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Shunt Active Power Filter Control Strategies for Harmonic Reduction: A Review

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ABSTRACT: Owing to the destructive impacts of harmonic currents, the topic of reducing their impactson power system has attracted tremendous research interests. In this regard, a shunt active power filter(SAPF) is recognized to be the most reliable instrument. It performs by first detecting the harmoniccurrents that are present in a harmonic-contaminated power system, and subsequently generates andinjects corrective mitigation current back into the power system to cancel out all the detected harmoniccurrents. This means that other than the ability to generate corrective mitigation current itself, it isactually more important to make sure that the SAPF is able to operate in phase with the operatingpower system, so that the mitigation current can correctly be injected. Hence, proper Control technique needs to be integrated when designing the control algorithms of SAPF. This paper critically discusses and analyzes various types of existing phase synchronization techniques which have beenapplied to manage operation of SAPF; in terms of features, working principle, implementation andperformance.

KEYWORDS: Active powers filter (APF);Totalharmonic Distortion;Hysteresis band current controller;Harmonic current compensation

I.INTRODUCTION

THE USE of shunt active power filters (APF) to compensate for the line current distortion and to improve the power factor has been deeply studied in the last years [1]–[4]. The interest in this subject is due to many factors as, for example, international standards regarding current distortion limits, national rules concerning the power factor, social and economical use of energy in a more efficient way, etc.The Electric Power Quality [EPQ] has become an important part of the distribution power system. Harmonics need attention in the EPQ of the distribution system because power factor is very important consideration for efficient functioning of system and also economic point of view which is very much effected by the harmonic content.To overcome the effects of harmonics in the EPQ, the passive filters are viable solution and they are usually designed for custom applications. However, they can mitigate only few harmonics (which can be tuned), and also they can introduce resonance in the power system. Due to the recent advances in power electronic fast commutating switches, APFs appear as a better solution to mitigate harmonics and thus improve power quality [1].The ever increasing use of power semiconductor switching devices in power supply for DC motors, computers and other microprocessor based equipment causes harmonics inelectric power system. Harmonics may cause serious problems such as excessive heating of electric motors and malfunction of sensitive electronic gadgets. Filtering of harmonics can be effected by using either passive or active power filters. Traditionally, passive filters have been used for harmonic mitigation purposes. Active filters have been alternatively proposed as an adequate alternative to eliminate harmonic currents generated by nonlinear loads as well as for reactive power compensation. Various control methods with various control strategies as discussed in [1]-[12], [14-15] were implemented for minimizing harmonics in the electric power network. However, to date the shunt active power filter is still extensively used. Active Power Filter consists of Voltage Source Converter operating at relatively high frequency togive the output which is used for cancelling low order harmonics in the power system network. With Shunt ActivePower Filter, crucial part involves generation of the reference signal used to generate gating signals for the VSC. Fig. 1 shows Block Diagram of PWM Controlled VSC operated as APF.

