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Comprehensive Review of DSTATCOM for Power Quality Improvement

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Abstract: *With the deregulation of electric power market, electric power quality (PQ) has become increasingly important for both power suppliers and consumers at the distribution level. Distribution static synchronous compensator (DSTATCOM) is one of the shunt connected custom power devices used to improve various PQ issues. This study presents a comprehensive review of the various DSTATCOM configurations for single-phase and three-phase systems, control strategies and status of topological aspects of DSTATCOM techniques for the compensation of different PQ problems in distribution network for the researchers, designers and engineers working in this area. This review helps to select a PQ improvement technique that suits a specific application in terms of technical and economical aspects. More than 150 research publications on the state of the art of PQ improvement techniques have been rigorously analyzed, classified and listed for quick reference.*

I INTRODUCTION

Power Quality (PQ) is a term which broadly refers to maintaining near sinusoidal waveform of power distribution bus voltages at rated voltage and frequency [1]. It is very important to maintain the electric power PQ within the standard limits [2–3]. Poor PQ can cause the undesirable operation of equipment, increased power losses, interference with communication lines etc.

The widespread use of electronic equipment, such as information technology equipment, adjustable speed drives (ASD), programmable logic controllers (PLC), energy-efficient lighting, are simultaneously the major causers and the major victims of power quality problems. Due to their non-linearity, all these loads cause disturbances in the voltage waveform. Various Power Quality (PQ) problems affecting industrial customers thus affecting industrial production process leading to revenue loss. To mitigate various PQ issues like voltage flicker, Poor Load Power Factor, Loads Containing Harmonics , Notching in Load

Voltage , DC Offset in Loads , Unbalanced Loads, Disturbance in Supply Voltage etc . Various custom power devices are available, amoung them DSTATCOM is one of the shunt connected device used for compensating various PQ Problems under Distribution side.

DSTATCOM can be operated either as the voltage mode control or current mode control. In the voltage mode control, it can make the bus voltage to be balanced sinusoids, irrespective of the unbalance and voltage distortion in the supply side or line current. In the current mode control, it can force the source side currents to be balanced sinusoids [4].

The performance of DSTATCOM is directly related to the design of power circuit components (such as DC-bus energy storage device, output filters and type of inverter), control algorithm used to estimate the compensation signals with less calculation, switching scheme to generate the switching pulses and stability of designed control algorithm [5].

This paper aims at presenting a comprehensive review of DSTATCOM for power quality improvement on distribution system. It covers the different DSTATCOM configurations used, the control methodologies, and their selection for specific applications.

II STATE OF THE ART

Various methods have been applied to reduce or mitigate the PQ problems. The conventional methods are by using capacitor banks, introduction of new parallel feeders and by installing uninterruptible power supplies (UPS). However, the PQ problems are not solved completely due to uncontrollable reactive power compensation and high costs of new feeders and UPS. Conventionally, Static Var Compensators (SVCs) have been used in conjunction with passive filters at the distribution Level for reactive power compensation and mitigation of the power quality problem. Though SVCs are very effective system controllers used to provide reactive power compensation at the transmission level, their limited bandwidth, higher passive element count that increases size and losses, and slower response make them unsuitable for the modern day distribution requirement. Another compensating system has been proposed by employing a combination of SVC and active power filter, which can compensate three phase loads in a minimum of two cycles. Thus, a controller which continuously monitors the load voltages and currents to determine the right amount of compensation required by the system and the less response time should be a viable alternative.

Distribution Static Compensator (DSTATCOM) has the capacity to overcome the above drawbacks by providing precise control and fast response during transient and steady state, with reduced foot print and weight . The DSTATCOM has emerged as a promising device to provide solution not only for voltage related issues but a host of other current related power quality problem's solutions such as voltage regulation , load balancing, reactive power compensation, power factor correction & improvement and current harmonic control.

The various aspects such as modeling, design, and simulation for reactive power compensation, unbalanced and harmonic compensations, and voltage regulation are reported in [6]–[10].Monitoring of electric power quality based on different techniques such as wavelet and neural networks is also reported in [7] and [13]. The modeling of the DSTATCOM system [6], [14] is necessary for feasibility and validating the design. The review of the present technology and concept of custom power park is discussed by Ghosh and Ledwich [6]. The voltage regulationfunction of the DSTATCOM is discussed in [15] and [16]. The concept of constant voltage at point of common coupling (PCC) is realized by pumping extra amount of reactive power into thesource side, so that the line drop can be compensated dynamically.

