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A REVIEW ON ACTIVE POWER FILTERS FOR POWER QUALITY IMPROVEMENT

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Abstract: Active filtering of electric power has now become a latest 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, other related technical considerations, and their performance. It is aimed at providing a broad perspective on the status of Active Power Filter 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: Research Publication, Active Power Filter, Power Filter line Conditioners.

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. Power filter have been classified based on their dominant contribution. This paper is included following parts. Starting with an introduction, the subsequent sections cover the state of the art of the Active filter technology, the different configurations used, the control methodologies, and technical considerations.

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. Active Power Filter 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 development and present status of the Active Power Filter technology. Following the widespread use of solid-state control of ac power, the power quality issues became significant. There area 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 load son 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 load sand cause power quality problems. Single-phase (two wire)Active Power Filter 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 [50-53]. 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 Active Power Filter. A major volume of work is reported [56-81] 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 Active Power Filter 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 Active Power Filter, it is important to develop good measuring systems, and these new concepts have given a new impetus to instrumentation technology in this field.

III. CONFIGURATIONS

Active power filters 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 Active power filters. Fig. 1 shows the current-fed pulse-width modulation (PWM) inverter bridge structure. It behaves as a non-sinusoidal 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 are considered sufficiently reliable [82-83], but have higher losses and require higher values of parallel ac power capacitors. They cannot be used in multilevel or multistep modes to improve performance in higher ratings. The other converter used as an Active Power Filter is a voltage-fed PWM inverter structure, as shown in Fig. 2. It has a self-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 Active Power Filter to eliminate harmonics of critical nonlinear loads.

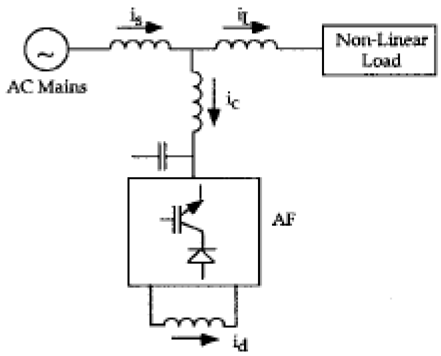

Fig. 1. Current-fed-type Active Power Filter

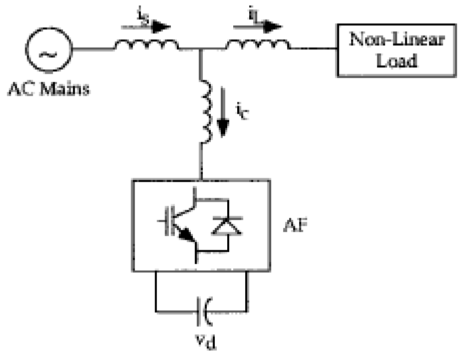

Fig. 2. Voltage- fed-type Active Power Filter

B. Topology-Based Classification

Active power filter can be classified based on the topology used as series or shunt filters [48, 87-90] and unified power quality conditioners [19, 27, 91-93] use a combination of both. Combinations of active series and passives hunt filtering are known as hybrid filters [20, 84,94-100]. 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 [88-89]. 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 actives hunt and active series filters [19, 39, 84-86, 101]. The dc-link storage element (either inductor [19, 39]or dc-bus capacitor [19, 84] 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, 84, 86, 101].

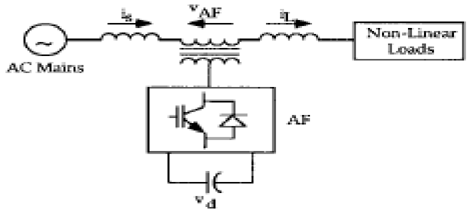

Fig. 3. Series-type Active power filter

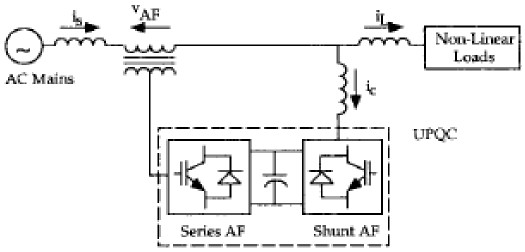

Fig. 4. Unified power quality conditioner as universal Active Power Filter

It is considered an ideal Active power filter 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, 86, 94, 98-100, 102-106]. 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 [86, 107-108] but for the sake of brevity, they are not discussed here; however, details can be found in the respective references.