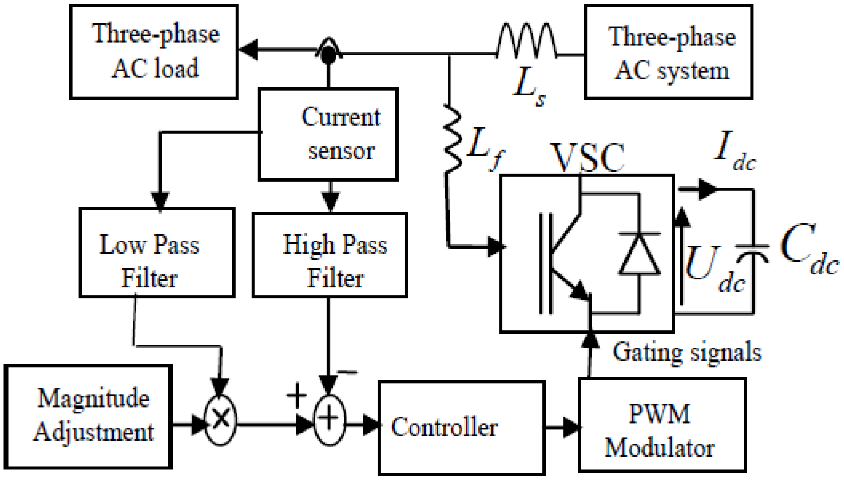

Fig.1 Block Diagram of PWM Controlled VSC operated as APF

Several control methods involved in generating reference signals have been discussed in [1]-[14] among them being the Synchronous Reference Frame method. Many control strategies have been proposed, for example in [14]-[15] discussed about taking care of delays which when not taken care of, may cause the controller to be unstable hence the whole system becoming unstable. However, where control is concerned, the integral component of the PI controller can lead to integrator windup resulting into instability of the controller and hence poor performance of the shunt active power filter. In order to improve performance, this paper presents a method to effectively compensate the windup of the integral term of the PI controller. It is an integrator antiwindup circuit.

II.SHUNT ACTIVE POWER FILTER (SAPF)

Modern active filters have the multiple functions like harmonic filtering, damping, isolation and termination, reactive power control for power factor correction and voltage regulation, voltage flicker mitigation and load balancing. It is cost effective and thus can be used commercially. The operation of APF depends on the algorithm applied to the controller [4]. The schematic of SAPF is as shown in Figure 2 The output voltage of Inverter can be controlled both in magnitude and phase, which is coupled to system voltage through a relatively small (0.15 -0.2 pu) tie reactance. For full compensation of load, converter has to supply reactive power (Q) of same magnitude, but of opposite sign. So, reactive power drawn from source is zero, thus unity power factor can be achieved.The Shunt Active Power Filter (SAPF) has the robust control of current harmonics within the limit and makes the system to be more efficient. The Figure 1 shows the configuration of the Shunt APF [3]. The coupling transformer connected to the system for the injection of the compensating harmonics to eliminate the distortion. The switching converter is based on VSC topology of three leg configuration of IGBT components. The Capacitor C connected along the DC terminal of the converter which supplies the DC voltage VDC to the converter. The 6 pulse converters which are operated in the 1800 phase shift to the IGBT of same leg, 1200 between the two legs and 600 phase shift between the n+ 1 component.

