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Review Article

Harmonic Mitigation Techniques Applied to Power Distribution Networks

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A growing number of harmonic mitigation techniques are now available including active and passive methods, and the selection of the best-suited technique for a particular case can be a complicated decision-making process. The performance of some of these techniques is largely dependent on system conditions, while others require extensive system analysis to prevent resonance problems and capacitor failure. A classification of the various available harmonic mitigation techniques is presented in this paper aimed at presenting a review of harmonic mitigation methods to researchers, designers, and engineers dealing with power distribution systems.

1. Introduction

The nonlinear characteristics of many industrial and commercial loads such as power converters, fluorescent lamps, computers, light dimmers, and variable speed motor drives (VSDs) used in conjunction with industrial pumps, fans, and compressors and also in air-conditioning equipment have made the harmonic distortion a common occurrence in electrical power networks. Harmonic currents injected by some of these loads are usually too small to cause a significant distortion in distribution networks. However, when operating in large numbers, the cumulative effect has the capability of causing serious harmonic distortion levels. These do not usually upset the end-user electronic equipment as much as they overload neutral conductors and transformers and, in general, cause additional losses and reduced power factor [1–5]. Large industrial converters and variable speed drives on the other hand are capable of generating significant levels of distortion at the point of common coupling (PCC), where other users are connected to the network [6, 7].

Because of the strict requirement of power quality at the input AC mains, various harmonic standards and engineering recommendations such as IEC 1000-3-2, IEEE 519 (USA), AS 2279, D.A.CH.CZ, EN 61000-3-2/EN 61000-3-12, and ER G5/4 (UK) are employed to limit the level of distortion at the PCC. To comply with these harmonic standards, installations utilizing power electronic and nonlinear loads often use one of the growing numbers of harmonic mitigation techniques [8]. Because of the number and variety of available methods, the selection of the best-suited technique for a particular application is not always an easy or straightforward process. Many options are available, including active and passive methods. Some of the most technically advanced solutions offer guaranteed results and have little or no adverse effect on the isolated power system, while the performance of other simple methods may be largely dependent on system conditions. This paper presents a comprehensive survey on harmonic mitigation techniques in which a large number of technical publications have been reviewed and used to classify harmonic mitigation techniques into three categories: passive techniques, active techniques, and hybrid harmonic reduction techniques using a combination of active and passive methods. A brief description of the electrical characteristics of each method is presented with the aim of providing the designer and site engineer with a more informed choice regarding their available options when dealing with the effects and consequences of the presence of these harmonics in the distribution network.

2. Passive Harmonic Mitigation Techniques

Many passive techniques are available to reduce the level of harmonic pollution in an electrical network, including the

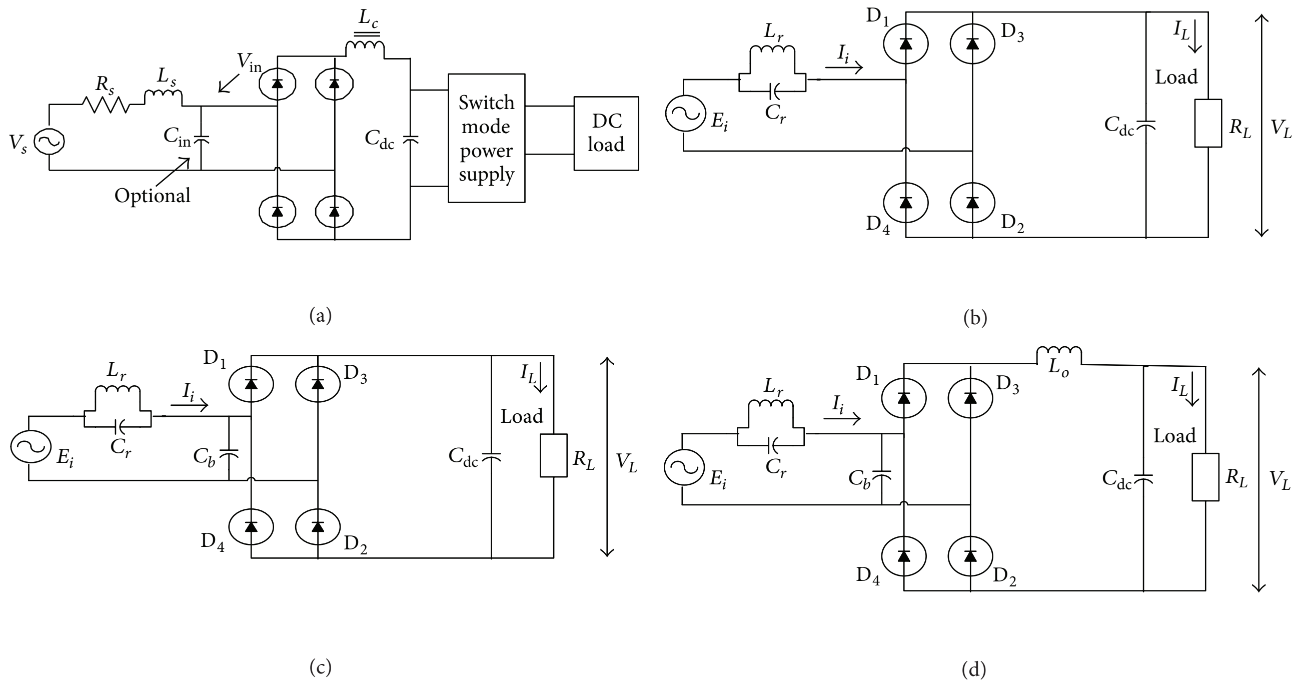

Figure 1: (a) The Series inductor filters for current shaping, (b) The Ziogas inductor capacitor filter, (c) The Yanchao improvement on Ziogas filter, and (d) The Hussein improvement on Yanchao filter.

