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A Survey on Hybrid Active Power Filter Topologies and Controllers

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Abstract— **Hybrid active power filter (HAPF) consisting of passive filter and active filter in various configurations to each other has now become preferred technology for harmonic compensation in two wire, three wire and four wire ac power networks with nonlinear loads. This paper presents a detailed survey of hybrid active power filters considering converter topologies, supply system and passive filter type. In addition, the control strategies are discussed in detail. The main aim of this paper is to provide a broad perspective on the status of HAPF technology to researchers and application engineers dealing with power quality. More than eighty research papers are reviewed and classified into categories and subcategories.**

Keywords-hybrid active filter; power quality; harmonics; review; referance extracion; time domain, frequency domain

I. Introduction

In recent years, with the increase of nonlinear loads in industrial manufacturers, the power quality issue has become more serious. There are various custom power devices to solve these power quality problems. Hybrid Active Power Filter is one of them and available in literature survey [1-83]. In the past, the passive power filters were often used to solve serious harmonic problems of the grid [32]. Although passive filters were preferred because of its economic and simple structure, new methods are needed due to the disadvantages of passive filter such as requirement of a separate filter for each harmonic current, having limited filtering characteristics, the negative effects caused by parallel and series resonance between grid and filter impedance [32,37,38,26,29,52,55, 60,63] . The active power filter which is developed to remedy the shortcomings of the passive filter consists of voltage or current source inverter, DC link storage and output filter. When active filter is compared to passive filter, although active filter has complex structure and more costly, today they can solve various power quality problems such as harmonic compensation, reactive power compensation, voltage imbalance, voltage flicker [53]. Even though the active power filter is an effective compensation system, their cost is increasing seriously with the proportion of increasing power capacity [26,29,33,52,54,57,60,62,66]. As a solution to this situation, the hybrid active power filters have been developed by using active and passive filters together [34,55,57, 59,61,62,83]. The main aim in the development of HAPF is to reduce the cost and rating of active filter by using passive filter that filters the dominant harmonics caused by non-linear loads and supplies reactive power requirement [52].

This paper aims at presents a comprehensive literature survey on HAPF. More than eighty publications [1-83] are referred and classified into five categories. First, all HAPF configurations are reviewed [1-83]. Then HAPF's are classified according to converter topologies [11-17], supply system [21-24,26-36,37-38], passive filter type [26-36,48-51,52-67] and controller strategies. In this paper, especially series active power filter in series connected shunt passive filter HAPF topology is emphasized.

II. CLASSIFICATION OF HYBRID ACTIVE FILTER

General classification of HAPF is shown in Figure-1.

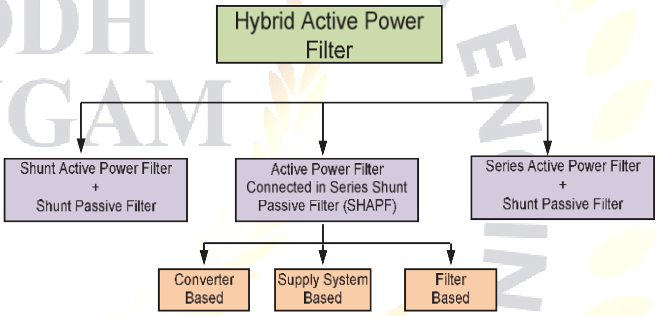

Figure -1:Classification of HAPF

A. Topology Based

Three basic topologies in literature exist for HAPF. These are series active power filter +shunt passive filter, shunt active power filter + shunt passive filter, active power filter connected in series with shunt passive filter. Figure-2 illustrates these topologies.

1) Series active power filter +shunt passive filter

This topology combines the series active filter and shunt passive filter [1-5]. Series active filter indicates high impedance with supplying harmonic isolation [4] and enabling the harmonic current to flow on passive filter. This type of filter is designed to compensate reactive power, harmonics and unbalanced loads in the medium voltage level of a power distribution system [1]. In recent studies, multilevel inverter has been used to reduce the switching losses [2]. This topology isn't preferred for practical application because of disadvantages of series active filter. Therefore, there are limited number of studies on this filter.