The concept of battery energy storage system (BESS) forDSTATCOM is presented [17], [18]. The operation of the DSTATCOM for weak or isolated generation is also important [6]. The DSTATCOM is proposed for compensating voltage quality problems such as sag and swell [7] and flicker [6]. The reactive power demand in isolated power generation for voltage regulation isachieved using STATCOM [19].

The control schemes of static compensators are developed using the well-known theory proposed by Akagi et al. [20]. The extraction of fundamental active and reactive components of currents is demonstrated in this theory. Another widely accepted control theory is synchronous reference frame (SRF) theory reported by Divan et al. [21]. This theory is based on the transformation of currents from a-b-c frame to synchronous rotating frame and then extracting the fundamental frequency components. Many other control techniques for shunt compensators have been reported such as sliding mode control [23], voltage template and PI controllers [25], instantaneous symmetrical component theory [6], and neural network theory [22], [24]. [41] provide a comprehensive study of design, operation, and flexible control of a DSTATCOM operating in voltage control mode using an external inductor.

III OPERATING PRINCIPLE OF DSTATCOM

DSTATCOM is one of the shunt connected custom power devices and consists of an inverter (voltage source inverter [VSI] is commonly preferred), DC-link energy storage device, output filter and a coupling transformer as shown in Fig. 1 [26].

VSI converts the DC voltage across the storage device into a set of three-phase AC output voltages. The generated voltages are in phase and interconnected with the utility grid through a coupling transformer. Proper adjustment of the phase and magnitude of the DSTATCOM output voltages allows effective control of active and reactive power flow between the DSTATCOM and the utility grid [27–29]. The single phase equivalent circuit of a power system with a DSTATCOM is shown in Fig. 2. V_1, V Coupling, V_{PCC} and V_S represent the inverter output voltage; the voltage drop caused by coupling impedance, the voltage at point of common coupling (PCC) and source voltage, respectively. If V_1 is equal to V_{PCC}, the

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reactive power exchange between DSTATCOM and utility grid is zero and the DSTATCOM does not absorb or generate any reactive power. When V_1 is greater than V_{PCC}, DSTATCOM performs an inductive reactance connected at its terminal. The current, flows through the transformer reactance from the DSTATCOM to the utility grid, and the device generates capacitive reactive power. If V_{PCC} is greater than V_1, DSTATCOM performs a capacitive reactance connected at its terminal. Then the current flows from the utility grid to the DSTATCOM, resulting in the device absorbing inductive reactive power [26, 30].

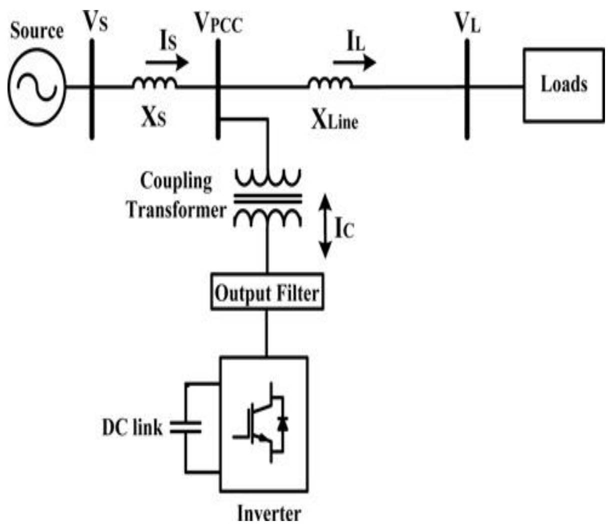

Fig. 1 Schematic diagram of DSTATCOM

DSTATCOM can manage active power flow with the utility grid by adjusting the phase angle between the DSTATCOM output and the utility grid voltages. This exchange can be used to mitigate the internal losses of the inverter and to maintain the DC capacitor charged to the proper DC voltage and thus DSTATCOM output voltage magnitude can be adjusted. Fig. 3 illustrates the vector diagram of DSTATCOM at fundamental frequency for the transition states from inductive to capacitive mode and vice versa. 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. 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 case causes a voltage rise in the DC-link [31].

