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Active power line conditioners for power quality improvement -A prospective

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Abstract

Active Power Line Conditioning (APLC) of electric power has now become a mature technology for eliminating harmonics 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. This paper presents a comprehensive status of APLC configurations, control strategies, selection of components, and related economic and technical considerations. It is aimed to provide a broad prospective on the status of APLC technology to researchers and application engineers dealing with power quality issues.

Keywords: Power quality, harmonics and reactive power compensation, active power line filters, active power line conditioners, non-linear loads.

1. 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 (ASDs), furnaces, computer power supplies, etc. Such Controllers are also used in HVDC systems and renewable electric power generation. As nonlinear loads increase, these solid state converters draw harmonics and reactive power components of current from ac mains. In three-phase system, they 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 non-linear loads. Conventionally passive L-C filters were used to reduce harmonics and capacitors were employed to improve the power factor of ac loads. However passive filters have 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 power quality problems. Such equipments generally known as Active filters (AF)[16–20], are also called as Active Power Line Conditioner (APLC), Instantaneous Reactive Power Compensator (IRPC), Active Power Filters (APF) and Active Power Quality Conditioner (APQC). In recent years, many texts have also appeared[21–25] on the harmonics, reactive power, load balancing and neutral current compensation associated with linear and non-linear loads. This paper aims to present a comprehensive state of art on the subject of APLC. More than one hundred publications[1–166] are reviewed and classified in four categories. The first category is on general development and survey of harmonic problems while second to fourth categories are on two-wire (single-phase), three-wire (three-phase without neutral) and four-wire (three-phase with neutral) APLCs. The paper is presented in six parts. Starting with an introduction, the subsequent sections cover the state of art of the APLC technology, different configurations used, control methodologies, economic and technical considerations and the concluding remarks.

2. State of art

The APLC technology is now matured 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 various configurations, control strategies and solid state devices. Active Power Line Conditioners are also used to eliminate voltage harmonics, to regulate terminal voltage, to suppress the voltage flicker and to improve voltage balance in three-phase systems. These wide range of objectives are achieved individually or in combination depending upon the requirements and accordingly control strategy and configurations are selected. This section describes the history of development and present status of APLC technology.

Following the wide spread use of solid state control of ac power, the power quality issues become significant. There are a large number of publications covering the power quality survey, measurements, analysis, cause and effects of harmonics and reactive power in electrical networks [1–25]. Active Power Line Conditioners are basically categorized in three types namely two-wire (single-phase), three-wire and four-wire three-phase configurations to meet the requirements of three types of non-linear loads on supply systems. Single-phase loads such as domestic lights and ovens, TVs, computer power supplies, air conditioners, laser printers and xerox machines behave as a non-linear loads and cause power quality problems. Single-phase (two-wire) APLCs are investigated[26–55] in varying configurations and control strategies to meet the needs of single-phase non-linear loads. Starting from 1971, many configurations such as active series filter[48], active shunt filter[26–47] and combination of shunt and series filter[39] have been developed and commercialized also for UPS applications[50,52,53]. Both concepts which are based on current source inverter with inductive energy storage and voltage source inverter with capacitive energy storage are used to develop single-phase APLCs.

Since major amounts of ac power is consumed by three-phase loads such as ASD (Adjustable Speed Drives) with solid state control, a substantial number of work have been reported on three-phase three-wire APLCs[56–155], starting from 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 APLCs 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 APLCs.

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

One of the major factors in advancing the APLC technology is the advent of fast, self commutating solid state devices. In the initial stages, thyristors, BJTs and Power MOSFETs were used for APLC fabrication; later SIT and GTO were employed to develop APLCs. With the introduction of IGBT, the APLC technology got a real boost and at present it is considered as ideal solid state devices for APLCs. The improved sensor technology has also contributed to the enhanced performance of APLCs. Availability of hall effect sensors and isolation amplifiers at reasonable cost and with adequate ratings have improved APLC performance.

