal for all load scenarios. To address this, Kalman Filter is incorporated to dynamically adjust the LMS learning rate in real time, taking advantage of its simplicity and real-time implementation [28].

The Kalman filter is a widely recognized filter based on linear quadratic estimation (LQE)-based filter [29]. It performs recursive calculations on the input signal contaminated with noise and distortions. The Kalman filter generates a noise and distortion-free output signal by computing the Kalman gain (Kk). Designing the Kalman filter aims to achieve the desired precision and a good dynamic response [30]. Figure 7 illustrates the controller based on the Kalman filter and least mean square.

Standard equations for the Kalman filter are applied to input in a recursive manner. Eq. (13) illustrates the fundamental equations that define a system.

$$X_k = AX_{k-1} + J_k$$
$$Y_k = HX_{k-1} + L_k \tag{13}$$

In the provided equations, the variables are defined as follows:

1. X_k represents the state vector, which has a size of Nx1.
2. J_k represents the process noise vector, with a size of Nx1.
3. Y_k represents the measurement vector, which has a size of Mx1.
4. H represents the constant output matrix, with a size of Mx1.
5. L_k represents the measurement noise vector, which has a size of Mx1.

These variables are commonly used in the context of the Kalman Filter algorithm, where the state vector (X_k) represents the estimated state of the system at time k, and the process noise vector (J_k) represents the noise or uncertainty associated with the process dynamics. The measurement vector (Y_k) consists of the measurements obtained from the system, while the output matrix (H) is a constant matrix used to relate the state vector to the measurements. The measurement noise vector (L_k) represents the noise or uncertainty associated with the measurements.

By utilizing these variables in the Kalman Filter equations, it becomes possible to estimate and update the state of the system based on the measurements and incorporate the uncertainty in the process and measurements to improve the accuracy of the estimation.

The Kalman gain (K_k) can be calculated using Equation (14).

$$P_k = (1 - K_k H)\frac{P_k}{k-1}$$
$$K_k = \frac{P_k}{k-1} H^T \left(H \frac{P_k}{k-1} H^T + R_k\right)^{-1} \tag{14}$$
$$\frac{P_k}{k-1} = AP_{k-1}A^T + Q_k$$

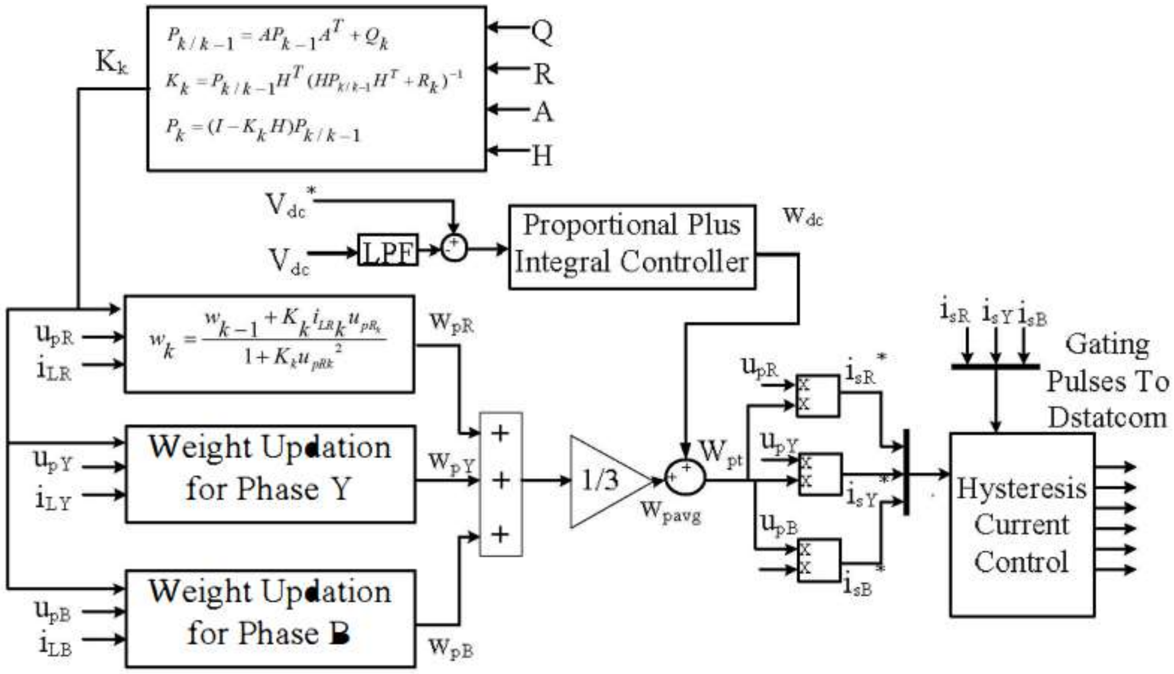


Fig. 7. Kalman Filter-Based Least Mean Square Controller [19]