In practical applications, power losses are not negligible. The losses on transformer windings and inverter switches are the main types of losses encountered in DSTATCOM. A small phase angle difference between V_{PCC} and V_C is added to the compensation signal to suppress these losses [32]. The power flow between the DSTATCOM and utility grid is related with DSTATCOM output voltage VC, the utility grid voltage V_{PCC} and their phase angle differences as illustrated in Table 1 [31].

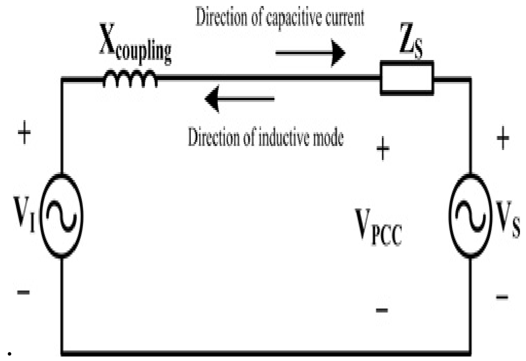

Fig. 2 Equivalent circuit of a single-phase power system with a DSTATCOM [33]

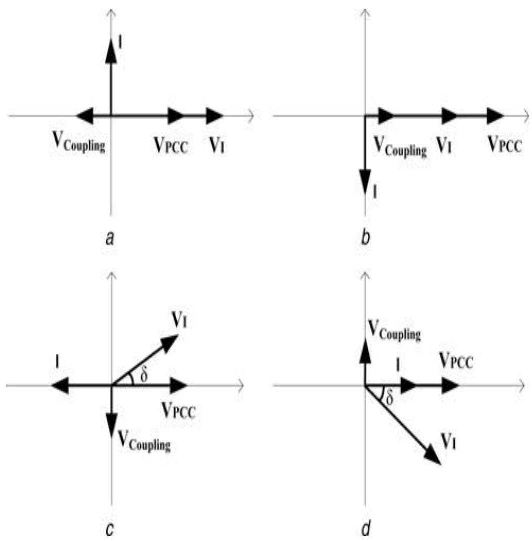

Fig. 3 Vector diagrams of DSTATCOM[33]

a Capacitive mode b Inductive mode

c Active power release d Active power absorption

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Table 1 Required conditions for power exchange between DSTATCOM and utility grid

Voltage relation	Power exchange		
	Dstatcom	↔	Utility grid
$\lvert V_1\rvert > \lvert VPCC\rvert$	Q	→	Q
$\lvert V_1\rvert < \lvert VPCC\rvert$	Q	←	Q
$\delta < 0$	P	→	P
$\delta > 0$	P	←	P

IV CLASSIFICATIONS OF DSTATCOM BASED ON POWER CIRCUIT STRUCTURE

DSTATCOMs can be classified by their circuit structure. As shown in Fig. 4, power circuit structure of the DSTATCOM can be mainly classified into three categories namely inverter topology, type of power source and advanced configuration. Recently developed new topologies and configurations for DSTATCOM have been also discussed in this section.