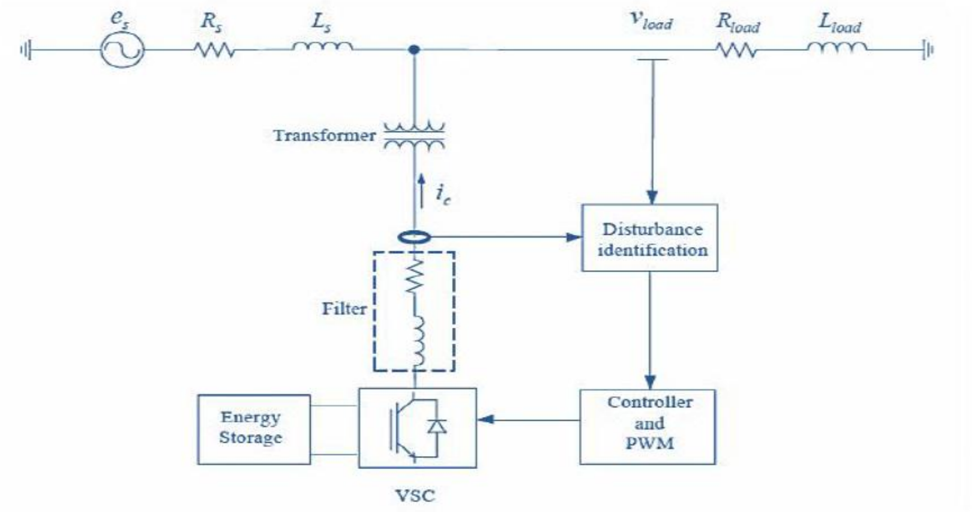

Figure 2. Shunt Active Power Filter (SAPF) Configuration

The main circuit of the shunt APF shown in Fig. 1(a) is implemented using the three-leg split-capacitor topology [1-4]. It uses three independent controllers acting on a half bridge pulse width modulation (PWM) VSI converter. A common capacitor is coupled to a dc-bus with the midpoint connected to the neutral wire, while the ac side is connected to the power supply system using three coupling inductors, which act as low pass filters (LPF). This topology requires a control strategy to balance the dc-bus capacitor voltages. The circuit shown in Fig. 3 is implemented using the four-leg full-bridge VSI topology [5-8]. The neutral wire current is controlled via an additional leg, requiring an additional coupling inductor. Despite needing an additional leg, smaller capacitors than those of the S-C topology are required, and balancing the dc-bus capacitor voltage is not necessary. shows the shunt APF implemented using three single-phase full-bridge VSI converters, as well as an increasing number of switching devices. However, the 3F-B topology allows independent control of the three phases [9], while the dc-bus voltage drops by a factor of 3 when compared with the F-L topology, and by factor of 2 when compared with the S-C topology [7] of common coupling (PCC), between voltage supply and harmonic-producing load (or morecommonly known as nonlinear load). In the literature, the harmonic-producing load is commonlydeveloped by using an uncontrolled bridge rectifier which is further connected to a combination ofresistor (R), inductor (L), and capacitor (C) elements [16,17].

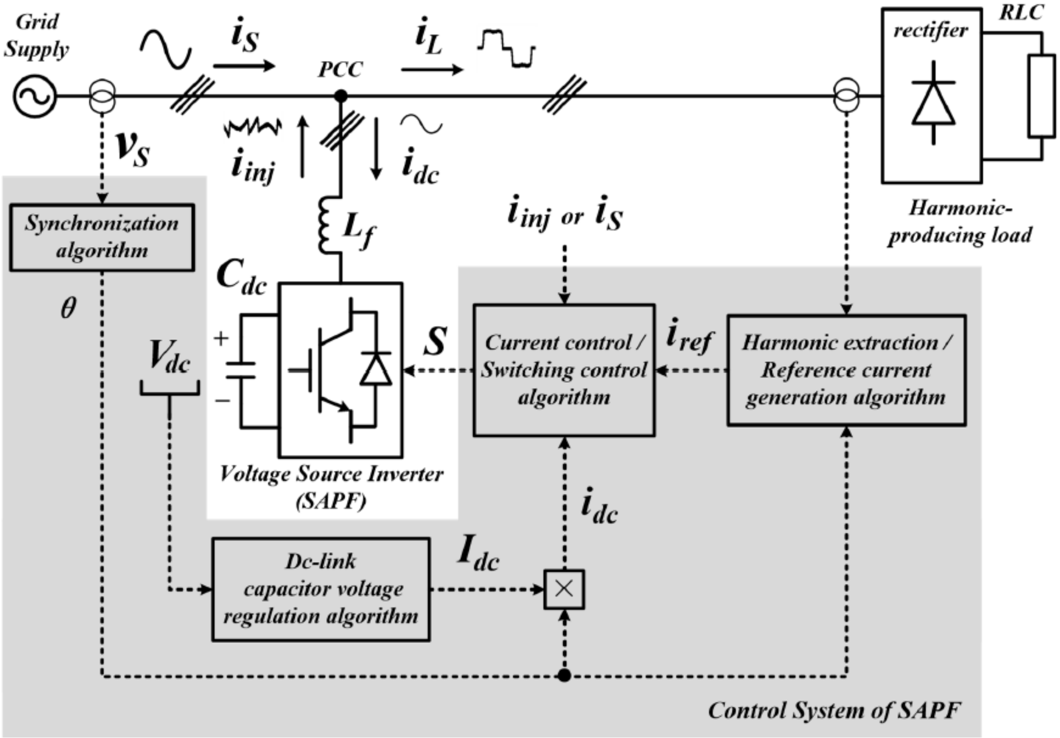

Figure 3. Typical power circuits connection of voltage source inverter (VSI)-based shunt active power filter (SAPF) and the associated control algorithms in its control system.

