A Review of Active Filters for Power Quality Improvement

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Abstract—Active filtering of electric power has now become a mature technology for harmonic and reactive power compensation in two-wire (single phase), three-wire (three phase without neutral), and four-wire (three phase with neutral) ac power networks with nonlinear loads. This paper presents a comprehensive review of active filter (AF) configurations, control strategies, selection of components, other related economic and technical considerations, and their selection for specific applications. It is aimed at providing a broad perspective on the status of AF technology to researchers and application engineers dealing with power quality issues. A list of more than 200 research publications on the subject is also appended for a quick reference.

Index Terms—Active power filters, active power line conditioners, harmonics and reactive power compensation, power quality.

I. Introduction

SOLID-STATE control of ac power using thyristors and other semiconductor switches is widely employed to feed controlled electric power to electrical loads, such as adjustable-speed drives (ASD's), furnaces, computer power supplies, etc. Such controllers are also used in HV dc systems and renewable electrical power generation. As nonlinear loads, these solid-state converters draw harmonic and reactive power components of current from ac mains. In three-phase systems, they could also cause unbalance and draw excessive neutral currents. The injected harmonics, reactive power burden, unbalance, and excessive neutral currents cause low system efficiency and poor power factor. They also cause disturbance to other consumers and interference in nearby communication networks. Extensive surveys **[1]—[15]** have been carried out to quantify the problems associated with electric power networks having nonlinear loads. Conventionally passive *L-C* filters were used to reduce harmonics and capacitors were employed to improve the power factor of the ac loads. However, passive filters have the demerits of fixed compensation, large size, and resonance. The increased severity of harmonic pollution in power networks has attracted the attention of power electronics and power system engineers to develop dynamic and adjustable solutions to the power quality problems. Such equipment, generally known as active filters (AF's) [16]-[20], are also called active power line conditioners (APLC's), instantaneous reactive power compensators (IRPC's), active power filters (APF's), and active power quality conditioners (APQC's). In recent years, many publications have also appeared [21]-[25] on the harmonics, reactive power, load balancing, and neutral current compensation associated with linear and nonlinear loads.

This paper aims at presenting a comprehensive survey on the subject of AF's. More than 200 publications [1]-[223] are reviewed and classified in six categories. The first **[1]—[25]** is on general development and survey of harmonic problems, while the second to fourth categories are on two-wire (single phase) [26]-[55], three-wire (three phase without neutral) [56]-[155], and four-wire (three phase with neutral) [156]-[166] AF's. The fifth category [167]-[192] includes the publications on theories of harmonics and reactive power associated with nonlinear loads. The sixth and final category of publications [193]-[223] is on the reactive power and load-balancing compensators. However, some publications belong to more than one category and have been classified based on their dominant contribution.

This paper is presented in seven parts. Starting with an introduction, the subsequent sections cover the state of the art of the AF technology, the different configurations used, the control methodologies, the economic and technical considerations, their selection for specific applications, and the concluding remarks.

II. State of the Art

The AF technology is now mature for providing compensation for harmonics, reactive power, and/or neutral current in ac networks. It has evolved in the past quarter century of development with varying configurations, control strategies, and solid-state devices. AF's are also used to eliminate voltage harmonics, to regulate terminal voltage, to suppress voltage flicker, and to improve voltage balance in three-phase systems. This wide range of objectives is achieved either individually or in combination, depending upon the requirements and control strategy and configuration which have to be selected appropriately. This section describes the history of development and present status of the AF technology.

Following the widespread use of solid-state control of ac power, the power quality issues became significant. There are a large number of publications covering the power quality survey, measurements, analysis, cause, and effects of harmonics and reactive power in the electric networks **[1]—[25].** AF's are basically categorized into three types, namely, two-wire (single phase), three-wire, and four-wire three-phase configurations to meet the requirements of the three types of nonlinear loads on

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supply systems. Single-phase loads, such as domestic lights and ovens, TV's, computer power supplies, air conditioners, laser printers, and Xerox machines behave as nonlinear loads and cause power quality problems. Single-phase (two wire) AF's are investigated [26]-[55] in varying configurations and control strategies to meet the needs of single-phase nonlinear loads. Starting in 1971, many configurations, such as the active series filter [48], active shunt filter [26]-[47], and combination of shunt and series filter [39] have been developed and commercialized also for uninterruptible power supply (UPS) applications [50], [52], [53]. Both concepts based on a current-source inverter (CSI) with inductive energy storage and a voltage-source inverter (VSI) with capacitive energy storage are used to develop single-phase AF's.