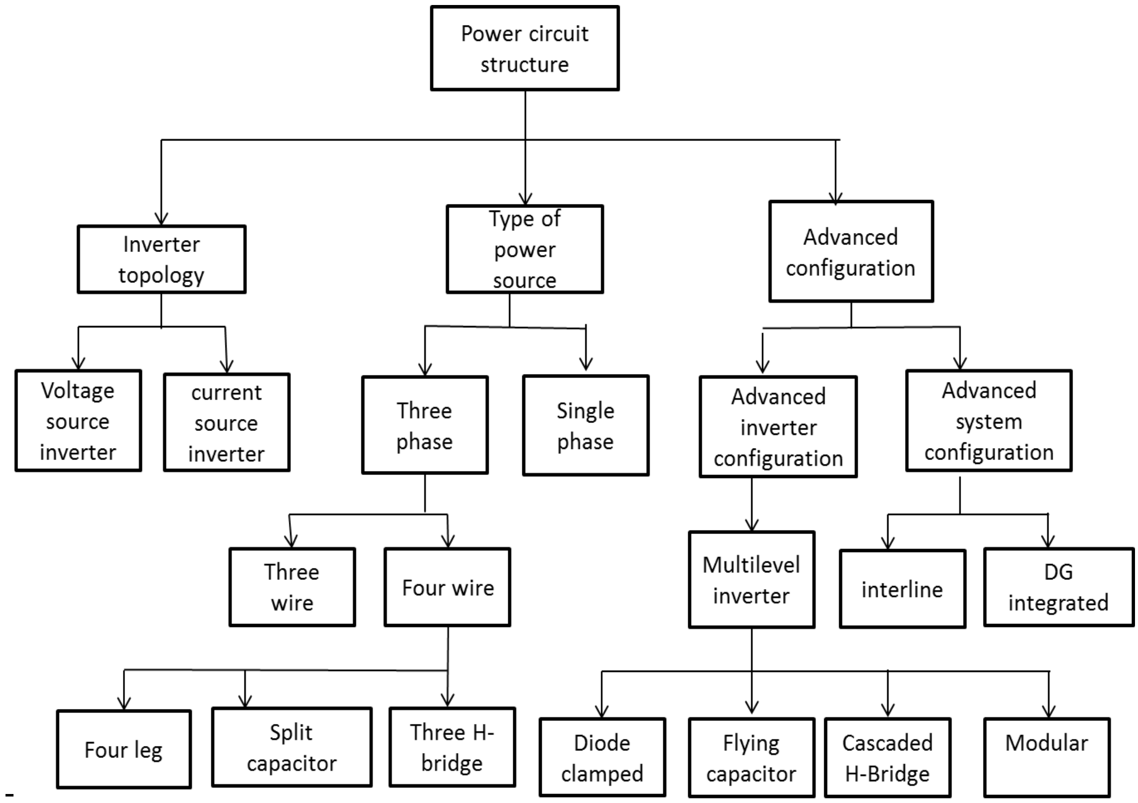

Fig 4 Classification of DSTATCOM based on power circuit structures [33]

5.1 Reference signal extractıon technıques

The development of real-time methods for the detection and analysis of disturbances is a major concern to evaluate the quality of supply voltage and to prevent the harmful effects on equipment. The performance of a DSTATCOM strictly depends on its reference signal generation technique. In general, frequency-domain and time-domain methods are used to generate the reference signal. The time-domain methods are faster and easy to implement than the frequency-domain methods but they present worse detection performance than the frequency-domain methods. Fig. 5 illustrates the classification according to reference signal extraction techniques used in DSTATCOM.

(1) Frequency-domain methods: Frequency-domain methods are suitable for both single and three-phase systems. They are mainly derived from the Fourier analysis and include the following three subdivisions.

(i) Fast Fourier transform (FFT): A FFT is used to compute the discrete Fourier transform (DFT) and inverse of it. A Fourier transform converts functions from time to frequency domains and vice versa. FFT computes such transformations by factorising the DFT matrix into a product of sparse factors. In DSTATCOMs, FFT is used to extract the harmonic components from the harmonic polluted signals. Owing to excessive computation in on-line application of FFT, it has high response time