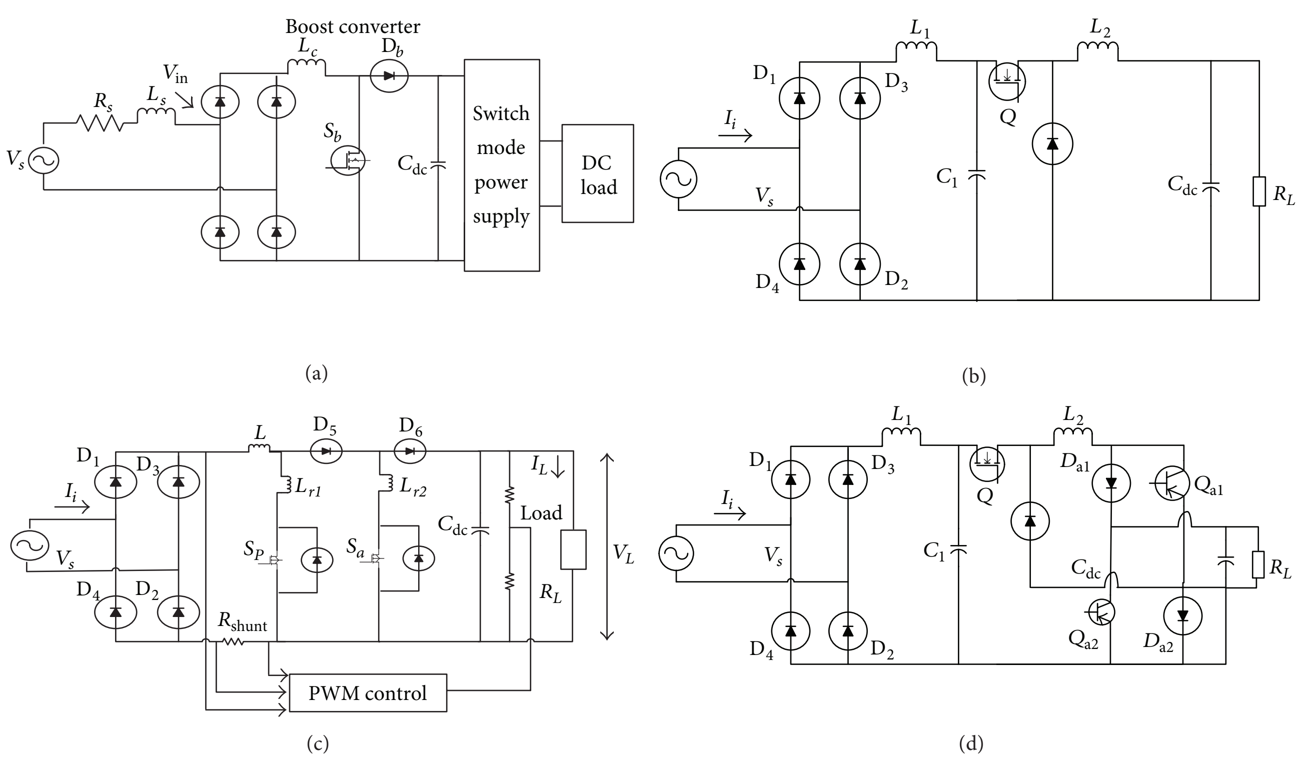

Figure 2: (a) Boost converter current shaping circuit, (b) buck converter current shaping circuit, (c) improve boost converter current shaping circuit, and (d) improve buck converter current shaping circuit.

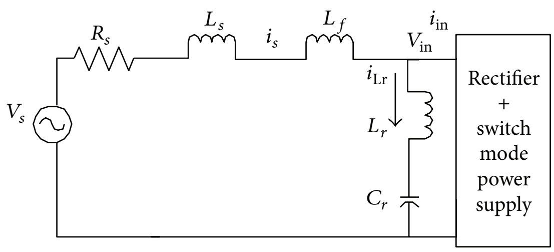

FIGURE 3: A parallel-connected resonant filter.

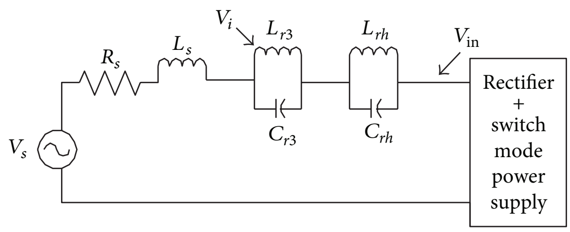

FIGURE 4: Double-tuned series-connected resonant filter.

connection of series line reactors, tuned harmonic filters, and the use of higher pulse number converter circuits such as 12-pulse, 18-pulse, and 24-pulse rectifiers. In these methods, the undesirable harmonic currents may be prevented from flowing into the system by either installing a high series impedance to block their flow or diverting the flow of harmonic currents by means of a low-impedance parallel path [9].