Since major amounts of ac power are consumed by three-phase loads such as ASD's with solid-state control. Lately, many ASD systems incorporate AF's in their front-end design. A substantial number of publications have reported on three-phase three wire AF's [56]-[155], starting in 1976. Active shunt, active series, and combinations of both, named as active power quality conditioners [138], [152], as well as passive filters combined with active shunt and active series AF's are some typical configurations used. Many control strategies such as instantaneous reactive power theory initially developed by Akagi *et al.* [63], synchronous frame *d*-*q* theory [145], synchronous detection method [143], and notch filter method are used in the development of three-phase AF's.

The problem of excessive neutral current [3], [4] is observed in three-phase four-wire systems, mainly due to nonlinear unbalanced loads, such as computer power supplies, fluorescent lighting, etc. Resolving the problems of neutral current and unbalanced load currents has been attempted in [156]-[166] for four-wire systems. These attempts are of varying nature, like elimination/reduction of neutral current, harmonic compensation, load balancing, reactive power compensation, and combinations of these.

A major volume of work is reported [167]-[192] on the theories related to the detection and measurement of the various quantities, such as real power, reactive power, etc., in the presence of harmonics in the supply systems with nonlinear loads. These theories and concepts are quite relevant to extract the control signals for AF's and for the development of instruments to measure conventional and newly defined quantities in the presence of harmonics and unbalance. For quantifying the effectiveness of AF's, it is important to develop good measuring systems, and these new concepts have given a new impetus to instrumentation technology in this field.

The problems of reactive power and load unbalance were recognized long ago, and they became aggravated in the presence of nonlinear loads. Many publications [193]-[223] report on solid-state compensators for voltage flicker, reactive power, and balancing the nonlinear reactive loads, such as arc furnace, traction loads, etc. Many more terminologies, such as static var compensators, static flicker compensators, static var generators, etc., have been used in the literature.

One of the major factors in advancing the AF technology is the advent of fast self-commutating solid-state devices. In the initial stages, thyristors, bipolar junction transistors (BJT's) and power MOSFET's were used for AF fabrication; later, static induction thyristors (SIT's) and gate-turn-off thyristors (GTO's) were employed to develop AF's. With the introduction of insulated gate bipolar transistors (IGBT's), the AF technology got a real boost and, at present, they are considered as ideal solid-state devices for AF's. The improved sensor technology has also contributed to the enhanced performance of the AF. The availability of Hall-effect sensors and isolation amplifiers at reasonable cost and with adequate ratings has improved the AF performance.

The next breakthrough in AF development has resulted from the microelectronics revolution. Starting from the use of discrete analog and digital components [162], the progression has been to microprocessors, microcontrollers [64], and digital signal processors (DSP's) [50], [148]. Now, it is possible to implement complex algorithms on-line for the control of the AF at reasonable cost. This development has made it possible to use different control algorithms such as, proportional integral (P-I) [40], [87], [149], variable-structure control [51], [127], [141], fuzzy logic, and neural nets [46] for improving the dynamic and steady-state performance of the AF. With these improvements, the AF's are capable of providing fast corrective action, even with dynamically changing nonlinear loads. Moreover, these AF's are found to compensate quite a sum of higher order harmonics (typically up to the 25th) [25].

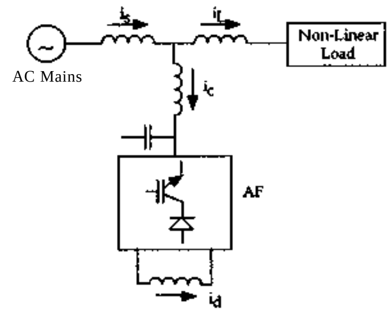

Fig. 1. Current-fed-type AF.

III. CONFIGURATIONS

AF's can be classified based on converter type, topology, and the number of phases. The converter type can be either CSI or VSI bridge structure. The topology can be shunt, series, or a combination of both. The third classification is based on the number of phases, such as two-wire (single phase) and three- or four-wire three-phase systems.