The structure of SAPF can distinctively be separated into two parts: power circuits whichcomprises of power semiconductor switches, capacitors, inductors, power diodes (in some SAPFtopologies); and a control system that is designed to control switching operation of the switches.The operation of SAPF is rather simple. One can easily grasp the basic idea by looking at thecurrent flow in a SAPF-installed power system. Referring to Figure 1 and by applying Kirchho’scurrent law (KCL) at PCC, current flow in a harmonic-polluted power system before connecting aSAPF can be written as

Harmonic Compensation

Synchronous frame theory (d-q theory) based controller is suggested because it has greater and gives better performance when the supply voltage is distorted. The advantage with SRF method is any harmonic component other than DC present in the element can be filtered out easily because the fundamental components are turned as DC components [6].

APF Control Methods

Instantaneous Active Power Theory

The instantaneous active, reactive power method, proposed by Akagi [4], for calculating the reference compensation currents are required to inject into the network at the connected point of the nonlinear load. It remains one of the most popular SAPF control schemes. Since then, the theory has inspired many works dealing with active power filter compensation strategies. One of the peculiar features of a shunt APF is that it can be designed without active energy source units, such as batteries, or in other forms in its compensation mechanism. In other words, an ideal APF does not consume any average power supplied by source [5].

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

$$P_{\alpha\beta} = V_\alpha i_\alpha + V_\beta i_\beta$$

$$Q_{\alpha\beta} = V_\alpha i_\beta + V_\beta i_\alpha$$

$$\overline{\overline{P}} = \tilde{P} + \vec{P}, \overline{\overline{Q}} = \tilde{Q}$$

Synchronous Reference Frame Method

A synchronous reference frame method for obtaining the load currents at the fundamental frequency, which will be the desired source currents. The APF reference compensation currents are then determined by subtracting the fundamental components from the load currents. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. The basic structure of SRF controller consists of direct (d-q) and inverse (d-q) park transformations as given below. These can be useful for the evaluation of a specific harmonic component of the input signals.

$$\begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} I_{la} \\ I_{lb} \\ I_{lc} \end{bmatrix}$$

$$\begin{bmatrix} I_{ld} \\ I_{lq} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} I_{l\alpha} \\ I_{l\beta} \end{bmatrix}$$

$$\text{Where, } \theta = \tan^{-1}\left(\frac{v_\beta}{v_\alpha}\right)$$

$$\overline{\overline{I_{ld}}} = \widetilde{I_{ld}} + \overline{I_{ld}}, \overline{\overline{I_{lq}}} = \widetilde{I_{lq}} + \overline{I_{lq}}$$

The DC voltage across the capacitor Vdc is to be kept within a range of a voltage throughout the operation of the system. The PI controller is connected to output of the voltage measurement Vdc and a constant is compared with the measured voltage of the system.

Reference current computation method

The active power filter control is based on the use of self-tuningfilters (STF) for the reference current generation and on a modulated hysteresis current controller.This active filter is intended for harmonic compensation of a diode rectifier feeding a RL load underdistorted voltage conditions**.**The proposed control strategy canbe divided in two parts. The first part is the harmonic isolator (reference current generation). Itconsists in generating the harmonic current references and uses STFinstead of HPF or LPF usually used in the p–q theory first proposedby Akagi et al. [8]. This harmonic isolator will be implementedinto a DSPACE system(DS1104 card) in the experimental study. Thesecond part is the current control of the power converter. This controllergenerates the suited switching pattern to drive the IGBTs ofthe inverter by using a modulated hysteresis current controller. Inthe experimental study, this controller is implemented into an analoguecard. Fig. 2 shows the schematic diagram of the active powerfilter system**.**

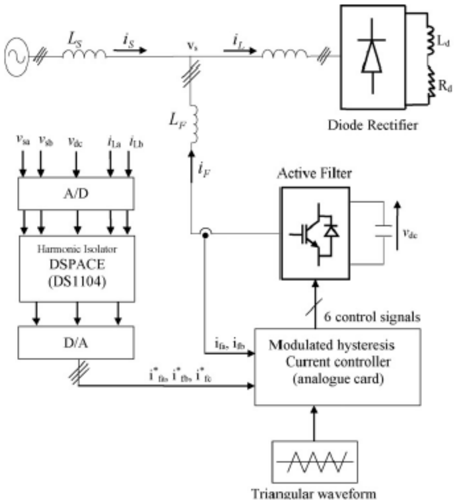

Fig. 2. Active filter system.