Harmonic mitigation techniques used for supply power factor correction and harmonics mitigation in two ways to qualify the products performance. One is to put a limit on the PF for loads above a specified minimum power. Utility companies often place limits on acceptable power factors for loads (e.g., <0.8 leading and >0.75 lagging). A second way to measure or specify a product is to define absolute maximum limits for current harmonic distortion. This is usually expressed as limits for odd harmonics (e.g., 1st, 3rd, 5th, 7th, etc.). This approach does not need any qualifying minimum percentage load and is more relevant to the electric utility.

Harmonic regulations or guidelines are currently applied to keep current and voltage harmonic levels in check. As an example, the current distortion limits in Japan illustrated in Tables 1 and 2 represent the maximum and minimum values of total harmonic distortion (THD) in voltage and the most dominant fifth harmonic voltage in a typical power system [10].

Certain techniques, such as the use of tuned filters, require extensive system analysis to prevent resonance problems and capacitor failures, while others, such as the use of 12-pulse or 24-pulse converters, can be applied with virtually no system analysis.

2.1. Effect of Source Reactance. Typical AC current waveforms in single-phase and three-phase rectifiers are far from a sinusoid. The power factor is also very poor because of the high harmonic contents of the line current waveform. In rectifier with a small source reactance, the input current is highly discontinuous, and, as a consequence, the power is drawn from the utility source at a very poor power factor.

TABLE 1: Voltage THD and fifth harmonic voltage in a high-voltage power transmission system.

	Over 154 kV		154–22 kV	
	THD	5th harmonic	THD	5th harmonic
Max.	2.8%	2.8%	3.3%	3.2%
Min.	1.1%	1.0%	1.4%	1.3%

TABLE 2: Voltage THD and fifth harmonic voltage in a 6.6 kV power distribution system.

	6.6 kV			
	Residential		Commercial	
	THD	5th harmonic	THD	5th harmonic
Max.	3.5%	3.4%	4.6%	4.3%
Min.	3.0%	2.9%	2.1%	1.2%

The magnitude of harmonic currents in some nonlinear loads depends greatly on the total effective input reactance, comprised of the source reactance plus any added line reactance. For example, given a 6-pulse diode rectifier feeding a DC bus capacitor and operating with discontinuous DC current, the level of the resultant input current harmonic spectrum is largely dependent on the value of AC source reactance and an added series line reactance; the lower the reactance, the higher the harmonic content [1–3].

Other nonlinear loads, such as a 6-pulse diode rectifier feeding a highly inductive DC load and operating with continuous DC current, act as harmonic current sources. In such cases, the amount of voltage distortion at the PCC is dependant on the total supply impedance, including the effects of any power factor correction capacitors, with higher impedances producing higher distortion levels [7, 11].

2.2. Series Line Reactors. The use of series AC line reactors is a common and economical means of increasing the source impedance relative to an individual load, for example, the input rectifier used as part of a motor drive system. The harmonic mitigation performance of series reactors is a function of the load; however, their effective impedance reduces proportionality as the current through them is decreased [12].

2.3. Tuned Harmonic Filters. Passive harmonic filters (PHF) involve the series or parallel connection of a tuned LC and high-pass filter circuit to form a low-impedance path for a specific harmonic frequency. The filter is connected in parallel or series with the nonlinear load to divert the tuned frequency harmonic current away from the power supply. Unlike series line reactors, harmonic filters do not attenuate all harmonic frequencies but eliminate a single harmonic frequency from the supply current waveform. Eliminating harmonics at their source has been shown to be the most effective method to reduce harmonic losses in the isolated power system. However, the increased first cost entailed presents a barrier to this approach. If the parallel-connected filter is connected further upstream in the power network, higher day-to-day costs will accumulate due to I^2R losses in the conductors and other plant items that carry the harmonic currents. Conversely, for series-connected filter at the load, there are increased losses in the filter itself. These losses are simply the result of the higher series impedance, which blocks the flow of harmonics but increases the line loss as a result of the flow of the remaining components of the load current [12, 13]. The quality factor of the filter inductor Q affects the actual value of the low-impedance path for each filter. Usually, a value of Q ranges between 20 and 100 [14]. Many types of harmonic filters are commonly employed, including the following:

2.3.1. Series Induction Filters. Harmonic currents produced by switched-mode power supplies and other DC-to-DC converter circuits can be significantly lowered by the connection of a series inductor that can be added on either the AC or DC power circuit [15–17], as shown in Figure 1. So many improvements on these filters have been made.

Ziogas passive filter for single-phase rectifiers has some reduction in Total Harmonics Distortion THD and improvement in PF in comparison with conventional rectifier. Also, Yanchoa waveshaping filter used to reduce THD and increase power factor. Connecting author filter at the output terminal of the rectifier will improve power factor and reduce input current THD of the supply.

2.3.2. DC-DC Converter Current Shaping. Like the series induction filter, this circuit (Figure 2) can greatly reduce current distortion produced by switched-mode power supplies and other DC converter circuits by modulating the duty cycle of switch S_b to control the shape of input supply current to track a desired sine waveshape [5, 18–20]. So many improvements on these filters have been made.

2.3.3. Parallel-Connected Resonant Filter. Passive LC filters tuned to eliminate a particular harmonic are often used to reduce the level of low-frequency harmonic components like the 5th and 7th produced by three-phase rectifier and inverter circuits. The filter is usually connected across the line as shown in Figure 3. If more than one harmonic is to be eliminated, then a shunt filter must be installed for each harmonic. Care must be taken to ensure that the peak impedances of such an arrangement are tuned to frequencies between the required harmonic frequencies to avoid causing high levels of voltage distortion at the supply's PCC because of the presence of an LC resonance circuit [7, 12].