The next breakthrough in APLC development is due to the microelectronics revolution. Starting from the use of discrete analog and digital components[162], the progress has been to microprocessors, microcontrollers[64] and DSPs[50,148]. Now it is possible to implement complex algorithms on-line for the control of APLC at reasonable cost. This development has made it possible to use different control algorithms such as 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 APLCs.

3. Configurations

Active Power Line Conditioners can be classified on converter type, topology and the number of phases. The converter type can be with current source or voltage source inverter bridge structures. The topology can be shunt, series or 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 APLCs. Fig. 1 shows the current fed PWM inverter bridge structure. It behaves as non-sinusoidal current source to meet harmonic current requirement of the non-linear load. A diode is used in series with the self commutating device (IGBT)for reverse voltage blocking. However, GTO based configurations do not need series diode, but they have restricted frequency of switching. These type of configuration are considered sufficiently reliable[68,79], but have higher losses and require higher values of parallel ac power capacitors. Moreover they can not be used in multilevel or multistep modes to improve performance in the higher ratings.

The other converter used as an APLC is voltage fed PWM inverter structure shown in Fig. 2. It has 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 for enhancing the performance with lower switching frequencies. It is more popular in UPS based applications because in presence of mains, the same inverter bridge can be used as APLC to eliminate harmonics of critical non-linear loads.

B. Topology Based Classification

APLC can be classified on the basis of topology used as series or shunt filters[48,106,115,121,146] and unified power quality conditioners[19,27,135,138,152] which use combination of both. Combinations of active series and passive shunt filters is known as hybrid filter[20,94,96,99,132,134,142,152,154]. Fig. 2 is an

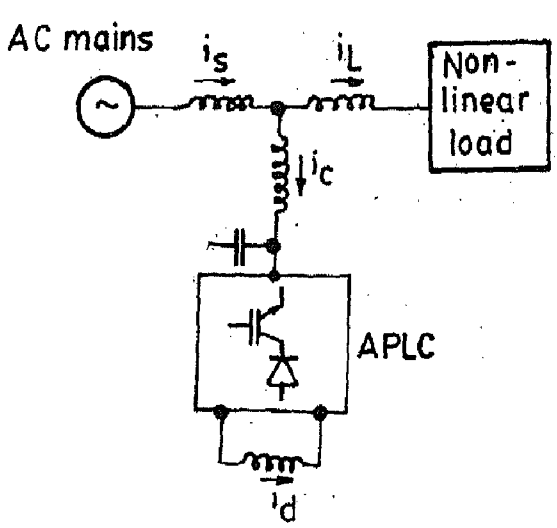

FIG. 1. Current fed type APLC.

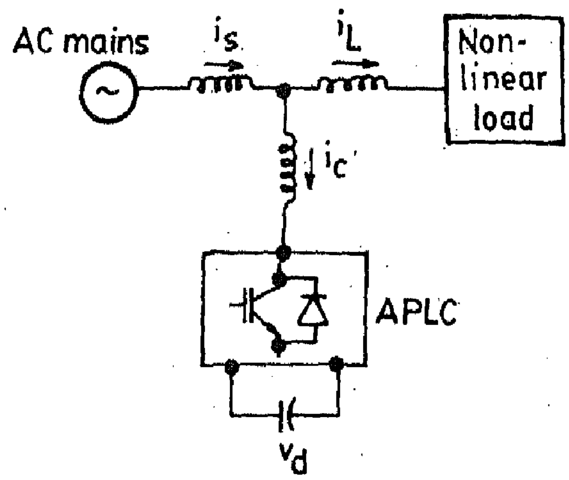

FIG. 2. Voltage fed type APLC.

example of active shunt power conditioner and most widely used to eliminate current harmonics, reactive power compensation (also known as STATCON) and balancing unbalanced currents. It is mainly used at load end because current harmonics are injected by non-linear loads. It injects equal compensating currents, opposite in phase to cancel harmonics and/or reactive components of the non-linear load current at the point of connection. It can also be used as static VAR generator (STATCON) in the power system network for stabilizing and improving the voltage profile.