A. Converter-Based Classification

There are two types of converters used in the development of AF's. Fig. 1 shows the current-fed pulsewidth modulation (PWM) inverter bridge structure. It behaves as a nonsinusoidal current source to meet the harmonic current requirement of the nonlinear load. A diode is used in series with the self commutating device (IGBT) for reverse voltage blocking. However, GTO-based configurations do not need the series diode, but they have restricted frequency of switching. They

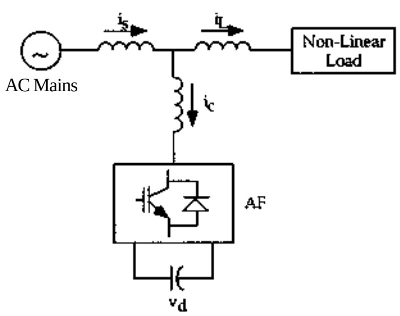

Fig. 2. Voltage-fed-type AF.

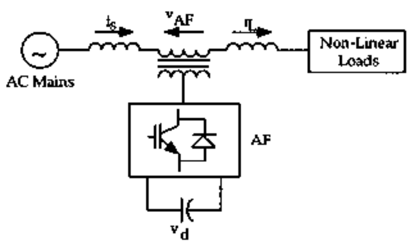

Fig. 3. Series-type AF.

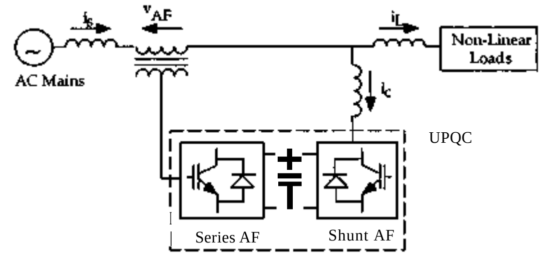

Fig. 4. Unified power quality conditioner as universal AF.

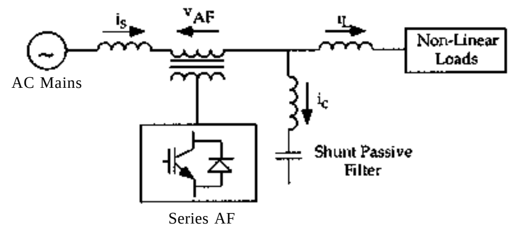

Fig. 5. Hybrid filter as a combination of active series and passive shunt filters.

are considered sufficiently reliable [68], [79], but have higher losses and require higher values of parallel ac power capacitors. Moreover, they cannot be used in multilevel or multistep modes to improve performance in higher ratings.

The other converter used as an AF is a voltage-fed PWM inverter structure, as shown in Fig. 2. It has a serf-supporting dc voltage bus with a large dc capacitor. It has become more dominant, since it is lighter, cheaper, and expandable to multilevel and multistep versions, to enhance the performance with lower switching frequencies. It is more popular in UPS-based applications, because in the presence of mains, the same inverter bridge can be used as an AF to eliminate harmonics of critical nonlinear loads.

B. Topology-Based Classification

AF's can be classified based on the topology used as series or shunt filters [48], [106], [115], [121], [146], and unified power quality conditioners [19], [27], [135], [138], [152] use a combination of both. Combinations of active series and passive shunt filtering are known as hybrid filters [20], [94], [96], [99], [132], [134], [142], [152], [154]. Fig. 2 is an example of an active shunt filter, which is most widely used to eliminate current harmonics, reactive power compensation (also known as STATCON), and balancing unbalanced currents. It is mainly used at the load end, because current harmonics are injected by nonlinear loads. It injects equal compensating currents, opposite in phase, to cancel harmonics and/or reactive components of the nonlinear load current at the point of connection. It can also be used as a static var generator (STATCON) in the power system network for stabilizing and improving the voltage profile.

Fig. 3 shows the basic block of a stand-alone active series filter. It is connected before the load in series with the mains, using a matching transformer, to eliminate voltage harmonics [48], and to balance and regulate the terminal voltage of the load or line. It has been used to reduce negative-sequence voltage and regulate the voltage on three-phase systems [115], [121]. It can be installed by electric utilities to compensate voltage harmonics and to damp out harmonic propagation caused by resonance with line impedances and passive shunt compensators.

Fig. 4 shows a unified power quality conditioner (also known as a universal AF), which is a combination of active shunt and active series filters [19], [39], [133], [135], [138], [152]. The dc-link storage element (either inductor [19], [39] or dc-bus capacitor [19], [135]) is shared between two current-source or voltage-source bridges operating as active series and active shunt compensators. It is used in single-phase [19], [39] as well as three-phase configurations [19], [133], [135], [152]. It is considered an ideal AF which eliminates voltage and current harmonics and is capable of giving clean power to critical and harmonic-prone loads, such as computers, medical equipment, etc. It can balance and regulate terminal voltage and eliminate negative-sequence currents. Its main drawbacks are its large cost and control complexity because of the large number of solid-state devices involved.