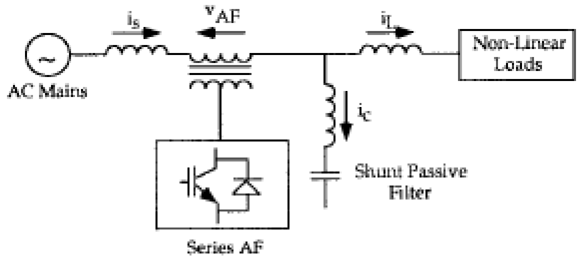

Fig. 5. Hybrid filter as a combination of active series and passive shunt filters

C. Supply-System-Based Classification

This classification of AF’s is based on the supply 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 and four-wire types [120-130].

1. Two-Wire Active Power Filter

Figs. 6–8 show three configurations of active series, actives hunt, 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 voltage harmonics, spikes, sags, notches, etc., while the shunt AF is used to eliminate current harmonics and reactive power compensation.

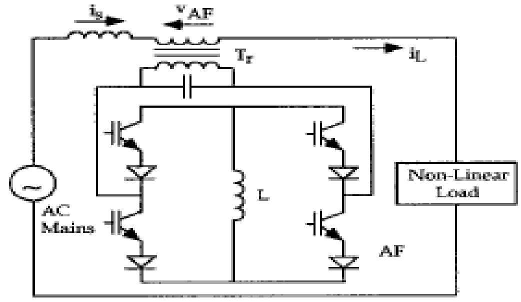

Fig. 6. Two-wire series AF with current-source converter

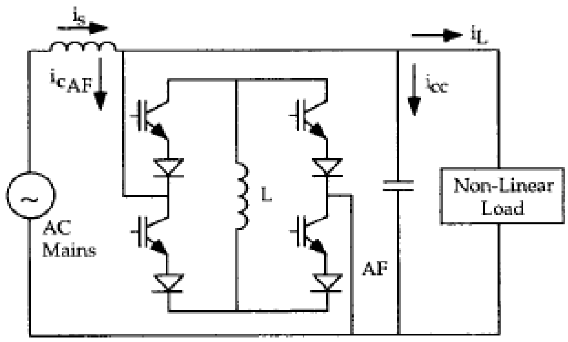

Fig. 7. Two-Wire shunt AF with current-source converter

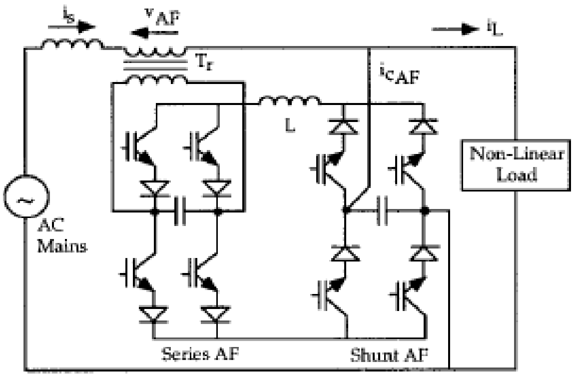

Fig. 8. Two-wire unified power quality conditioner with current-source converter

2. Three-Wire Active Power Filter

Figs. 1–5 are developed for three-wire Active Power Filter, with three wires on the ac side and two wires on the dc side. Shunt active power filter are developed in the current-fed type (Fig. 1) or voltage fed type with single-stage (Fig. 2) or multistep, multilevel and multi-series [92-93, 131-132] configurations. Shunt active power filter are also designed with three single-phase power filter 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, 100, 102-103, 105, 133-139] 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, 85-86, 140].

3. Four-Wire Active Power Filter
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 Active Power Filter have been attempted [109-119]. They have been developed as: 1) active shunt mode with current feed [141] and voltage feed [110-111, 113-118; 2) active series mode 116-118; and 3) hybrid form with active series and passive shunt [117] mode. Figs. 9–11 show three typical configurations of shunt Active Power Filter[111]. The first configuration of a four-wire shunt Active Power Filter 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 poleis used to stabilize the neutral of the AF. The three single phase bridge configuration, shown in Fig. 11, is quite common [110-115], and this version allows the proper voltage matching for solid-state devices and enhances the reliability of the Active Power Filter system. A detailed comparison of the features of these three configurations (Figs. 9–11), is given in [111].