Thehardware implementation has been performed based on the optimisationof the reference current generation and using a modifiedversion of the p–q theory. The control of the active filterwas dividedin two parts, the first one realized by the DSPACE system to generate the reference currents and the second one achieved by an analogue card for the switching pattern generation, implementinga modulated hysteresis current controller.Self-tuning filters have been introduced in the proposed modifiedversion of the p–q theory instead of classical extraction filters(high pass and/or low pass filters) for both grid voltages and loadcurrents. The use of this filter experimentally leads to satisfactoryperformances since it perfectly extracts the harmonic currentsunder distorted conditions. For the current controller, we implementedthe modulated hysteresis current controller to obtain afixed switching frequency for the IGBTs.The simulation and the experimental results have demonstratedand comforted the major advantages of using STF and modulatedhysteresis current controller in the filter control. In conclusion,the proposed control for shunt active power filter is effective ininstallation on an actual power system under distorted conditions.

Adaptive Hysteresis Band Current Controller

a novel adaptive hysteresis bandcurrent controller is proposed for active power filter toeliminate harmonics and to compensate the reactive powerof three-phase rectifier. The novel adaptive hysteresisband current controller changes the hysteresis bandwidthaccording to modulation frequency, supply voltage, DCcapacitor voltage and slope of the *i*, referencecompensator current wave. The hysteresis band currentcontroller determines the switching signals of the ActivePower Filter (APF), and the algorithm based on anextension of synchronous reference frame theory (d-q-0) isused to determine the suitable current reference signals**.**The hysteresis band current control can be implemented to generate the switching pattern in order to get precise and quickresponse. The hysteresis band current control technique hasproven to be most suitable for all the applications of currentcontrolled voltage source inverters in active power filters. Thehysteresis band current control is characterized byunconditioned stability, very fast response, and good accuracy.On the other hand, the basic hysteresis technique exhibits alsoseveral undesirable features; such as uneven switchingfrequency that causes acoustic noise and difficulty indesigning input filters.an adaptive hysteresis-band current control PWM technique where the bandwidth can beprogrammed as a function of system parameters to optimizethe PWM performance. It is proposed an adaptive hysteresisbandalgorithm for the implementation of the fixed-frequencyadaptive hysteresis current control for voltage source invertersin active power filters. Although various criteria ofoptimization are possible, the paper illustrates a case wherethe modulation frequency is held nearly constant.The switching frequency of the hysteresis band current control method described above depends on how fast the current changes from the upper limit of the hysteresis band to the
lower limit of the hysteresis band, or vice versa. The rate of change of the actual active power filter line currents vary the switching frequency, therefore the switching frequency does not remain constant throughout the switching operation, but varies along with the current waveform. Furthermore, the line inductance value of the active power filter and the dc link

capacitor voltage are the main parameters determining the rate of change of active power filter line currents. The switching frequency of the active power filter system also depends on the capacitor voltage and the line inductances of the active power filter configuration.

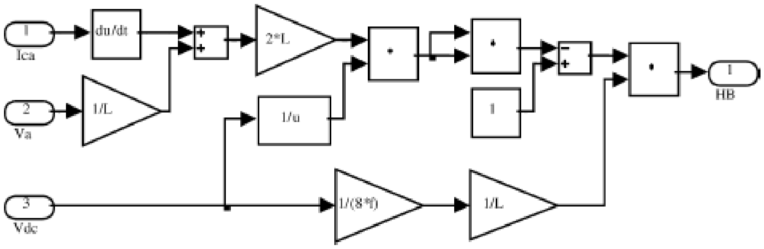

Fig. 5. The adaptive hysteresis bandwidth calculation block diagram.