Fig. 5 shows the hybrid filter, which is a combination of an active series filter and passive shunt filter [20], [94], [109], [120], [134], [137], [139], [142], [145], [152], [154]. It is quite popular because the solid-state devices used in the active series part can be of reduced size and cost (about 5% of the load size) and a major part of the hybrid filter is made of the passive shunt *L-C* filter used to eliminate lower order harmonics. It has the capability of reducing voltage and current harmonics at a reasonable cost. There are many more hybrid configurations [136], [152], [153], but for the sake of brevity, they are not discussed here; however, details can be found in the respective references.

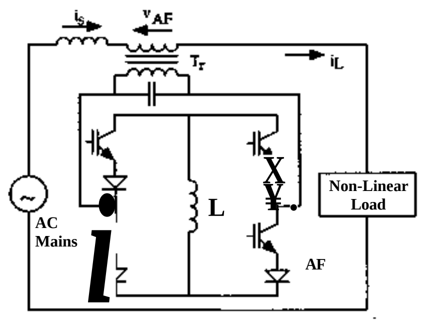

Fig. 6. Two-wire series AF with current-source converter.

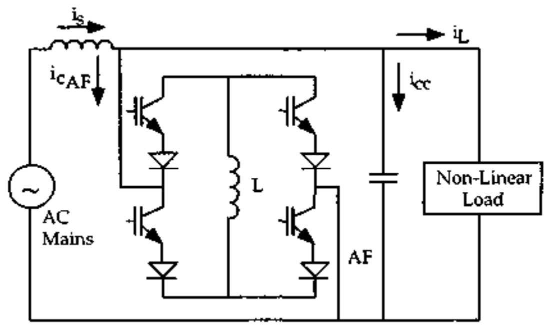

Fig. 7. Two-Wire shunt AF with current-source converter.

C. Supply-System-Based Classification

This classification of AF's is based on the supply and/or the load system having single-phase (two wire) and three-phase (three wire or four wire) systems. There are many nonlinear loads, such as domestic appliances, connected to single-phase supply systems. Some three-phase nonlinear loads are without neutral, such as ASD's, fed from three-wire supply systems. There are many nonlinear single-phase loads distributed on four-wire three-phase supply systems, such as computers, commercial lighting, etc. Hence, AF's may also be classified accordingly as two-wire [26]-[55], three-wire [56]-[155], and four-wire types [156]-[166].

1) Two-Wire AF's: Two-wire (single phase) AF's [19], [26]-[55] are used in all three modes as active series [27], [48], active shunt [26]-[38], [40]-[47], [49]-[55], and a combination of both as unified line conditioners [19], [27], [39]. Both converter configurations, current-source PWM bridge [19], [27], [38], [39] with inductive energy storage element and voltage-source PWM bridge [19], [27]-[38], [40]-[55] with capacitive dc-bus energy storage elements, are used to form two-wire AF circuits. In some cases, active filtering is included in the power conversion stage [36], [40], [41] to improve input characteristics at the supply end.

Figs. 6-8 show three configurations of active series, active shunt, and a combination of both with current-source bridge, using inductive storage elements. Similar configurations, based on a VSI bridge, may be obtained by considering only two wires (phase and neutral) at each stage of Figs. 2-4. In the case of a series AF with voltage-fed converter, sometimes the transformer is removed and load is shunted with passive *L-C* components [48]. The series AF is normally used to eliminate

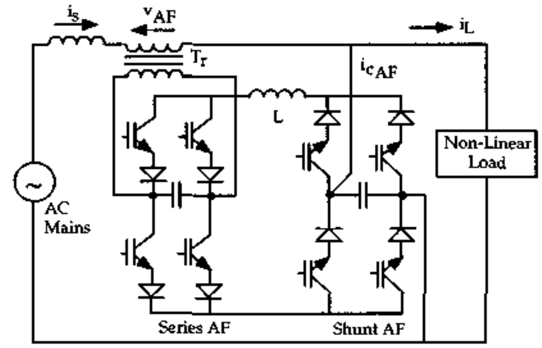

Fig. 8. Two-wire unified power quality conditioner with current-source converter.

voltage harmonics, spikes, sags, notches, etc., while the shunt AF is used to eliminate current harmonics and reactive power compensation.