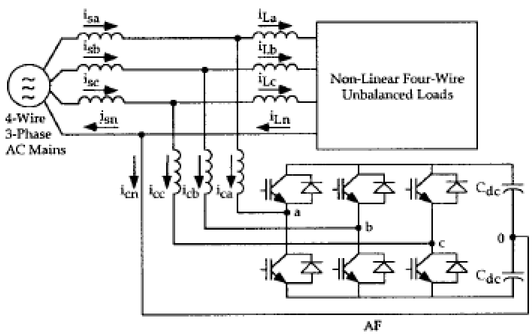

Fig. 9. Capacitor midpoint four-wire shunt Active Power Filter

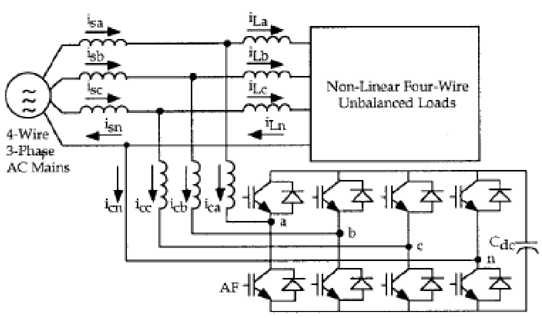

Fig. 10. Four-pole four-wire shunt Active Power Filter

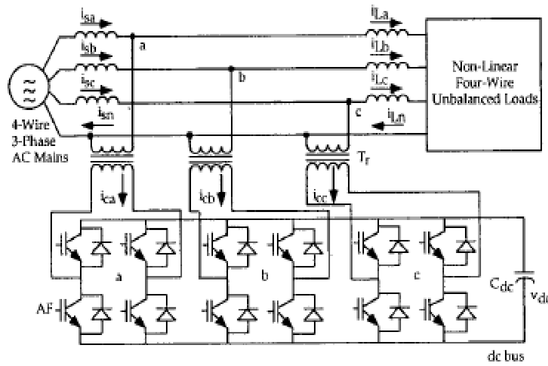

Fig. 11. Three-bridge four-wire shunt Active Power Filter

IV. CONTROL STRATEGIES

Control strategy is the heart of the Active Power Filter control 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 and Active Power Filter configurations. In the third stage of control, the gating signals for the solid-state devices of the Active Power Filter are generated using PWM, hysteresis, sliding-mode, or fuzzy-logic-based control techniques. The control of the Active Power Filter 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, dc-bus voltage of the Active Power Filter, and voltages across series elements. The current signals to be sensed are load currents, supply currents, compensating currents, and dc-link current of the Active Power Filter. 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 a void noise problems. The filters are either hardware based (analog) or software based (digital) with either low-pass, high-pass, or band-pass characteristics.

B. Derivation of Compensating Signals
Development of compensating signals either in terms of voltages or currents is the important part of Active Power Filter 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, 142-149].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 cumber some computation and results in a large response time.

2. Compensation in Time Domain:
Control methods of the Active Power Filter 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 [142-149] synchronous d–q reference frame method [19, 20, 100, 102, 149] synchronous detection method [157-159, 162] flux-based controller [144], notch filter method [105, 111, 113-117], P–I controller [150-152] sliding mode controller [150-152], etc.

3. Generation of Gating Signals to the Devices of the Active Power Filter control
The third stage of control of the Active Power Filter control 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, dead beat 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 Active Power Filter control.

V. TECHNICAL CONSIDERATIONS

Technical literature on the Active Power Filter has been reported since1971 [26] and, in the last two decades, has boomed. Around1990, 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, 94-95] without deteriorating the overall filter performance.

VI. CONCLUSION

An extensive review of Active Power Filter has been presented to provide a clear perspective on various aspects of the Active Power Filter to there searchers 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, Active Power Filter technology is well developed, and many manufacturers [16]–[18] are fabricating Active Power Filter with large capacities. The utilities in the long run will induce the consumers with nonlinear loads to use the Active Power Filter for maintaining the power quality at acceptable levels. A large number of Active Power Filter configurations are available to compensate harmonic current, reactive power, neutral current, unbalance current, and harmonics. The consumer can select the Active Power Filter with the required features. It is hoped that this survey on Active Power Filter will be a useful reference to the users and manufacturers.

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