Reference Compensation Current Strategy

The APF referencecompensation currents, one of the mainstreams is to maintainsinusoidal source currents supplying average real power to the load. With the use of sinusoidal source current strategy, it is proved that the APF can have better performance than other strategies[15]. To achieve full compensation of both reactive power andharmonic/neutral currents of the load, this paper presents a novelapproach to determine the shunt APF reference compensationcurrents, even if the source voltages and load currents are bothimbalanced and distorted**.**compensation strategy of the active power filter is based on the requirement that the source currents need to be balanced, undistorted, and in phase with the positive-sequence source voltages. The goals of the shunt APF control are: 1) unity source power factor at positive-sequence fundamental frequency; 2) minimum average real power consumed or supplied by the APF; 3) harmonic current compensation; and 4) neutral current compensation. Therefore, the active power filter must provide full compensation (i.e., harmonic/neutral currents and reactive power) for the nonlinear load. To achieve these goals, the desired three-phase source currents must be in phase with the positive-sequence fundamental source voltage components.

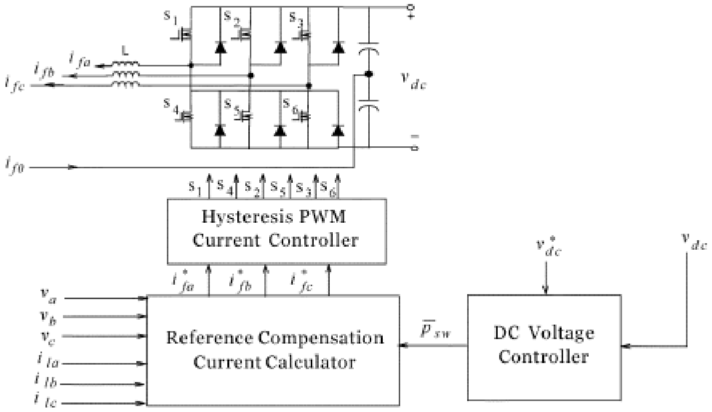

Fig. 2. Circuit configuration of the APF for Simulink simulation based on the proposed approach.

it is found that all of thesestrategies work well on reactive power and/or harmonic currentcompensation for the imbalanced and/or distorted load underideal source voltages, where (10), (20), and (55) are identical.
However, the synchronous reference frame (SRF) strategy of(15) only computes the sinusoidal fundamental components ofthe load currents; the reactive power compensation and a nullneutral current thus cannot be achieved if the load

imbalanceat the fundamental frequency occurs. As shown in the results, when the source voltages are imbalanced and/or distorted, it isfound that the proposed compensation approach is superior tothe reviewed control strategies on achieving the main goals ofthe APF described in Section III. Overall, the proposed strategygives the best APF performance in comparison with the reviewedapproaches.As described in the paper, a well-designed active power filtershould be able to effectively compensate reactive power andsuppress harmonic/neutral currents of the imbalanced/distortedload without supplying or consuming average real power. Thetheory of the proposed compensation strategy for the APF isdescribed in detail and the APF performance is demonstrated through simulations by using Matlab and Simulink. Both resultsyield good agreement with the expected APF goals.

Synchronous Detection Method

In this algorithm, the three-phase sourcecurrents are assumed to be balanced after compensation[6].The real power p(t) consumed by the load could be calculated from the instantaneous voltages and loadcurrents.The average value Pdc is determined by applying p(t) to a low passfilter.This method can be extensively used for compensation of reactive power, current imbalance andmitigation of current harmonics. It is the simplest methodas it requires minimum calculations. However thismethod suffers a drawback from individual harmonicdetection and its mitigation.

Perfect Harmonic Cancellation (PHC) method

The Perfect Harmonic Cancellation (PHC)method can be regarded as a modification of the threeprevious theories. Its objective is to compensate all theharmonic currents and the fundamental reactive powerdemanded by the load in addition to eliminating theimbalance. The source current will therefore be in phasewith the fundamental positive-sequence component ofthe voltage at the PCC [7]the fundamental components of the load voltages and can be obtained using a positive sequence detector. Also, Pdcis filtered from P(t) using a simple low pass filter (LPF). The desired currents calculated using this method are symmetrical and sinusoidal.