2) Three-Wire AF's: Three-phase three-wire nonlinear loads, such as ASD's, are major applications of solid-state power converters and, lately, many ASD's, etc., incorporate AF's in their front-end design. A large number of publications [15]-[20], [56]-[155] have appeared on three-wire AF's with different configurations. All the configurations shown in Figs. 1-5 are developed, in three-wire AF's, with three wires on the ac side and two wires on the dc side. Active shunt AF's are developed in the current-fed type (Fig. 1) or voltage-fed type with single-stage (Fig. 2) or multistep/multilevel and multiseries [65], [66], [85], [86] configurations. Active shunt AF's are also designed with three single-phase AF's with isolation transformers [18] for proper voltage matching, independent phase control, and reliable compensation with unbalanced systems. Active series filters are developed for stand-alone mode (Fig. 3) or hybrid mode with passive shunt filters (Fig. 5). The latter (hybrid) has become quite popular [20], [99], [105], [109], [110], [120], [133], [139], [142], [143], [145], [153], [154] to reduce the size of power devices and cost of the overall system. A combination of active series and active shunt is used for unified power quality conditioners (Fig. 4) and universal filters [19], [135], [138], [152].

3) Four-Wire AF's: A large number of single-phase loads may be supplied from three-phase mains with neutral conductor [3], [4], [10], [11]. They cause excessive neutral current, harmonic and reactive power burden, and unbalance. To reduce these problems, four-wire AF's have been attempted [156]-[166]. They have been developed as: 1) active shunt mode with current feed [156] and voltage feed [157], [158], [160], [165]; 2) active series mode [163], [165]; and 3) hybrid form with active series and passive shunt [164] mode. Figs. 9-11 show three typical configurations of shunt AF's [158]. The first configuration of a four-wire shunt AF is known as the capacitor midpoint type, used in smaller ratings. Here, the entire neutral current flows through dc-bus capacitors which are of a large value. Fig. 10 shows another configuration known as the four-pole switch type, in which the fourth pole is used to stabilize the neutral of the AF. The three single-phase bridge configuration, shown in Fig. 11, is quite common [157], [159], [162], and this version allows the proper voltage

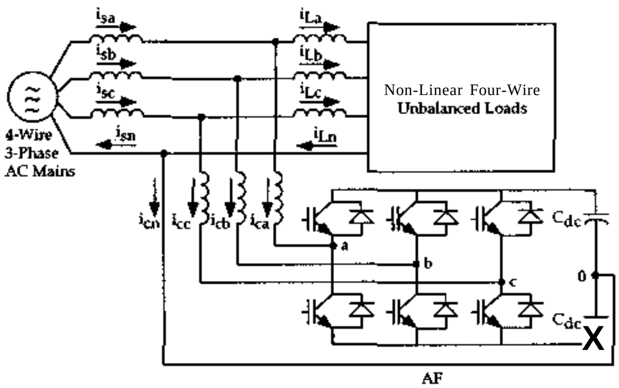

Fig. 9. Capacitor midpoint four-wire shunt AF.

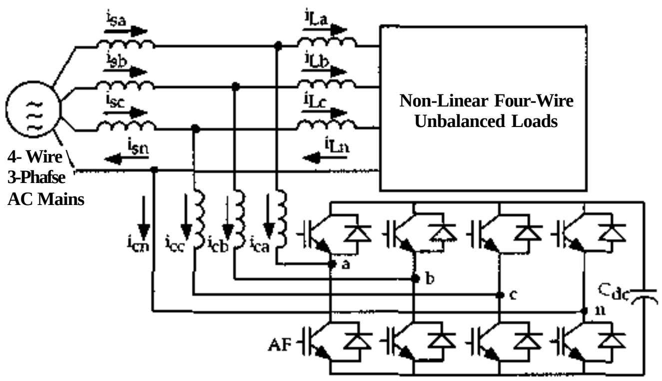

Fig. 10. Four-pole four-wire shunt AF.