Fig. 3 shows the basic block of stand alone active series power line conditioner. It is connected before the load in series with mains, using matching transformer, to eliminate voltage harmonics[48], and to balance and regulate the terminal voltage of the load or line. It has also been used to reduce negative sequence voltage and regulate the voltage on three-phase systems[115,121]. It can be installed by electrical 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 universal active filter) 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 bridge operating as active series and active shunt compensators. It is used in single

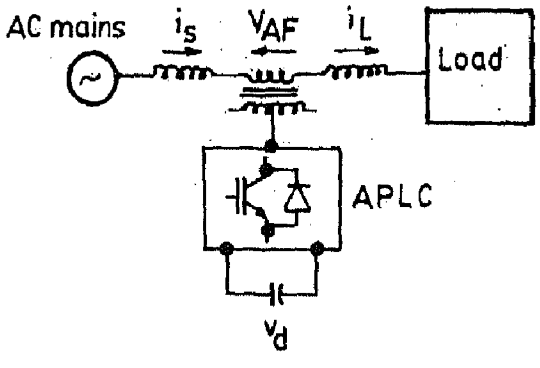

FIG. 3. Series type APLC.

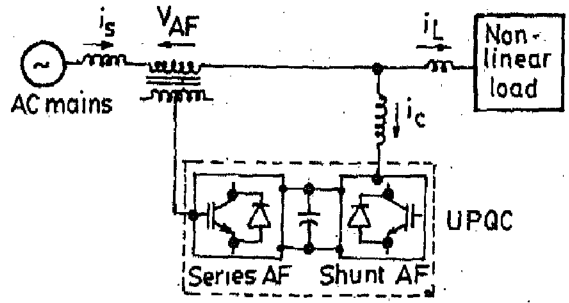

FIG. 4. Unified power quality conditioner as universal APLC.

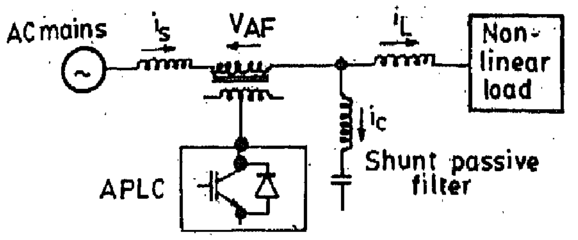

FIG. 5. Hybrid filter as a combination of active series and passive shunt filter.

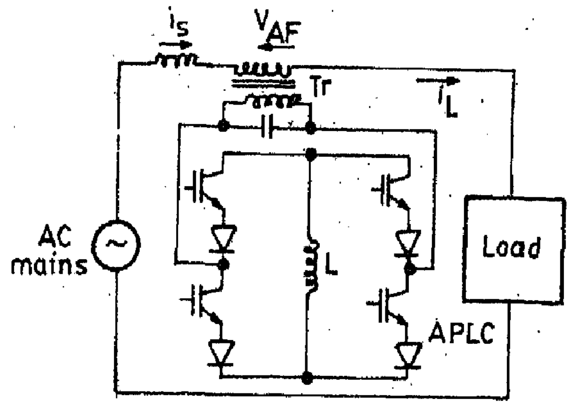

FIG. 6. Two-wire series APLC with current source converter.

phase[19,39] as well as three-phase configurations[19,133,135,152]. It is considered as ideal APLC which eliminates voltage and current harmonics and capable of giving clean power to critical and harmonic prone loads such as computers, medical equipments, 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 APLC which is a combination of active series filter and passive shunt filter[20,94,109,120,134,137,142,145,152,154]. It is quite popular because the solid state devices used in active series part can be of reduced size and cost (about 5% of load size) and major part is the passive shunt L-C filter is used to eliminate lower order harmonics. It has the capability of reducing voltage and current harmonics at reasonable cost. There are many more hybrid configurations[136,153] but for brevity they are not discussed here, but the details can be found in respective references.