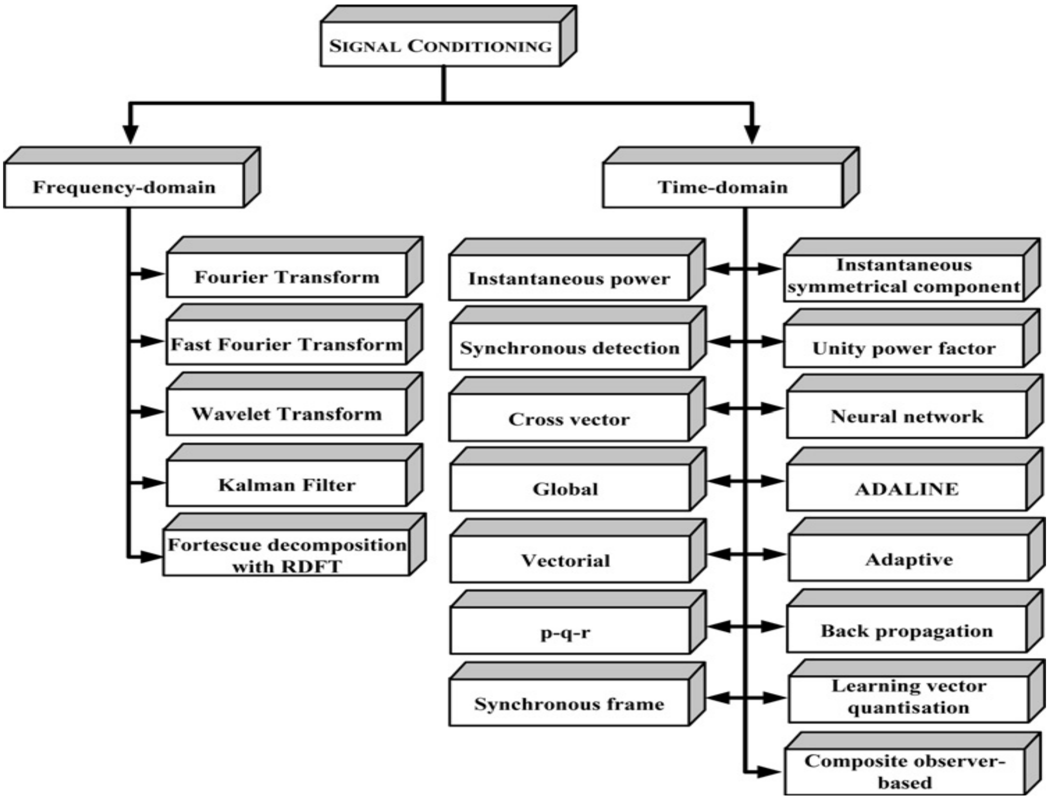

Fig.5 Classification according to reference signal extraction techniques [33]

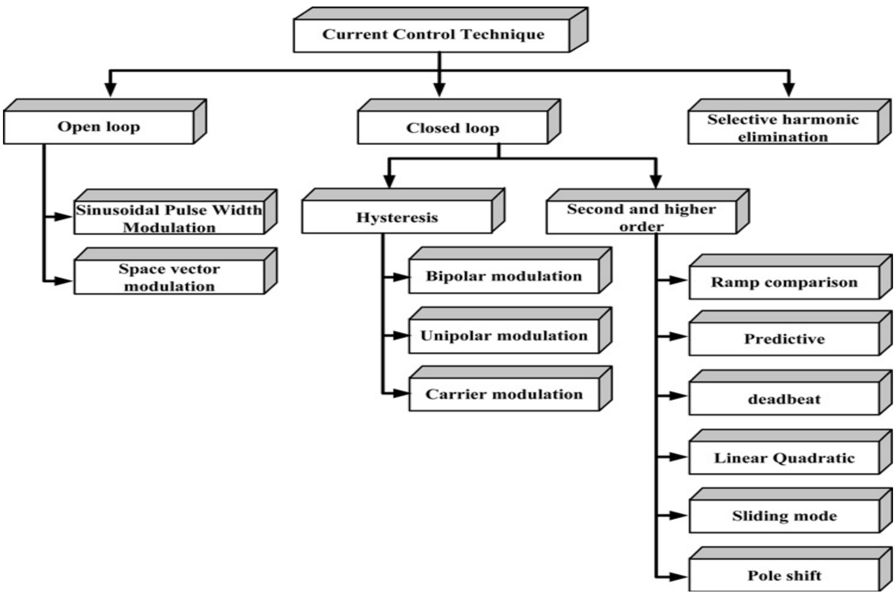

Fig. 6 Classification of current control methods [33]

(ii) Kalman filter: Kalman filter is a recursive optimal estimator and requires a state variable model for the parameters to be estimated and a measurement equation that relates the discrete measurement to the state variables. Kalman filter uses a mathematical model of the states to be estimated and suitable for real time applications. If the harmonic contents have a time varying amplitude, Kalman filter-based algorithm tracks the time variation after the initialisation period.

(iii) Wavelet transform base algorithm: This method is based on the definition of the active and reactive power in the time-frequency domain using the complex wavelet transform. The voltage and current signals are transformed to the time-frequency domain using the complex wavelet with scaling and translation parameters to set the frequency range and localise the frequency, respectively.[40] presents a dual tree-complex wavelet transform-based control algorithm for a distribution static compensator (DSTATCOM) to improve the power quality (PQ) in a distribution system.

(2) Time-domain methods: The following time-domain approaches are mainly used for three-phase systems.