2.3.4. Series-Connected Resonant Filter. This work on a similar in principle to the parallel version, but with the tuned LC circuits connected in series with the supply. The series filter can be tuned to a single harmonic frequency, or it may be multituned to a number of harmonic frequencies. The multituned arrangement connects multiple tuned filters in series as shown in Figure 4 showing a third harmonic tuned LC circuit, L_{r3} and C_{r3}, and a high-frequency tuned LC circuit, L_{rh} and C_{rh}, to eliminate high-order harmonics [5, 7, 12].

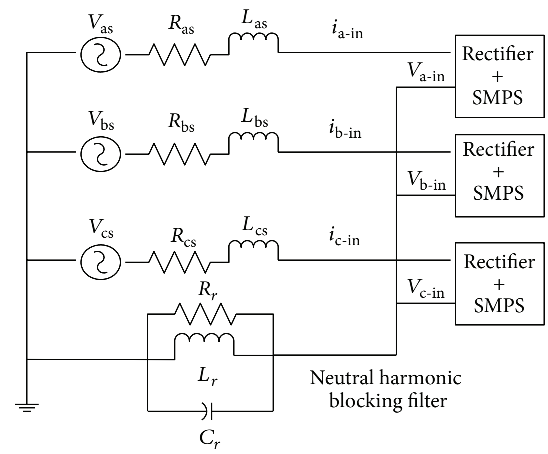

FIGURE 5: A neutral current blocking filters.

2.3.5. Neutral Current Filter. This filter is connected in the neutral conductor between the site transformer and the three-phase load to block all triple frequency harmonics, as shown in Figure 5. Because these triple zero-sequence harmonics are in phase with each other, they all flow through the neutral conductor, and it is more economical to block them in the neutral instead of individual phases [5, 12].

2.3.6. Zigzag Grounding Filter. By integrating phase shifting into a single or multiphase transformer with an extremely low zero-sequence impedance, substantial reduction of triple, 5th, and 7th harmonics can be achieved. This method provides an alternative to protect the transformer neutral conductor from triple harmonics by canceling these harmonics near the load. In this method, an autotransformer connected in parallel with the supply can provide a zero-sequence current path to trap and cancel triple harmonics as shown in Figure 6 [16].

2.4. Higher Pulse Converters. Three phases, 6-pulse static power converters, such as those found in VSD, generate low-frequency current harmonics. Predominantly, these are the 5th, 7th, 11th, and 13th with other higher orders harmonics also present but at lower levels. With a 6-pulse converter circuit, harmonics of the order $6k \pm 1$, where $k = 1, 2, 3, 4$, and so forth, will be present in the supply current waveform. In high-power applications, AC-DC converters based on the concept of multipulse, namely, 12, 18, or 24 pulses, are used to reduce the harmonics in AC supply currents. They are referred to as a multipulse converters. They use either a diode bridge or thyristor bridge and a special arrangement of phase-shifting magnetic circuit such as transformers and inductors to produce the required supply current waveforms [9, 21–27].

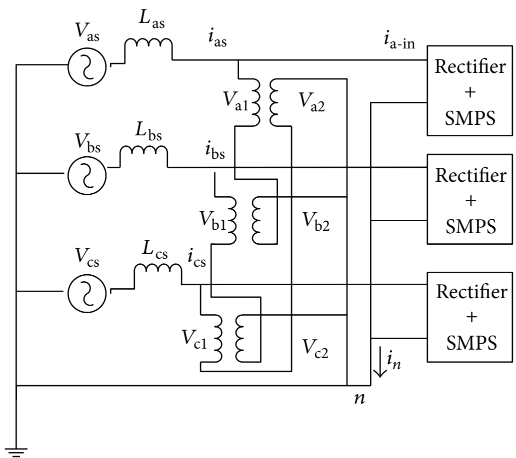

Figure 6: Zigzag autotransformer connected to three-phase nonlinear loads.

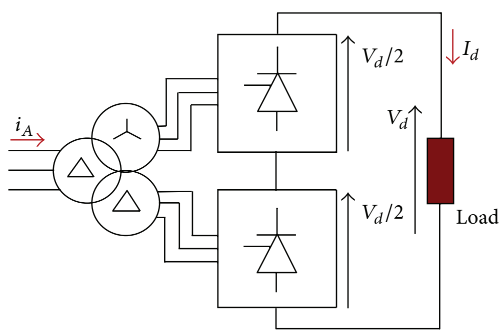

Figure 7: Series 12-pulse rectifier connection.

2.4.1. 12-Pulse Rectification. In large converter installations, where harmonics generated by a three-phase converter can reach unacceptable levels, it is possible to connect two 6-pulse converters in series with star/delta phase-shifting transformers to generate a 12-pulse waveform and reduce the harmonics on the supply and load sides, as shown in Figure 7. This could be beneficial despite the considerable extra cost of the transformers. Twelve-pulse rectifier is frequently specified by consulting engineers for heating, ventilating, and air-conditioning applications because of their theoretical ability to reduce harmonic current distortion.