C. Supply System Based Classification

This classification of the APLCs is based on supply and/or load system having single-phase (two-wire) and three-phase (three-wire or four-wire) systems. There are many non linear loads such as domestic appliance connected to single-phase supply system. Some three-phase non-linear loads are without neutral, such as ASD (Adjustable Speed Drives) fed from three-wire supply system.

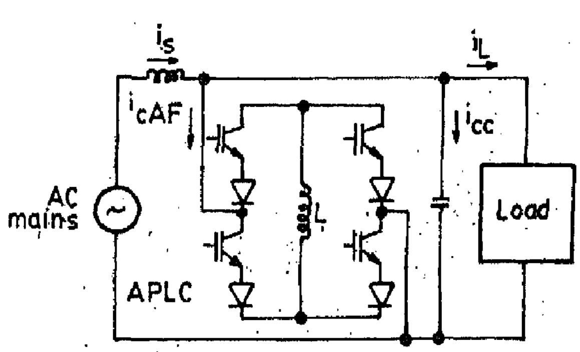

FIG. 7. Two-wire shunt APLC with current source converter.

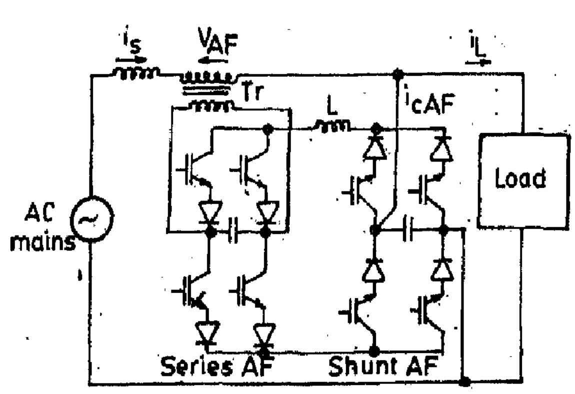

FIG. 8. Two-wire unified power quality conditioner with current source converter.

There are many non-linear single-phase loads distributed on four-wire, three-phase supply system, such as computers, commercial lighting, etc. Hence APLCs may also be classified accordingly as two-wire[26–55], three-wire[56–155], and four-wire types[156–166].

Two-wire APLCs

Two-wire (single-phase) APLCs[19,26–55] are used in all the 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 APLC circuits. In some cases, active filtering is included in the power conversion stage[36,40,41] to improve input characteristics at supply end.

Figs. 6-8 show three configurations of active series, active shunt and a combination of both having current source bridge with inductive storage element. Similar configurations based on voltage source inverter bridge, may be obtained by considering only two-wires (phase and neutral) at each stage of Figs 2–4. In case of series APLC with voltage fed converter, sometimes the transformer is removed and load is shunted with passive L-C components[48]. Series APLC is normally used to eliminate voltage harmonics, spikes, sags, notches, etc. contributed by source while shunt APLC is used to eliminate current harmonics contributed by load.

Three-wire APLCs

Three-phase, three-wire non-linear loads such as ASDs are one of the major applications of solid state power converters and a large number of publications[15–20,56–155] have appeared on three-wire APLCs with different configurations. All the configurations shown in Figs 1–5 are developed, in three-wire APLCs with three-wires on ac side and two-wires on dc side. Active shunt APLCs are developed in current fed type (Fig. 1) or voltage fed type with single stage (Fig. 2) or multistep/multilevel and mutiseries[65,66,85,86] configurations. Active shunt APLCs are also designed with three single-phase APLCs 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 overall system. A combination of active series and active shunt is used as unified power quality conditioners (Fig. 4) and universal filters[19,135,138,152].