3.2.2 Wavelet transformation theory

A DSTATCOM algorithm based on wavelet transform is proposed [31]. Wavelet theory is one of several digital strategies that have emerged with the advancement of high-speed computers and quick A/D converters to improve power quality. By employing the discrete wavelet transform (DWT), a well-known method for analysing non-stationary signals, transients in voltage sags can be detected. The wavelet-based denoising controller used in this technique compensates for voltage sags and brief interruptions. The original (distorted) signal is first identified and then decomposed into multiple scales or components (detailed and scaled) using low-pass filter (LPF) and high-pass filter (HPF) banks. In the initial phase, the original signal is detected and decomposed using wavelet transform. In the subsequent phase, inverse wavelet transform is applied to reconstruct the original signal, reducing transients in the voltage sag. Figure 8 illustrates the discrete wavelet transform (DWT) controller.

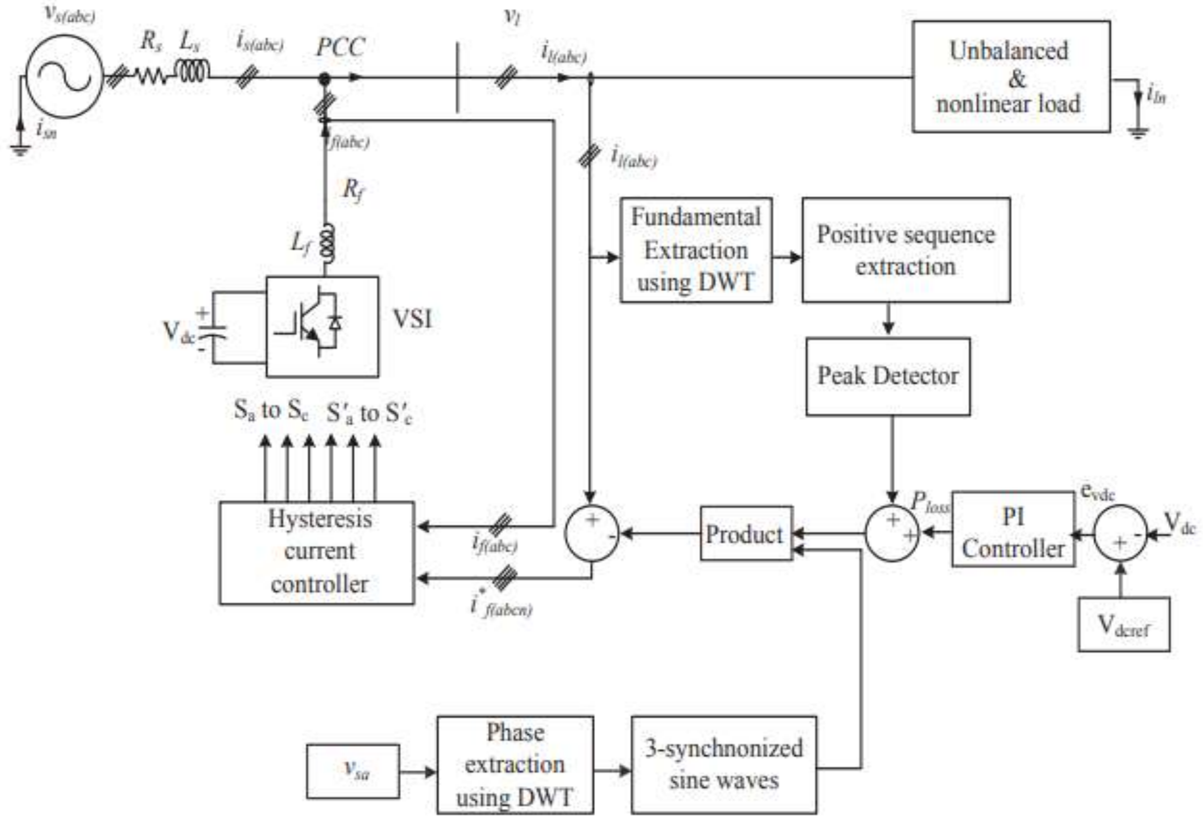


Fig. 8. Discrete Wavelet Transform (DWT) Controller [31]

3.2.3 Fast Fourier transforms theory (FFT)

The Fast Fourier Transform (FFT) is employed as a control algorithm for DSTATCOM [32]. The FFT is a computationally efficient algorithm used for calculating the Discrete Fourier Transform (DFT), which enables signal analysis in the frequency domain. By utilizing Fourier analysis, the FFT converts signals from the time (or space) domain to the frequency domain and vice versa. The FFT algorithm accomplishes fast computations by decomposing the DFT matrix into a product of sparse elements, including numerous zeros. This technique allows for efficient processing and analysis of signals in DSTATCOM control applications. This factorization allows for significant computational savings compared to the traditional DFT, making the FFT substantially faster. As a result, the FFT has found widespread use in various engineering, scientific, and mathematical applications [33]. In the context of DSTATCOM control, the FFT algorithm is employed to analyze the waveform and adjust accordingly. By utilizing the FFT algorithm, the control system can efficiently extract frequency components from the measured signals and generate appropriate compensation signals. This simplifies the control algorithm as it does not involve complex calculations beyond waveform adjustments. Figure 9 in the paper illustrates the basic circuit diagram of a DSTATCOM system that incorporates the FFT control algorithm. This indicates how the FFT theory is applied within the DSTATCOM system to achieve effective control and compensation based on frequency domain analysis.