Instead of connecting the two converter bridges in series, they could also be connected in parallel to give 12-pulse operation. A parallel 12-pulse arrangement is shown in Figure 8. Parallel connections require special care to ensure adequate balance between the currents drawn by each bridge. Secondary leakage reactance must be carefully matched, and extra reactors are needed on the DC side to absorb the instantaneous differences between the two DC voltage waveforms, [9, 22, 28].

When using a 12-pulse system, the 5th and 7th harmonics disappear from line current waveforms leaving the 11th as the first to appear. Only harmonics of the order $12k \pm 1$, where $k = 1, 2, 3, 4$, and so forth, will be present in the supply current waveform, thus resulting in a high power factor, low THD at input AC mains, and ripple-free DC output of high quality.

2.4.2. 18-Pulse Rectification. Eighteen-pulse converter circuits, shown in Figure 9, use a transformer with three sets of secondary windings that are phase-shifted by 20 degrees with respect to each other. Only harmonics of the order $18k \pm 1$, where $k = 1, 2, 3, 4$, and so forth, will be present in the supply current waveform [9, 29].

2.4.3. 24-Pulse Rectification. Connecting two 12-pulse circuits with a 15° phase shift produces a 24-pulse system. Figure 10 shows one such system in which the two 12-pulse circuits are connected in parallel to produce the required 24-pulse system. The 11th and 13th harmonics now disappear from the supply current waveform leaving the 23rd as the first to appear. Only harmonics of the order $24k \pm 1$, where $k = 1, 2, 3, 4$, and so forth, will be present in a 24-pulse system [9, 30].

3. Active Harmonic Mitigation Techniques

When using active harmonic reduction techniques, the improving in the power quality came from injecting equal-but-opposite current or voltage distortion into the network, thereby canceling the original distortion. Active harmonic filters (AHFs) utilize fast-switching insulated gate bipolar transistors (IGBTs) to produce an output current of the required shape such that when injected into the AC lines, it cancels the original load-generated harmonics. The heart of the AHF is the controller part. The control strategies applied to the AHF play a very important role on the improvement of the performance and stability of the filter. AHF is designed with two types of control scheme. The first performs fast Fourier transforms to calculate the amplitude and phase angle of each harmonic order. The power devices are directed to produce a current of equal amplitude but opposite phase angle for specific harmonic orders. The second method of control is often referred to as full spectrum cancellation in which the full current waveform is used by the controller of the filter, which removes the fundamental frequency component and directs the filter to inject the inverse of the remaining waveform [31–38].

Typically, these filters are sized based on how much harmonic current the filter can produce, normally in amperage increments of 50 Amps. The proper amperage of AHF can be chosen after determining the amount of harmonic cancellation current.

Essentially, the filter consists of a VSD with a special electronic controller which injects the harmonic current onto the system 180 out of phase to the system or drive harmonics. This results in harmonics cancellation. For example, if the VSD created 50 A of 5th harmonic current, and the AHF produced 40 A of 5th harmonic current, the amount of 5th harmonic current exported to the utility grid would be 10 A. The AHF may be classified as a single-phase or three-phase filters.

Also, it could be classified as parallel or series AHF according to the circuit configuration.

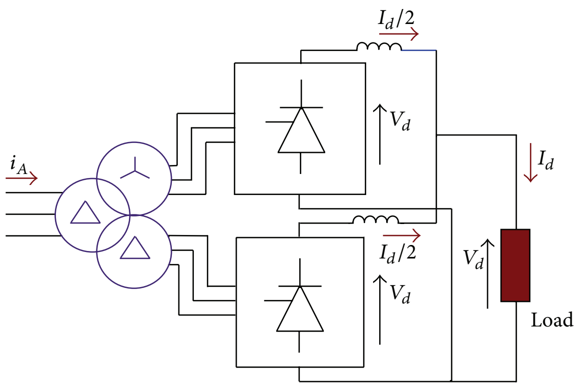

Figure 8: Parallel twelve-pulse rectifier connection.

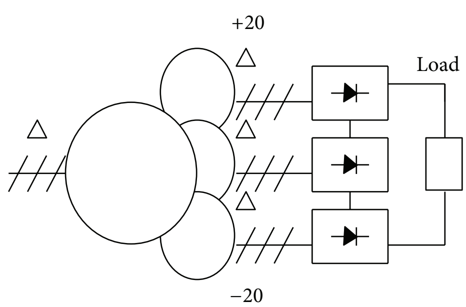

Figure 9: 18-pulse rectifier connection.

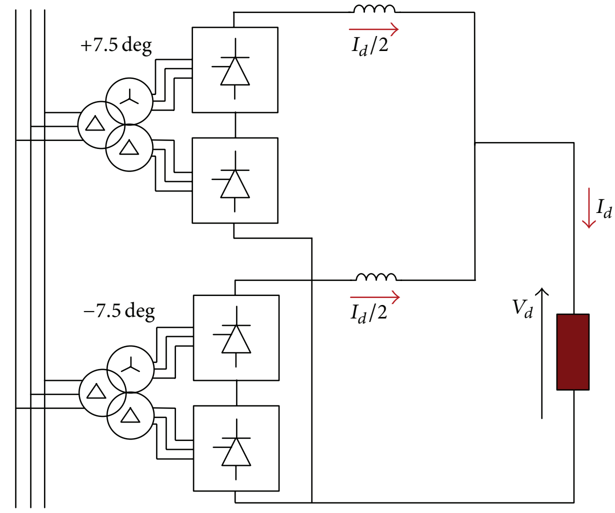

Figure 10: 24-pulse rectifier connection.