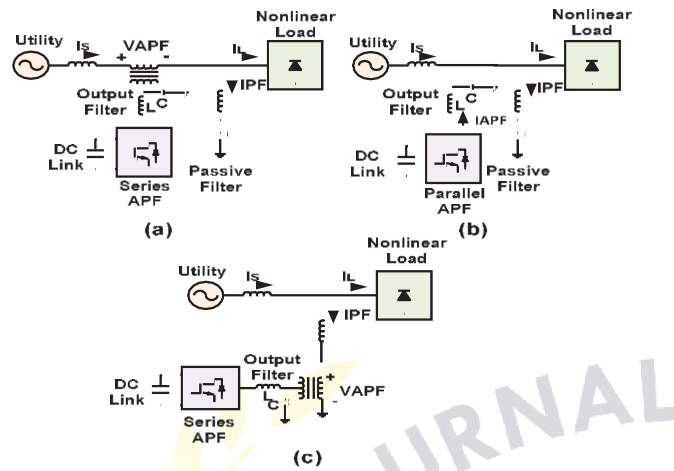

Figure -2: HAPF Topologies (a)series active power filter +shunt passive filter, (b)shunt active power filter + shunt passive filter, (c)active power filter connected in series with shunt passive filter

2) Shunt active power filter+shunt passive filter

This type of filter is combined with passive and active power filter in parallel configuration [6-10]. The aim of using passive filter is to both filter dominant harmonics of nonlinear loads in low frequency and supply reactive power compensation [7]. Besides, the parallel active power filter not only compensates the harmonics that passive filter couldn't filter but also supports reactive power compensation. With this topology, the rated current of APF is reduced [9].

The aim of this work is that while passive part compensates the fundamental reactive power and low order harmonics, active part compensates high order harmonics [8]. In this topology, the resonance problem between passive part and power system is disappeared. In addition, the compensation capacity of active power filter is decreased. With this topology, the compensation capacity of active filter is greatly smaller when reactive compensation is necessary [7]. In addition, the attenuation and phase shift of the compensation current which is occurred by passive filter will not exist anymore [8].

3) Active power filter connected in series with shunt passive filter

This type of filter is the most common to others. This topology consists of shunt passive filter in series with active power filter [11-82]. Active power filter part supplies to hold on DC link voltage that only requires for harmonic compensation. Passive filter part holds on the voltage of fundamental component in grid. The rated voltage of APF can be reduced the ratio of 1/10 compared to parallel active power filter. Therefore, not only the inverter of APF and dc link capacity but also cost is significantly decreased. In addition, the switching loss of the inverter can reduce with decreasing the rated voltage of APF. This topology is examined detail to this article.

B. Converter Configuration

HAPF topologies consist of active power filter and passive filter. The active part includes inverters. These inverter topologies are as follows:

One of them is three phase voltage source inverter [11-17]. VSI which has a self supporting dc voltage bus with a large dc capacitor has many advantages. This type of inverter is lighter, cheaper and easily converted to multilevel to increase the performance for achieving low switching frequency [16,17]. The other converter used as in HAPF is current source inverter. This inverter acts as a non sinusoidal current source in order to satisfy the harmonic current which the nonlinear load requires. The output current is kept constant irrespectively of the load on the inverter the output voltage forced to change. The drawbacks of this inverter are that it has higher losses and requires higher values of parallel ac power capacitors. In addition, it is not expandable to multilevel to improve performance in higher ratings. Besides, it requires extra control stage to control the current. The dynamic response is slower. Last type is multilevel inverter. The multilevel inverters [19-20,41,45] have become popular in power industry. In high power and high voltage applications, they have some drawbacks such as switching loss and constraints of device ratings in operations. Multilevel structure can succeed high power and high voltage inverter without requiring higher ratings. In addition, with this structure, the use of transformer or synchronized switching device isn't required [19]. In literature, there are three type of multilevel converters: Diode clamped [20,41], flying capacitor, cascaded. Figure-3 shows diode clamped multilevel inverter topology.

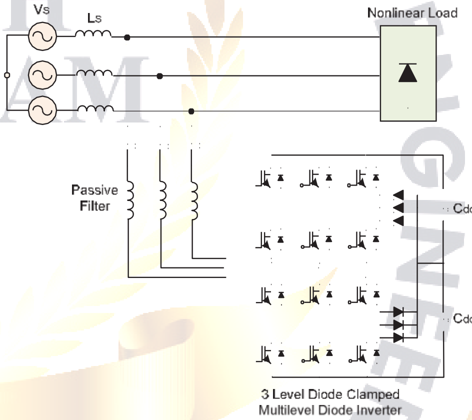

Figure -3: Multilevel inverter based Hybrid APF

C. Supply System

There are three configurations based on supply system. These configurations are shown in Figure-4. The first configuration is two-wire. Two wire hybrid active power filters [22-24] are generally available in low power ratings. The advantage of two wire hybrid active power filter is that they have to deal with low power [22]. Besides, they are able to be operated at relatively higher frequencies leading to improved performance [23].