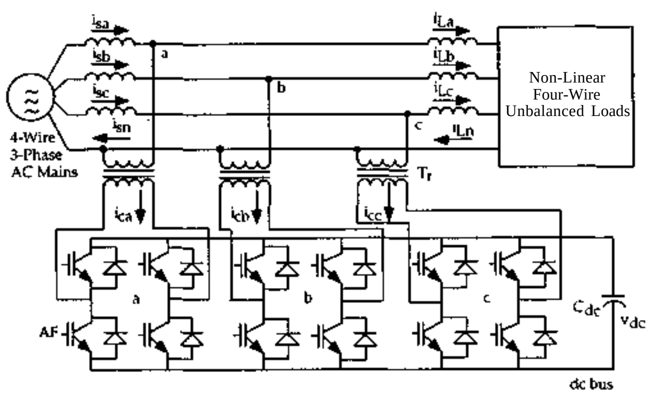

Fig. 11. Three-bridge four-wire shunt AF.

matching for solid-state devices and enhances the reliability of the AF system. A detailed comparison of the features of these three configurations (Figs. 9-11), is given in [158].

IV. CONTROL STRATEGIES

Control strategy is the heart of the AF and is implemented in three stages. In the first stage, the essential voltage and current signals are sensed using power transformers (PT's), CT's, Hall-effect sensors, and isolation amplifiers to gather accurate system information. In the second stage, compensating commands in terms of current or voltage levels are derived based on control methods [167]-[192] and AF configurations. In the third stage of control, the gating signals for the solid-state devices of the AF are generated using PWM, hysteresis, sliding-mode, or fuzzy-logic-based control techniques. The control of the AF's is realized using discrete analog and digital devices or advanced microelectronic devices, such as single-chip microcomputers, DSP's, etc.

A. Signal Conditioning

For the purpose of implementation of the control algorithm, several instantaneous voltage and current signals are required. These signals are also useful to monitor, measure, and record various performance indexes, such as total harmonic distortion (THD), power factor, active and reactive power, crest factor, etc. The typical voltage signals are ac terminal voltages, de-bus voltage of the AF, and voltages across series elements. The current signals to be sensed are load currents, supply currents, compensating currents, and dc-link current of the AF. Voltage signals are sensed using either PT's or Hall-effect voltage sensors or isolation amplifiers. Current signals are sensed using CT's and/or Hall-effect current sensors. The voltage and current signals are sometimes filtered to avoid noise problems. The filters are either hardware based (analog) or software based (digital) with either low-pass, high-pass, or bandpass characteristics.

B. Derivation of Compensating Signals

Development of compensating signals either in terms of voltages or currents is the important part of AF control and affects their rating and transient, as well as steady-state performance. The control strategies to generate compensation commands are based on frequency-domain or time-domain correction techniques.

1) Compensation in Frequency Domain: Control strategy in the frequency domain is based on the Fourier analysis of the distorted voltage or current signals to extract compensating commands [50], [56], [60], [64], [74], [81], [88], [92], [97]. Using the Fourier transformation, the compensating harmonic components are separated from the harmonic-polluted signals and combined to generate compensating commands. The device switching frequency of the AF is kept generally more than twice the highest compensating harmonic frequency for effective compensation. The on-line application of Fourier transform (solution of a set of nonlinear equations) is a cumbersome computation and results in a large response time.

2) Compensation in Time Domain: Control methods of the AF's in the time domain are based on instantaneous derivation of compensating commands in the form of either voltage or current signals from distorted and harmonic-polluted voltage or current signals. There is a large number of control methods in the time domain, which are known as instantaneous *"p-q"* theory [59], [63], [65], [66], [75], [85], [86], [89], [91], synchronous *d-q* reference frame method [19], [20], [109], [132], [154], synchronous detection method [157], [159], [162], flux-based controller [144], notch filter method [139], [158], [160], [164], P-I controller [51], [87], [149], sliding-mode controller [51], [112], [127], [141], etc.

The instantaneous active and reactive power *(p-q)* theory [178] has been widely used and is based on *"a-/3"* transformation of voltage and current signals to derive compensating signals. The instantaneous active and reactive power can be computed in terms of transformed voltage and current signals. From instantaneous active and reactive powers, harmonic active and reactive powers are extracted using low-pass and high-pass filters. From harmonic active and reactive powers, using reverse "a-/?" transformation, compensating commands in terms of either currents or voltages are derived. In the synchronous *cl-q* reference frame and flux-based controllers, voltage and current signals are transformed to a synchronously rotating frame, in which fundamental quantities become dc quantities, and then the harmonic compensating commands are extracted. The dc-bus voltage feedback is generally used to achieve a serf-supporting dc bus in voltage-fed AF's. In the notch-filter-based method, the compensating commands are extracted using notch filters on distorted voltage or current signals. In P-I and sliding-mode controllers, either dc-bus voltage (in a VSI) or dc-bus current (in a CSI) is maintained to the desired value and reference values for the magnitudes of the supply currents are obtained. Subtracting load currents from reference supply currents, compensating commands are derived. The different theories and concepts reported to support the various control methods can be found in [167]-[192].