Phase Synchronization Techniques

The phase synchronization techniques which have so far been integrated in the control system of SAPF. It includes the two common techniques in the literaturenamely zero-crossing detection (ZCD) [19,51,52] and phase-locked loop (PLL) [53–55], and the more recent techniques such as artificial neural-network (ANN) or adaptive linear neuron (ADALINE) [56–58], fundamental component extraction [59,60], and unit vector generation [61–63]. In this manuscript, the synchronization techniques are classified according to the intended application of SAPF, i.e., either for single-phase or three-phase power system, as illustrated in Figure 3. Over the years, works onSAPF for three-phase system are more popular compared to single-phase system particularly due to wider applications of power electronics devices and nonlinear loads in three-phase environment [64–66].However, to avoid redundancy, this manuscript will examine the synchronization technique itself andsubsequently, suitability of each technique for single-phase and three-phase system applications willbe highlighted.

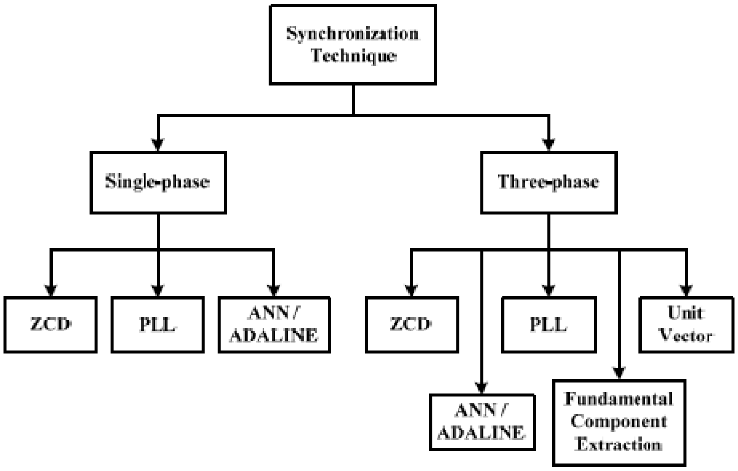

Figure 3. Overview of synchronization techniques applied to SAPF. ZCD: zero-crossing detection; PLL: phase-locked loop; ANN: artificial neural network; ADALINE: adaptive linear neuron.

Modified Synchronous Reference Frame with Fuzzy Logic Control

The performance of the modified synchronous reference frame extraction (MSRF)algorithm with fuzzy logic controller (FLC) based current control pulse width modulation (PWM)inverter of three-phase three-wire SAPF to mitigate current harmonics. The proposed FLC isdesigned with a reduced amount of membership functions (MFs) and rules, and thus significantlyreduces the computational time and memory size. Modeling and simulations of SAPF are carriedout using MATLAB/Simulink R2012a with the power system toolbox under steady-state condition,and this is followed with hardware implementation using a TMS320F28335 digital signal processor (DSP), Specrum Digital Inc., Stafford, TX, USA. The results obtained demonstrate a good andsatisfactory response to mitigate the harmonics in the system. The total harmonic distortion (THD)for the system has been reduced from 25.60% to 0.92% and 1.41% in the simulation study with andwithout FLC, respectively.the MSRF technique is employed for the extraction of the harmonics so as to generate the reference signals. This method is based on the SRF technique, and it consists of simplified unit vector generation instead of the phase-locked loop (PLL) circuit for synchronization purposes [20,21], DC bus capacitor for voltage regulation, and stationary/rotating frames for the extraction of harmonic currents [14]. Although the MSRF technique shares a few similar features with the conventional SRF method, the main difference is in the calculation of rotating angles for the reference d-q frame [22–25]. Despite using the α-β voltages for calculating the transformation angle, low pass filters (LPF) are used in reducing the voltage harmonics of the input signals, and are consequently used in control process. This filter is essential because the method becomes less affected by harmonics from the source voltage [15,26]. The extracted signal is compared with the compensation or inverter's current so as to produce the required pulses for the inverter. Figure shows the diagram of the modified SRF method.