Another configuration is three-wire [26-36]. Three wire active power filters are suitable not only for low power but also medium and high power applications [26]. In literature, most publications are on three wire HAPF's with different topologies. Last configuration is four-wire [21,37-38]. Single phase loads which are supplied from three phase mains with causing unbalance. To overcome these problems, four wire HAPF has been developed [37]. The most widely used four wire topologies are: the capacitor midpoint type [37] and the four leg switch type [38]. The capacitor midpoint type is used for lower ratings. All neutral current flows through dc-bus capacitor. The four leg switch type is operated to stabilize the neutral of HAPF.

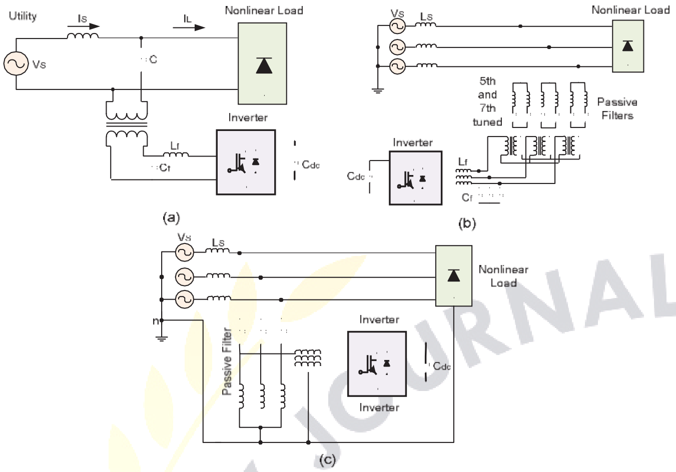

Figure-4: Hybrid APF (a) Single Phase Two Wire, (b) Three-Phase Three Wire and (c) Three Phase Four Wire

D. *Passive Filter Type*

Hybrid active filter topologies consist of passive and active filters. The passive filters have an important role to tune at fundamental frequency and reduce the power rating of APF. In literature many types of passive filters are applied.Figure-5 illustrates this type of filters. Most common filter is LC filter. The LC filter [26-36] consists of an inductor and capacitor in series tune a single frequency. The LC circuit provides a zero impedance path for a selective harmonic current to be filtered [27,29,32,35]. LCL [48] output filters shows more effective performance than LC output filters. Some studies prefer this type of filter. RLC [49-51] filter consists of a resistor, an inductor and a capacitor connected in series. It constitutes a harmonic isolator [50]. The resistor is used for damping [49].Injection type of filter [52-66] is created by adding a LC circuit that is tuned to fundamental frequency of the transformer. It prevents to flow leading current occurring because of the passive filter of HAPF over the inverter of active filter so the current rating of active filter is significantly reduced [52,54,57,60,63,65].In addition, this topology can be applied for high voltage levels because the current at the fundamental frequency doesn't flow over the active filter [55].Another type filter topology is parallel resonant filter [67]. A new passive filter topology that is tuned at the fundamental frequency of the system is used instead of conventional passive filter topology. This filter consists of parallel LC with series. LC is tuned at fundamental frequency of the system. C in parallel LC filter and series L is tuned at desired harmonic frequency. This filter demonstrates high impedance at fundamental frequency component so it prevents to flow fundamental frequency component over the active power filter. For the harmonic frequency, this filter demonstrates low impedance so the current harmonics flow over active power filter. The power capacity and loss of the inverter are decreased [67].

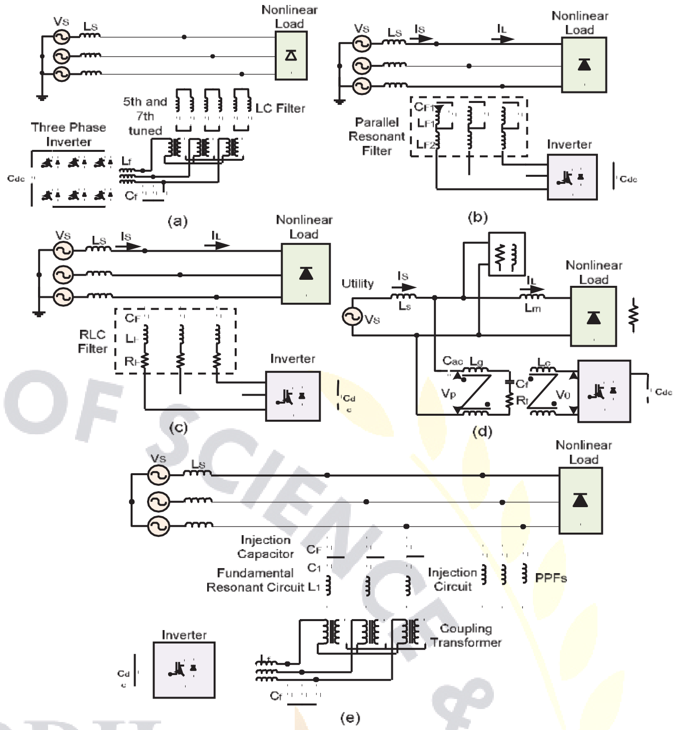

Figure-5: Classification according to filter: (a) LC, (b) Parallel resonant , (c) RLC, (d) LCL and (e) Injection- Type