(i) p–q Theory: In p–q theory, voltages/currents of 3P3 W system are

converted into two-phase voltage/current components by Clarke transformation on orthogonal α–β coordinates, thus the instantaneous active and reactive powers can be determined without any time delay. P–q theory provides a theoretical validation that the instantaneous active and reactive powers are uniquely related with the instantaneous active and reactive currents, respectively, in 3P3 W systems. P–q theory does not follow power conservation and conflicts with the general understanding of power in that the zero sequence instantaneous reactive power cannot be defined by this theory in 3P4 W systems.

(ii) Synchronous detection theory: This technique, is similar to p–q theory, and comprises of three approaches-equal power, equal current and equal resistance criterion. The average power is calculated and divided equally between the three phases. In synchronisation process, the compensation signals are synchronized with relative utility grid phase voltage. It is easy theory to implement but it is affected from voltage harmonics.

(iii) Cross vector theory: In cross vector theory, the instantaneous active and reactive power is defined by scalar/vector product of the voltage and the current space vectors in a 3P4 W system. Cross vector theory identifies one instantaneous active power and three instantaneous reactive powers. However the three components of instantaneous reactive powers are linearly dependent to each other. In the presence of a zero sequence voltage, the neutral line current cannot be eliminated completely by compensating the instantaneous reactive power.

(iv) Global theory: Since the reference compensation currents are determined in the A-B-C reference frame, there is no reference-frame transformation requirement. Therefore the global theory gives less complexity in realising the control circuit of the DSTATCOM. By using this theory, DSTATCOM able to compensate reactive power and suppress harmonic/neutral currents of the imbalanced/distorted load without supplying or consuming real power .

(v) Vectorial theory: In this method, vectorial formulation does not need to undergo any kind of coordinates translation. Vectorial theory utilises the same power variables as p–q theory and identifies the instantaneous reactive power in phase coordinates. The current vector is split into three components. The first one is collinear with respect to the modified voltage vector, and it transports the instantaneous real power. The second one is collinear with respect to the zero-sequence voltage vector, and it transports the instantaneous zero-sequence power. The last one is normal with respect to the modified and zero-sequence voltage vectors, and it transports the instantaneous imaginary power.

(vi) p–q–r theory: The p–q–r theory takes the advantages of both p–q theory and cross vector theory. The defined instantaneous powers follow power conservation. Both instantaneous active and reactive powers can be defined in the zero sequence circuit in three-phase four-wire systems. The three power components are linearly independent of each other. In the presence of a zero sequence voltage, the neutral line current can be eliminated completely by applying the p–q–r theory.

(vii) Synchronous frame-based theory: This algorithm is based on the transformation of the three-phase system into synchronously rotating frame to extract the direct, quadrature and zero-sequence components of signals. The active and reactive components of the system are defined by the direct and quadrature components, respectively. The high-order harmonics still remain in the signal; however they are modulated at different frequencies. These are the undesired components to be eliminated from the system and they represent the reference harmonic current. The system is very stable since the controller deals mainly with DC quantities. The computation is instantaneous but causes a time delay in filtering the DC quantities

(viii) Instantaneous symmetrical component theory: In instantaneous symmetrical components method, a symmetrical voltage and current are transformed by symmetrical components to obtain positive sequence, negative sequence and zero sequence components of three phase variables. The instantaneous symmetrical component theory has advantages such as: it is simple in formulation, computationally less intensive for reference currents generation thus ensuring fast dynamic response and avoids interpretation of various definitions of instantaneous reactive powers and complex transformations. Numerous studies focused on symmetrical components theory were used for extraction the reference signal .

(ix) Unity power factor theory: This is another technique, except thev fact that it forces the instantaneous current signal to track the voltage-reference waveform. This implies that the power factor would be fixed to unity and the system would only be suitable for the combined system of VAr and current harmonic compensation.

(x) Neural network (NN)-based theory: NN-based algorithms are used to extract required information after processing of signals by learning or training and activation function. Arya and Singh proposed an algorithm based on load conductance estimation using NN is implemented on a three phase DSTATCOM. Its structure is reflected as Kohonen learning or Kohonen feature maps. It is used for extraction of fundamental component of load currents in terms of conductance and susceptance. Arya et al., [34] proposed a NN based Anti-Hebbian control algorithm for PQ improvement under linear/non-linear type consumer loads which is used for extraction of fundamental active and reactive power components of load currents i11n terms of weighted signals. Reference [35] used a NN based adjustable step least mean square (LMS) for signal extraction. It uses autocorrelation time mean estimate error signal for updating the step size in place of simple error signal.