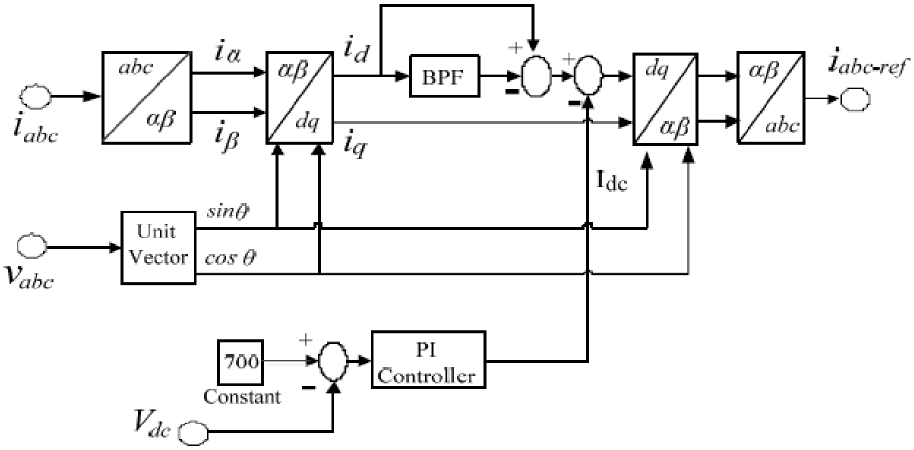

Figure 2. Block diagram of modified synchronous reference frame (MSRF) method.

The quality of the applied current control strategy influences the performance of the PWM voltage source inverter. In order to implement the direct current control technique, both load and compensation currents are sensed [27–31]. The three output reference signals are obtained using the reference current extraction control technique. The PWM switching pulses are generated by sensing the three-phase compensation currents from the SAPF and by comparing with their reference extracted signals. The hysteresis technique and sinusoidal PWM technique are widely used by many researchers, due to their simplicity and fast dynamic responses. However, the major setback of the hysteresis current controller in the operation of SAPF is uneven switching frequency which leads to acoustic noise and difficulty in designing input filters during load variation [32]. The challenge due to the switching frequency can be minimized by reducing the band width of the hysteresis band. However, this increases the current error and thus, produces more distortion in the output current. In order to reduce this problem to a certain extent, a fuzzy PWM controller is used to improve the performance of the VSI. Pulse width modulation (PWM) is a powerful technique for controlling analog circuits in digital form with a microprocessor's digital outputs. The key advantage of the PWM technique is that the on-off behavior changes the average power of the signal with the output signal alternates between on and off within a specified period. This helps to control the delivered power, so that power loss in the switching devices is very low. The PWM switching frequency must be higher than the working frequency of the load (the connected equipment), which means that the resultant waveform observed by the load must be as smooth as possible.Recently, FLC has been an interesting and fruitful area for research. The concept was first developed by Zadeh in 1965 [33,34]. It is used instead of classical conventional controllers like the proportional integral and derivative (PID) and proportional and integral (PI) to improve the performance of a system. It is a simple idea comprised of four different parts: fuzzifier, knowledge base, inference, and defuzzifier. Fuzzy logic incorporates human skills and the experience of the operator in the design of a controller for adjusting a process whose input-output relationship is defined by a group of fuzzy control rules. Initially, a crisp set of input data is collected and transformed to a fuzzy set using fuzzy linguistic variables, fuzzy linguistic terms, and membership functions [35]. This is known as fuzzification. Knowledge base comprises data and the rule base so as to coordinate with the other unit. Meanwhile, inference is developed based on this set of rules. Finally, the result is converted back into a specific control output value at the defuzzification stage. One advantage of fuzzy logic control is that it does not require any accurate mathematical model of a system [36].

III.CONCLUSION

Generally, the effectiveness of the applied control techniques depend on theirperformance in distorted and unbalanced grid conditions, phase tracking accuracy, dynamicperformance, noise immunity, and compatibility with other algorithms in the control system ofSAPF. Besides that, control structure complexity and computational burden are also important criteriato be considered in selecting the most suitable control techniques.

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