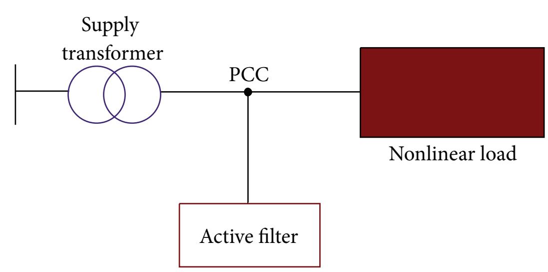

Figure 11: Parallel active filter.

3.1. Parallel Active Filters. This is the most widely used type of AHF (more preferable than series AHF in terms of form and function). As the name implies, it is connected in parallel to the main power circuit as shown in Figure 11. The filter is operated to cancel out the load harmonic currents leaving the supply current free from any harmonic distortion. Parallel filters have the advantage of carrying the load harmonic current components only and not the full load current of the circuit [39–44].

AHF can be controlled on the basis of the following methods:

(i) the controller detects the instantaneous load current i_L,

(ii) the AHF extracts the harmonic current i_{Lh} from the detected load current i_L by means of digital signal processing,

(iii) the AHF draws the compensating current i_{AF} $(= -i_{Lh})$ from the utility supply voltage v_S so as to cancel out the harmonic current i_{Lh} [45].

3.2. Series Active Filters. The main circuit configuration for this type of AHF is shown in Figure 12. The idea here is to eliminate voltage harmonic distortions and improve the quality of the voltage applied to the load. This is achieved by producing a sinusoidal pulse width modulated (PWM) voltage waveform across the connection transformer, which is added to the supply voltage to counter the distortion across the supply impedance and present a sinusoidal voltage across the load. Series AHF has to carry the full load current increasing their current ratings and I^2R losses compared with parallel filters, especially across the secondary side of the coupling transformer [43].

Unlike the shunt AHF, the series AHF is controlled on the basis of the following methods:

(i) the controller detects the instantaneous supply current i_S,

(ii) the AHF extracts the harmonic current i_S from the detected supply current by means of digital signal processing,

(iii) the active filter applies the compensating voltage v_{AF} $(= -Ki_{Sh})$ across the primary of the transformer. This will result in a significant reduction in the supply harmonic current (i_{Sh}), when the feedback gain K is set to be high enough [45].

An AHF with both series and parallel (shunt) connected sections, as shown in Figures 11 and 12, respectively, can be used to compensate for both voltage and current harmonics simultaneously [34–36]. In all cases, the critical requirement of any AHF circuit is to calculate the required compensation current accurately and in real time.

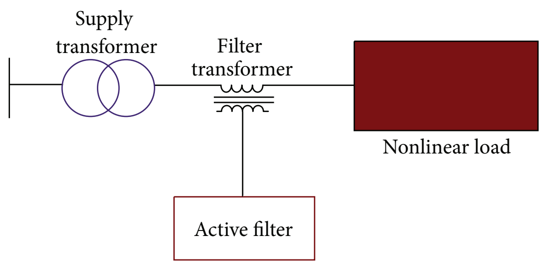

Figure 12: Series active filter.

4. Hybrid Harmonic Mitigation Techniques

Hybrid connections of AHF and PHF are also employed to reduce harmonics distortion levels in the network. The PHF with fixed compensation characteristics is ineffective to filter the current harmonics. AHF overcomes the drawbacks of the PHF by using the switching-mode power converter to perform the harmonic current elimination. However, the AHF construction cost in an industry is too high. The AHF power rating of power converter is very large. These bound the applications of AHF used in the power system. Hybrid harmonic filter (HHF) topologies have been developed [46–51] to solve the problems of reactive power and harmonic currents effectively. Using low cost PHF in the HHF, the power rating of active converter is reduced compared with that of AHF. HHF retains the advantages of AHF and does not have the drawbacks of PHF and AHF. Figure 13 shows a number of possible hybrid combinations. Figure 13(a) is a combination of shunt AHF and shunts PHF. Using a combination of PHF will make a significant reduction in the rating of the AHF. As a result, no harmonic resonance occurs, and no harmonic current flows in the supply. In [50], author claimed that in HHF the AHF can improve the filter performance and suppress the harmonic resonance of existing PHF. Figure 13(b) shows a combination of AHF series with the supply and a shunt PHF. The author of reference [46] found that this topology is not suitable for low-frequency interharmonic compensation because the AHF introduces a high compensation voltage which can interfere with downstream phase-controlled nonlinear loads.

Figure 13(c) shows an AHF in series with a shunt PHF. In all cases, it is required that the filters in a hybrid combination share compensation properly in the frequency domain [51]. A lot of improvements and researches have been made on the control strategies of hybrid harmonic filters.

The AHF and PHF are used to generate the equivalent voltage which is related to the mains harmonic current using different methods (i.e., impedance variation method) as shown in Figure 13(c). The mains harmonic current is suppressed by increasing the ratio of effective source impedance to the harmonic components. To achieve a constant DC bus voltage of the AHF, a PI voltage controller is employed. A hysteresis voltage comparator is employed to track the output voltage to perform the equivalent impedance of active converter [48, 49]. HHF is cost effective and becomes more practical in industry applications.