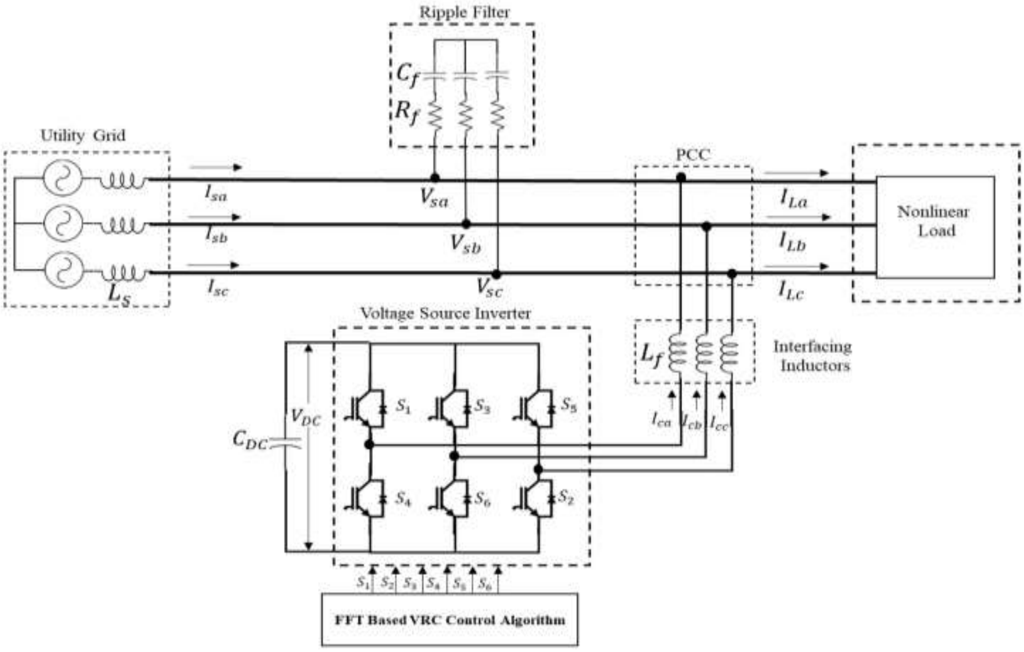


Fig. 9. Basic circuit diagram of a DSTATCOM system with FFT control algorithm

Table 2 summarizes the advantages of the entire control algorithm for DSTATCOM that is being discussed in this paper.

Control Algorithm	Advantages	Disadvantages
Synchronous reference frame (SRF) theory	More efficient in producing unity power factor for linear as well as non-linear loads [10].	Transient response time will be longer during low-order harmonic [34] Cannot compensate current harmonic if load terminal voltage is distorted.
Instantaneous reactive power theory (IRPT)	Excellent for steady-state and transient analysis of three-phase systems with or without a neutral conductor [35].	Cannot immediately determine the power characteristics of three-phase loads [36].
Harmonic reference theory	Accurate harmonic compensation	Struggle in handling non-linear load.
Kalman filter-based control algorithm	It is easy to use, quick, highly accurate, and converges after fewer iterations. It also performs well under a range of loading circumstances [27].	Limited robustness when confronted with inaccuracies in the system model.
Wavelet transformation theory	Shown to be a dependable and efficient technique for the early detection and mitigation of PQ disturbances in the power system [31].	Shift invariance is not present. Limited directionality [37].
Fast Fourier transform theory	Efficient computation.	Resolution limitations.

4. Conclusions

This paper discusses regarding control algorithm and configuration of DSTATCOM. DSTATCOM is divided into three category which is single-phase two-wire, three-phase three-wire, and three-phase four-wire systems. Control method of DSTATCOM is divided into two category which is time domain and frequency domain where two control methods from each category has been reviewed as the performance of DSTATCOM depend on it control method. Frequency domain proved to be simpler and faster as it does not involve many mathematical functions compared to time domain method. However, from the study that has been made, frequency domain method is usually combined with other method in order to get the desired result whereas the time domain method can be a standalone.

Acknowledgement

The author would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2020/TK0/UNIMAP/02/113 from the Ministry of Education Malaysia.

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