C. Generation of Gating Signals to the Devices of the AF

The third stage of control of the AF's is to generate gating signals for the solid-state devices of the AF based on the derived compensating commands, in terms of voltages or currents. A variety of approaches, such as hysteresis-based current control, PWM current or voltage control, deadbeat control, sliding mode of current control, fuzzy-based current control, etc., are implemented, either through hardware or software (in DSP-based designs) to obtain the control signals for the switching devices of the AF's.

V. SELECTION OF COMPONENTS AND ADDITIONAL FEATURES OF AF'S

The selection of components of the AF's is an important factor to achieve improved performance. The main component of the AF is the solid-state device. In the earlier days, BJT's followed by MOSFET's were used in small ratings. Nowadays, the IGBT is an ideal choice up to medium ratings, and GTO's are used in higher ratings. A series inductor (L_c) at the input of a VSI bridge working as an AF is normally used as the buffer between supply terminal voltage and PWM voltage generated by the AF's. The value of this inductor is very crucial in the performance of the AF's. If a small value of L_c is selected, then large switching ripples are injected into the supply currents, and a large value of L_c does not allow proper tracking of the compensating currents close to the desired values. An optimum selection of L_c is essential to obtain satisfactory performance of the AF. Generally, a passive ripple filter is used at the terminal of the supply system, which compensates for switching harmonics and improves the THD of the supply voltage and current. The design of the passive ripple filter is also important, because source impedance can cause an interaction with its components. The dc-bus capacitor value Cdc of the AF's is another important parameter. With a small value of C_{dc}, large ripples in the steady state and wide fluctuations in the dc-bus voltage under transient conditions are observed. A higher value of C_{dc} reduces ripples and fluctuations in the dc-bus voltage, but increases the cost and size of the system.

In general, AF's are used to compensate current and voltage harmonics, but in most cases, they also have additional functions, such as compensation for reactive power, current and voltage unbalance, neutral current, voltage flicker, voltage spikes, and for voltage regulation. Most of the voltage-related compensations (voltage unbalance, regulation, flicker, etc.) are carried out using series AF's, while current-related compensations (reactive power, current unbalance, etc.) are made using shunt AF's. Sometimes, the structure similar to AF's is used exclusively for additional features, such as reactive power compensation [193]-[223], load balancing [193], [197], [209], [210], [212], voltage regulation and voltage unbalance compensation [151], [181], [219], etc.

VI. TECHNICAL AND ECONOMIC CONSIDERATIONS

Technical literature on the AF's has been reported since 1971 [26] and, in the last two decades, has boomed. Around 1990, many commercial development projects were completed [16]—[18] and put into practice. A number of configurations discussed earlier have been investigated, but could not be developed commercially because of cost and complexity considerations. Initially reported configurations were quite general and the rating of solid-state devices involved was substantial, which resulted in high cost. Due to these reasons, the technology could not be translated to field applications. Later on, the rating of active filtering was reduced by the introduction of supplementary passive filtering [20], [94], [96], without deteriorating the overall filter performance. Moreover, modern AF's are capable of compensating quite high orders of harmonics (typically, the 25th) dynamically. However, as high-order harmonics are small, they are compensated by using a passive ripple filter [66]. This approach has given a boost to field applications, and in countries such as Japan and the U.S., AF acceptability for field applications has increased up to the 1000-kVA range. Another major attempt has been to separate out various compensation aspects of the AF's to reduce the size and cost. However, additional features get included on specific demand. Economic considerations were the hindrance at the initial stages of AF development, but now they are becoming affordable due to a reduction in the cost of the devices used. With the harmonic pollution in present-day power systems, the demand for the AF is increasing. Recommended standards such as IEEE-519 [15], will result in the increased use of AF's in the coming years.

VII. SELECTION CONSIDERATIONS OF AF's FOR SPECIFIC APPLICATIONS

Selection of the AF for a particular application is an important task for end users and application engineers. There are widely varying application requirements, such as single-phase or three-phase, three-wire and four wire systems, requiring current- or voltage-based compensation. Moreover, there is a number of AF configurations which may cater to the needs of individual users. A brief list of criteria for selection of an appropriate AF for a specific application is discussed in this section. Table I shows a brief summary of selection of suitable AF's for specific users.