Four-wire APLCs

A majority 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 APLCs have been attempted[156–166]. They have been developed as: (i) active shunt mode with current fed[156] and voltage fed[157,158,160,165], (ii) active series mode[163,165] and (iii) hybrid form with active series and passive shunt[164] mode. Figs. 9–11 show three typical configurations of shunt APLCs[158]. First configuration of four-wire shunt APLCs is known as capacitor mid-point type, used in smaller ratings. Here, the entire neutral current flows through dc bus capacitors which are of large value. Fig. 10 shows the another

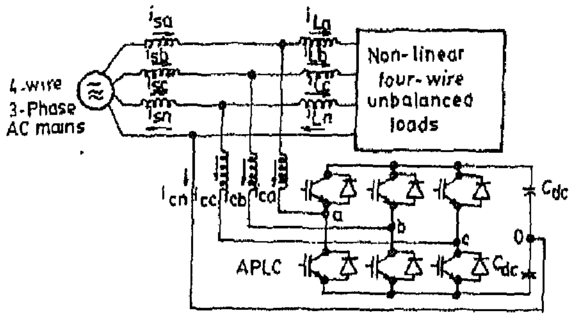

FIG. 9. Capacitor midpoint, four-wire shunt APLC.

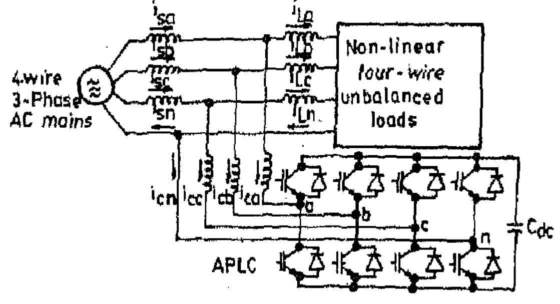

FIG. 10. Four-pole, four-wire shunt APLC.

configuration known as four pole switch type, in which the fourth pole is used to stabilize the neutral of APLC. Three single-phase bridge configurations shown in Fig. 11 is quite common[157,159,162] and this version allows the proper voltage matching for solid state devices and enhances the reliability of the APLC system. A detailed comparison of the features of these three configurations (Figs. 9–11) is given in reference[158].

4. Control strategies

Control strategy is the heart of APLC and is implemented in three stages. In the first stage, the essential voltages and current signals are sensed using PTs, CTs, hall effect sensors and isolation amplifiers to gather accurate system information. In the second stage, compensating commands in term of current and voltage levels are derived based on control methods and APLC configurations. In the third stage of control, the gating signals to solid state devices of the APLC are generated using PWM, hysteresis, sliding mode, or fuzzy logic based control techniques. The control of the APLCs is realized using discrete analog and digital devices or advanced microelectronic devices such as single chip microcomputers, DSPs, etc.

A. Signal conditioning

For the purpose of implementation of control algorithm, several instantaneous voltage and current signals are required. These signals are also useful to monitor, measure and record various parameter indices such as THD, power-factor, active and reactive power, crest factor etc. The typical voltage signals are ac terminal voltages, dc bus voltage of the APLC and voltage across series elements. The current signals to be sensed are load currents, supply currents, compensating currents and dc link current of the APLC. Voltage signals are sensed using either PTs or hall effect voltage sensor or isolation amplifiers. Current signals are sensed using CTs and/or hall effect current sensors. The voltage and current signals are sometimes used after filtering to avoid noise problems. The filter are either hardware based (analog) or software based (digital) with low pass or 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 APLC 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.

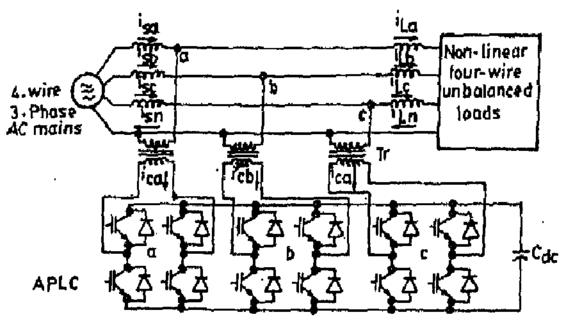

FIG. 11. Three-bridge, four-wire shunt APLC.