AHF controller mainly is divided into two parts, that is, reference current generation and PWM current controller. The PWM current controller is principally used for providing gating pulse to the AHF. In reference to current generation scheme, reference current is generated by using the distorted waveform. Many control schemes are there for reference current generation, such as p-q theory, deadbeat controller, neuro, adaptive control, wavelet control, fuzzy, delta-sigma modulation, sliding mode control, vector control, repetitive control, and SFX control for improving the steady state and dynamic performance of AHFs [52–59].

4.1. p-q Method. Instantaneous reactive power theory has been published in 1984. Based on this theory, the so-called "p-q method" was applied successfully in the control of AHF. Zero-sequence component is neglected in this method, and because of that the p-q method is not accurate when the three-phase system is distorted or unbalanced.

4.2. d-q Method. Based on the park transformation, the d-q method came. The three-phase load current can be decomposed in positive-sequence, negative sequence and zero-sequence component. The current in the d-q frame i_d and i_q can be transformed from the positive sequence and negative sequence using a PLL (phase locked loop). The division of the AC and DC components can be obtained across a low-pass PHF. The reference current signal can be achieved by the AC component in d-q frame through a countertransformation.

4.3. Direct Testing and Calculating Method (DTC). Separation of the harmonic and reactive components from the load current is the aim of current reference generator. The main characteristic of this method is the direct derivation of the compensating component from the load current, without the use of any reference frame transformation. In fact, this method presents a low-frequency oscillation problem in the AHF DC bus voltage.

4.4. Synchronous Reference Fame Method (SRF). Real currents are transformed into a synchronous reference frame in this method. The reference frame is synchronized with the AC mains voltage and is rotating at the same frequency. In this method, the reference currents are derived directly from the real load currents without considering the source voltages, which represent the most important characteristics of this method. The generation of the reference signals is not affected by distortion or voltage unbalance, therefore increasing the compensation robustness and performance.

4.5. Current Hysteresis Control. The basic principle of this control method is that the switching signals are derived from the comparison of the current error signal with a fixed width hysteresis band. This current control technique exhibits some unsatisfactory features due to simple, extreme robustness, fast dynamic, good stability, and automatic current limited characteristics.

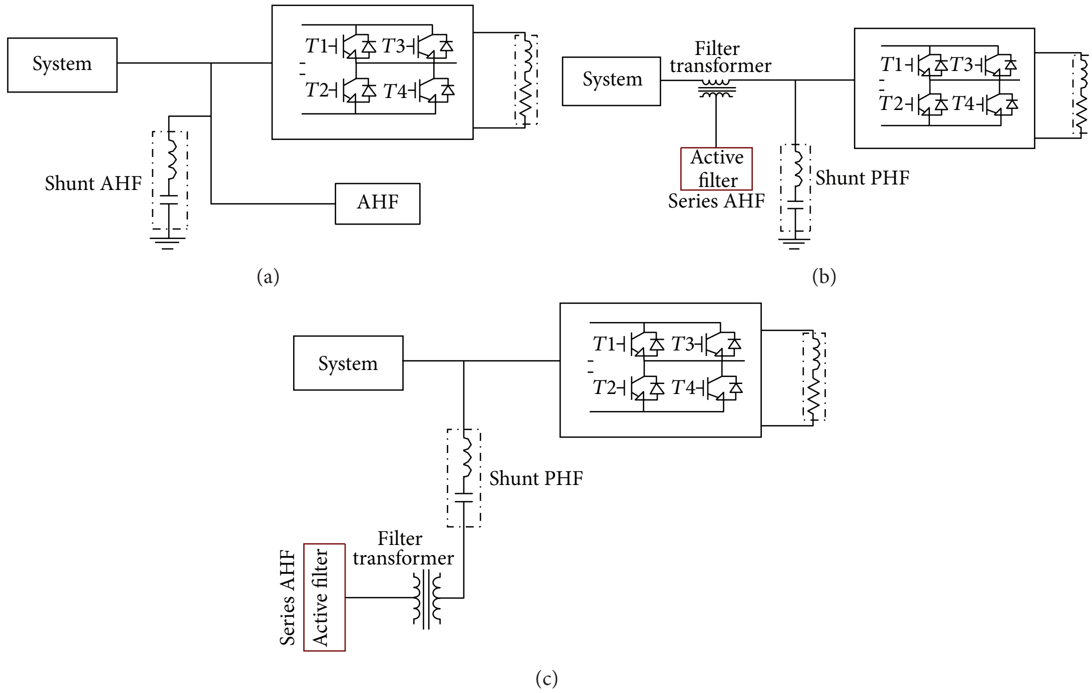

FIGURE 13: Hybrid connections of active and passive filters.

4.6. Triangle-Comparison PWM Control. This control method is also called linear current control. The conventional triangle-comparison PWM control principle is that the modulation signal achieved by a current regulator from the current error signal is intersected with the triangle wave. After that, pulse signals obtained are to control the switches of the converters. With analog PWM circuit, this control method has simple implementation with fast speed of response. Because the modulation frequency equals the triangle frequency, the current loop gain crossover frequency must be kept below the modulation frequency.

4.7. Space Vector Modulation (SVM). The aim of this method is to find the appropriate switching combinations and their duty ratios according to certain modulation scheme. The SVM operates in a complex plane divided in the six sectors separated by a combination of conducting or nonconducting switches in the power circuit. The reference vector is used to locate two adjacent switching-state vectors and compute the time for which each one is active. SVM is of low speed of response caused by the inherent calculation delay, due to the strong antijamming and the good reliability of digital control technique. In order to solve the drawback, the improvement of adopting deadbeat control and a certain oversize of the system reactive components is advised.