A. Current-Based Compensation

Current-based compensation is classified as current harmonics compensation, reactive power compensation, load balancing, and neutral current compensation. This compensation may either be required individually or in a combination by the individual users. For the current harmonics compensation, the active shunt filter is an ideal device, but a hybrid of active series with passive shunt filter is considered most suitable because of its reduced cost, caused due to the low rating of power electronics (typically 4%-5% of load). Reactive power compensation is carried out by using active shunt filters (similar to a STATCON) for adjustable loads and by using ac capacitors for fixed load. Load balancing in either three-wire or four-wire systems is generally done by using an active shunt filter configuration. Neutral current compensation is carried out by employing an active shunt filter [161]. For most of the combinations of these current-based compensations, the active shunt filter is technically the right choice, but a hybrid of active series with passive shunt filter is the most preferable choice, because of the reduced cost for the combination of these compensation methods.

B. Voltage-Based Compensation

Voltage-based compensation is categorized as voltage harmonics compensation, improving voltage regulation, voltage balancing, voltage flicker reduction, and removing voltage sags and dips. Voltage-based compensation, in general, is carried out by using active series filters. However, the voltage flicker is compensated by using the active shunt filters. Table I shows a brief summary of AF's for compensation in order of preference. Nowadays, the AF's can also correct voltage compensation of momentary voltage dips or sags of very short duration.

C. Voltage- and Current-Based Compensation

Many applications require a compensation of a combination of voltage- and current-based problems, a few of them being interrelated. A hybrid of active series with active shunt filters is an ideal choice for such mixed compensation. Moreover, this hybrid of both AF's (also known as a unified power quality conditioner, UPQC) is also quite suitable for individual current- or voltage-based compensation. However, the rating, size, and cost of this UPQC is on the higher side, therefore, for few combinations of compensation such as voltage and current harmonics, other AF's (active series with passive shunt) are considered most suitable. Table I gives brief guidelines for the proper selection of AF's suited to the needs of individual requirements. It is only a basic preliminary guide for selection of suitable AF's. Since nowadays many industries (ABB, Toshiba, Fuji, Mitsubishi, Westinghouse, etc.) are manufacturing AF's, more details for suitable selection of AF's may also be found in their application notes.

TABLE I
SELECTION OF AF'S FOR SPECIFIC APPLICATION CONSIDERATIONS

Compensation for specific Application	Active Filters			
	Active Series	Active Shunt	Hybrid of Active Series and Passive Shunt	Hybrid of Active Shunt and Active Series
A. Current Harmonics		**	***	*
B. Reactive Power		***	**	*
C. Load Balancing		*		
D. Neutral Current		**	*	
E. Voltage Harmonics	***		##	*
F. Voltage Regulation	***	*	**	*
G. Voltage Balancing	***		**	*
H. Voltage Flicker	**	***		*
I. Voltage Sag&Dips	***	*	**	*
J. (A + B)		***	**	*
K. (A+B+C)		**		*
L. (A+B+C+D)		*		
M. (E+F)	**			*
N. (E+F+H+I)	**			*
O. (A+E)			**	*
P. (A+B+E+F)			*	**
Q. (F+G)	**		*	
R. (B+C)		*		
S. (B+C+D)		*		
T. (A+B+G)		**	*	
U. (A+C)		*		
V. (A+D+G)		*	**	

AF Configuration with higher number of * is more preferred

VIII. CONCLUSION

An extensive review of AF's has been presented to provide a clear perspective on various aspects of the AF to the researchers and engineers working in this field. The substantial increase in the use of solid-state power control results in harmonic pollution above the tolerable limits. Utilities are finding it difficult to maintain the power quality at the consumer end, and consumers are paying the penalties indirectly in the form of increased plant downtimes, etc. At present, AF technology is well developed, and many manufacturers **[16]—[18]** are fabricating AF's with large capacities. The utilities in the long run will induce the consumers with nonlinear loads to use the AF's for maintaining the power quality at acceptable levels. A large number of AF configurations are available to compensate harmonic current, reactive power, neutral current, unbalance current, and harmonics. The consumer can select the AF with the required features. It is hoped that this survey on AF's will be a useful reference to the users and manufacturers.

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