(xi) Back propagation (BP) based theory: BP algorithm includes three steps namely, the feed-forward of the input signal training, calculation and BP of the error signals, and upgrading of training weights. Continuity, differentiability, and non-decreasing monotony are the main characteristics of this algorithm. It is based on a mathematical equation and does not need special features of function in the learning process. It also has smooth variation on weight correction because of batch updating features on weights. In the training process, it is slow because of more number of learning steps, but after the training of weights, this algorithm generates very fast trained output response [36].

(xii) Learning vector quantisation (LVQ)-based theory: It is a standard statistical clustering technique which is also known as special case of competitive network. The desired values arevextracted through training of weighed values of load currents using the gradient descent method. In the training process, the desired signals are at the position of the learning stage. After training, LVQ network classifies the supply current vector by assigning it to the same class as the output stage. It has its weighted vector closest to the input vector. In the LVQ network, each unit has a known value or elements and used supervised learning which differed from the Kohonen self-organising map [37].

(xiii) Adaptive-based theory: It is a closed loop controller that can adjust system behaviour in terms of response to disturbances. An area of adaptive control provides an automatic adjustment of the controller gains and parameters in real time, to achieve a desired level of performance. Characteristics of these control algorithms are the ability to extract required information from real online data to tune the controller, and also used for grid synchronization. Based on this control theory, many control algorithms are alsoreported in available literature such as adaptive nature for synchronous extraction , adaptive theory-based improved linear sinusoidal tracer, adaptive control strategy based on artificial immune system and leaky LMS adaptive filter [38].

(xiv) Composite observer-based theory: Composite observer is used to extract individual harmonics from repetitive signals. The settling period and the bandwidth of the observer depend on how far the observer poles have been placed from the origin of the S-plane or the Z-plane. The errors in the magnitude and phase of the extracted components, because of the deviation of the signal from the central frequency of the observer, are made very small by providing an integrated phase-locking arrangement. Further improvement in the accuracy, particularly in the extracted higher harmonics, is because of the introduction of multi-rate sampling. Advantages of this algorithm are that it is less sensitive with supply frequency variation, low distortion in the extracted signal without leakage of harmonics and so on [39].

(3) Other algorithms: There are numerous optimisation and estimation techniques such as adaptive linear neuron (ADALINE), LMS-based ADALINE, differential evolution , time-varying Fourier coefficient series, Fortescue decomposition with recursive DFT , peak detection, based algorithms used to extract the reference signal.

5.2 Current control techniques

Generation of suitable switching signal is the most significant part of DSTATCOM's control algorithm and has a high influence on the compensation performance. PWM is the most reliable way of reconstructing a desired output voltage waveform. The frequency of the switching should be significantly higher than that of the desired signal for a reliable signal representation. PWM methods are often categorised as open loop (feed-forward) and closed loop (feed-back) methods. The open loop method is subdivided into SPWM and space vector PWM (SVM). The closed loop method are classified into hysteresis current control and linear current control involving ramp comparison, state feedback, synchronous vector, predictive, deadbeat, sliding mode, linear quadratic regulator, pole shift controllers. Apart from these methods the selective harmonic elimination technique also used for generation proper switching signal. Fig. 6 illustrates the classification of current control methods used in DSTATCOM

VI PRACTICAL CONSIDERATIONS

In practical applications, the selection of the DSTATCOM structure is an important task for scientists and engineers. The main design considerations for proper selection of inverter topology are [33]

(i) Output voltage level.

(ii) Power rating.

(iii) Current/voltage distortion level.

(iv) dv/dt stresses level.

(v) Common-mode voltages level.

(vi) Manufacturing cost level

VII CONCLUSIONS AND FUTURE SCOPE

A comprehensive state of the art of DSTATCOM for power quality improvement in the three-phase power distribution system has been presented to explore the topologies and control techniques. The detailed classification, state of the art, design considerations, and comparison have been given for easy selection of a DSTATCOM for specific applications. The future research fields on DSTATCOM technology can be summarised by the following goals [33]:

(i) Novel control algorithms should be developed to increase the capability of DSTATCOMs for simultaneous mitigation of multiple PQ problems

(ii) There is a lack of research studies about the simultaneous compensation of flicker and harmonics on DSTATCOMs.

(iii) There are no enough research studies on DSTATCOMs to extract and eliminate the interharmonic components.

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