Currently, the research trends of the AHF control strategies are mainly towards the optimizing and practical application of the control strategies. At the end, the comparative criteria for PHF, AHF, and HHF could be summarized based on the following:

(i) cost of the equipment and installation,

(ii) harmonic indices (ex. i_h, THD_i, THD_v, TDD, and PWHD),

(iii) life time and failure rate,

(iv) maintenance and engineering.

5. Conclusions

Electrical system reliability and normal operation of electrical equipment rely heavily upon a clean distortion free power supply. Designers and engineers wishing to reduce the level of harmonic pollution on a power distribution network where nonlinear harmonic generating loads are connected have several harmonic mitigation techniques available. Because of the number and variety of available methods, selection of the best-suited technique for a particular application is not always an easy or straightforward process. A broad categorization of different harmonic mitigation techniques (passive, active, and hybrid) has been carried out to give a general viewpoint on this wide-ranging and rapidly developing topic. PHF is traditionally used to absorb harmonic currents because of low cost and simple robust structure. However, they provide fixed compensation and create system resonance. AHF provides multiple functions such as harmonic reduction, isolation, damping and termination, load balancing, PF correction, and voltage regulation. The HHF is more attractive in harmonic filtering than the pure filters from both viability and economical points of view, particularly for high-power applications. It is hoped that the discussion and classification of harmonic mitigation techniques presented in this paper will provide some useful information to help make the selection of an appropriate harmonic reduction method for a given application on an easier task.

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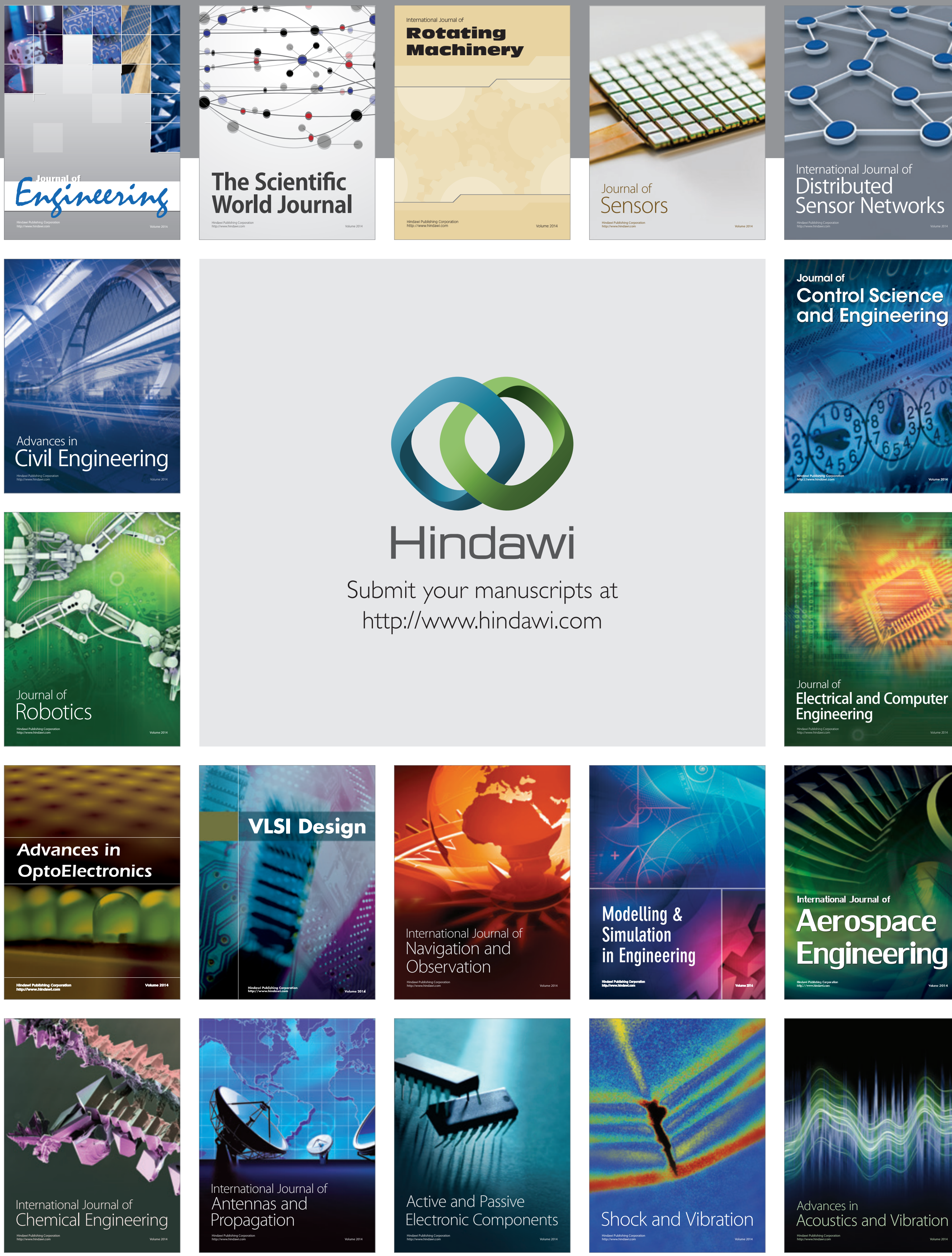

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