III. CONTROL STRATEGIES

The control strategy is a fairly critical issue in hybrid active power filter. All control strategies consist of four stages which are called as detection of signals, generation of compensating signals, dc link voltage control and generation of firing signals.

A. *Signal Conditioning*

In control strategy, for the calculation of reference signals to achieve harmonic and reactive power compensation, instantaneous voltage and current signals need to be measured. Instrumentation transformers and Hall-effect sensors are used to measure the voltage and current signals in system. Then, these measured signals are used to generate the reference signals for harmonic and reactive power compensation.

B. *Generation of Reference Signals*

Reference signals are generated using time domain and frequency domain methods in literature.

1) *Frequency Domain Methods*

Frequency domain methods uses Fourier Transform (FT) to generate reference signals. FT is used in [23] and [55]. Fast Fourier Transform (FFT) which is a method based on Fourier transform, is used to estimate harmonics in [23]. Even though it enables selective harmonic elimination and provides to generate reference signals rapidly, it has main drawbacks such as requirement at least one cycle to estimate the reference current and control complexity compared to control methods in time domain which will be explained more detailed in next topics.

2) Time Domain Methods

Synchronous Reference Frame (SRF) and Instantaneous Reactive Power Theory (IRPT) are the most common and popular control techniques to determine the reference signals based on time-domain. IRPT also called as p-q theory transforms voltage and current signals from a stationary reference system in abc coordinates, to a system with coordinates *a*-�[75] So it determines the harmonic distortion by calculating instantaneous power in a three phase system[76]. To generate reference signals, Dividing Frequency Control[54], Lagrange Interpolator[52], Optimal Linear Prediction Theory[77], Generalised Integral PI Controller[60] and Extension PQ Theorem[72,78] are also control methods based on p-q method. SRF also called as d-q theory look likes *a*�transform. However, d-q theory calculates reference signals of voltage/current in rotating reference frame unlike p-q theory. Notch filter-based method[13], Indirect Current Control[12,23], adaptive fuzzy-dividing frequency control[83], Recursive Integral combined with Fuzzy Controller [15,59], Recursive Integral Controller[52], Neural network[15,24,48], RL [1], Sliding-Mode Controller[79], Deadbeat Control[48], Integer Lifting Wavelet Transform[80], PI-Type Iterative Learning Control Strategy[58] are also control methods used in Hybrid APF.

C. DC Link Control

DC link control is one of significant subjects which draw attention in literature. Although Hybrid APF uses up lower dc link voltage and has less noise compared to conventional APF, It is very important to keep the voltage magnitude at required level or constant in order to stabilise power exchange. PI Controller[1,13,14,19,31,32,33,39,54,69,78], Sliding Mode [79], Fuzzy [59,83], Adaptive DC link Controller[37] are employed to control dc link voltage in Hybrid APF topologies.

D. Generation of Firing Signals

The fourth step is generation of firing signals for switching devices There are several techniques to generate firing signals for solid-state devices in inverter. These techniques play important role in effective performance of Hybrid APF. PWM[1,14,27,39] and Hysteresis Controller[1,7,12] are the most common techniques which are used to generate gate signals. Conventional Sine Triangle PWM[20,25], Modified Sine-triangle PWM[30,32,35], Modified PWM[23], Unipolar PWM[82] are controllers based on pulse-width-modulation. Space Vector Modulation (SVM)[82] is also another control technique. For instance, SVM-based hysteresis current controller[72] and Deadbeat Current Controller based SVM[81] are preferred to control the generation of firing signals. Adaptive Fuzzy Dividing Frequency Controller[83] and Fuzzy Controller[5] are implemented to obtain the control signals for the solid-state devices.

IV. CONCLUSION

An extensive literature survey of HAPF is presented to provide a clear perspective on various aspects of HAPF to the researchers and engineers working in this field. The review and classification of published work in this field shows that there has been a significant increase in interest in hybrid active power filters and related control method. A large number of HAPF configurations are available to compensate harmonics. Even though control strategies of Hybrid Active Power Filters have advanced greatly, still more study needs to be done to maintain near perfect power quality as more and more sensitive as well as complex loads are coming into the power networks.

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