Compensation in Frequency Domain

Control strategy in 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 signal and combined to generate compensating commands. The APLCs device switching frequency is kept generally more than a decade above the highest frequency to be compensated for effective compensation. The on line application of Fourier transform (solution of a set of non-linear equations) is a cumbersome compensation and results in a large response time.

Compensation in Time Domain

Control methods of the APLCs in time domain are based on instantaneous derivation of compensating commands in form of either voltage or current signals from distorted and harmonic polluted voltage or current signals. There are large number of control methods in time domain and are known as instantaneous "p-q" theory[59,63,65,66,75,85,86,89,91], synchronous d-q reference 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[59] has been widely used and is based on "α-β" 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 power, harmonic active and reactive powers are extracted using low pass and high pass filters. From harmonic active and reactive powers, using reverse "α-β" transformation, compensating commands in terms of either currents or voltages are derived. In synchronous d-q reference frame and flux based controller, voltage and current signals are transformed to synchronously rotated 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 make it self supporting dc bus in voltage fed APLCs. In notch filter based methods, the compensating commands are extracted using notch filter on distorted voltage and current signals. In P-I and sliding mode controller, either dc bus voltage (in VSI) or dc bus current (in CSI) is maintained to desired value and reference peak currents of the supply are obtained. Subtracting load current from reference supply currents, compensating commands are derived.

C. Generation of Gating Signals to APLCs Devices

The third stage of control of the APLCs, is to generate gating signals to the solid state devices of the APLC 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, etc., are implemented either through hardware or software (in DSP based designs) to obtain the control signals for switching devices of the APLCs.

5. Selection of components and additional features of APLCs

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

In general, APLCs 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 regulations. Most of the voltage related compensations (voltage unbalance, regulation, flicker, etc.) are carried out using series APLCs while current related compensations (reactive power, current unbalance, etc.) are made using shunt APLCs. Sometimes, the structure similar to APLCs is used exclusively for additional feature such as reactive power compensation, load balancing, voltage regulation and voltage unbalance compensation, etc.

6. Technical and economic considerations

Technical literature on the APLCs has been reported since 1971[26] and in the last two decade their number has boomed. Around 1990, many commercial development projects got completed[16–18] and put to practice. A number of configurations as discussed earlier have been investigated but could not developed commercially because of cost and complexity considerations. Initially reported configurations were quite general and rating of solid state device involved was substantial which resulted in heavy cost of development. Due to these reasons, the technology could not be translated to field applications. Later on, rating of active filtering got reduced by the introduction of supplementary passive filtering[20,94,96] without deteriorating the overall filter performance. this approach has given a boost to field applications and in countries such as Japan and U.S., APLCs acceptability for field applications has increased up to 1000 kVA range. Another major attempt has been to separate out various compensation aspects of the APLCs to reduce the size and cost. However, additional features get included on specific demand. Economic considerations were the hindrance at the initial stage of APLC development but now it is becoming affordable due to reduction in the cost of devices used. With the harmonic pollution in present day power system, the demand for APLC is increasing. Recommended standards such as IEEE-519[15] will result in the increased use of APLCs in the coming years.

7. Conclusion

An extensive review of the APLCs has been presented to provide a clear perspective on various aspects of the APLC to the researchers and engineers working in the 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 customer end, and consumers are paying penalties indirectly in the form of increased plant down times, etc. At present, APLC technology has developed well and many manufacturers[16–18] are fabricating APLCs with large capacities. The utilities in the long run will induce the consumers with non-linear loads to use the APLCs for maintaining power quality to acceptable level. A large number of APLC configurations are available to compensate harmonic current, reactive power, neutral current, unbalanced current and harmonics. The consumer can select the APLC with the required features. It is hoped that this exhaustive survey on the APLCs will be useful reference to the users and manufacturers.

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