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Active Power Filter: Review of Converter Topologies and Control Strategies

Ahmet TEKE[1], Lütfü SARIBULUT[1,♠], M. Emin MERAL[2], Mehmet TÜMAY[1]

[1] *Çukurova University, Department of Electrical and Electronics Engineering, Sarıçam/Adana*
[2] *Yüzüncü Yıl University, Department of Electrical and Electronics Engineering, Zeve/Van*

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Abstract: Decrease in the cost of power electronic devices and improvement in the efficiency of both power converters and energy storage components have increased the applicability of new technological solutions such as Custom Power (CP) and Flexible AC Transmission Systems (FACTS) Devices. Active Power Filter (APF) is one of the CP devices and can mitigate harmonics, reactive power and unbalanced load currents originating from load side. In this study, a comprehensive review of APF studies, the advantages and disadvantages of each presented techniques are presented. The study also helps the researchers to select the optimum control strategies and power circuit configuration for APF applications.

Keywords: *Active Power Filter, Power Quality, Literature Review, Custom Power*

1. INTRODUCTION

Power electronics based devices/equipments are a major key component of today's modern power processing, at the transmission as well as the distribution level because of the numerous advantages offered by them. These devices, equipments, nonlinear load including saturated transformers, arc furnaces and semiconductor switches and so on, draw non-sinusoidal currents from the utility. Therefore a typical power distribution system has to deal with harmonics and reactive power support [1].

The presence of harmonics and reactive power in the grid is harmful, because it will cause additional power losses and malfunctions of the grid components [2]. Conventionally, passive filters consisting of tuned L–C components have been widely used to suppress harmonics because of their low initial cost and high efficiency. However, passive filters have many disadvantages, such as large size, mistuning, instability and resonance with load and utility impedances [3]. Active Power Filters have become an alternative solution for controlling current harmonics in supply networks at the low to medium voltage distribution level or for reactive power and/or voltage control at high voltage distribution level [4]. Active power filters such as shunt APFs, series APFs, hybrid APFs, unified power quality conditioner (UPQC) and other combinations have made it possible to mitigate some of the major power quality problems [1].

APF system can be divided into two sections as given in Figure 1: The control unit and the power circuit. The control unit consists of reference signal generation, gate signal generation, capacitor voltage balance control and voltage/current measurement. Power circuit of APF generally consists of energy storage unit, DC/AC converter, harmonic filter and system protection.

Corresponding author, e-mail: lsaribulut@cu.edu.tr

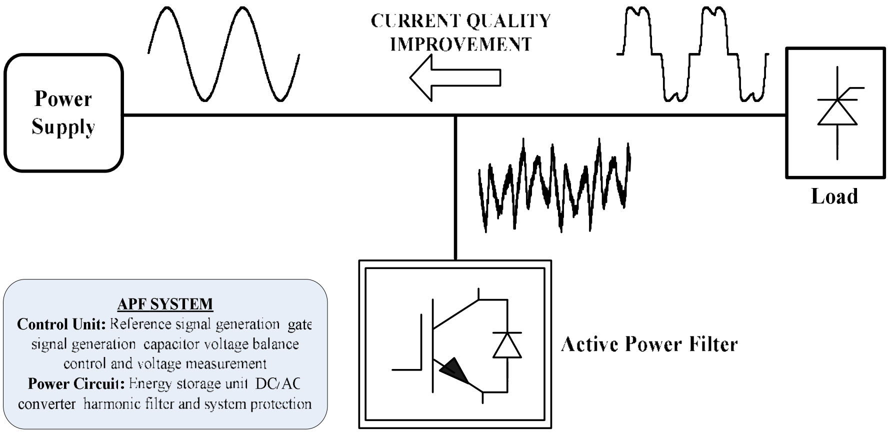

Figure 1. Basic representation of APF

The findings of the comprehensive literature survey summarize the available studies related with the control unit and the power circuit of the APF. The rest of the paper is organized as follows. The power circuit configurations are presented in Section 2. The control unit of APF is examined in Section 3. Section 4 includes field applications of APF. Finally, the conclusions of this paper are given in Section 5.

2. POWER CIRCUIT CONFIGURATIONS OF APF

APFs are basically categorized into four types, namely,

- Two-wire (single-phase) [5],
- Three-phase three-wire [3],
- Three-phase three-wire with Zig–Zag transformer [6]
- Three-phase four-wire [7]

These configurations to meet the requirements of the various types of nonlinear loads on supply systems [8]. Basic topologies of APF are shown in Figure 2.

APFs are used in low power (<100 kVA), medium power (100 kVA-10 MVA) and high power (>10 MVA) applications [4]. For low power applications, APFs can be applied for single-phase and three-phase systems. For single-phase systems, APFs generally mitigate the current harmonics. For three-phase systems, APFs generally provide acceptable solution for unbalanced load currents and mitigate the current harmonics. For medium power applications, the main aim is to eliminate or reduce the current harmonics. Because of economic considerations, reactive power compensation using active filters at the high voltage distribution level is not generally regarded as viable [4]. For high power applications, the harmonic pollution in high-power ranges is not such a major problem as in lower-power systems. One of the few applications of active filters in high power systems is the installation of parallel combination of several active filters because the control and co-ordination requirements of these filters are complicated. The power circuit of APF generally consists of DC energy storage unit, DC/AC converter and passive filter.

2.1. DC Energy Storage

The DC capacitor serves two main purposes: (1) It maintains a DC voltage with a small ripple in steady state and (2) It serves as an energy storage element to supply the real power deference between load and source during the transient period [9]. DC link voltage should be higher than maximum peak of the source voltage. DC link voltage can be controlled using proportional-integral (PI) controller [10], proportional-integral-derivative (PID) controller [11] and fuzzy logic [12]. In [3], DC link is fed from separate voltage source to stabilize DC-side voltage within a certain range. Switched capacitor APF that brings new dimension to APF as it reduces components and ratings (particularly capacitor) while performing at low switching frequency is evaluated in [13]. DC link, instead of a capacitor, is used as a battery pack, which is charged from a photovoltaic array in [14].

2.2. DC/AC Converter

The converter types of APF can be either Current Source Inverter or Voltage Source Inverter (VSI) bridge structure. VSI structures with insulated gate bipolar transistors (IGBTs) or gate turn-off thyristors (GTO) have become more dominant, since it is lighter, cheaper and expandable to multilevel and multi step versions, to enhance the performance with lower switching frequencies [8]. IGBTs are generally used up to 1 MVA rating, GTO thyristors are generally used higher than 1 MVA rating. Power circuit configuration of APFs can be parallel active filter [15], series active filter [16] and combination of series and parallel filters [4], [8]. The purpose of parallel active filters is to cancel the load current harmonics fed to the supply. It can also perform the reactive power compensation and balancing of three-phase currents. The series active filter produces a PWM voltage waveform which is added/subtracted to/from the supply voltage to maintain a pure sinusoidal voltage waveform across the load. However, series active filters are less common industrially than their rivals, parallel active filters [8]. Combinations of several types of filter can achieve greater benefits for some applications.

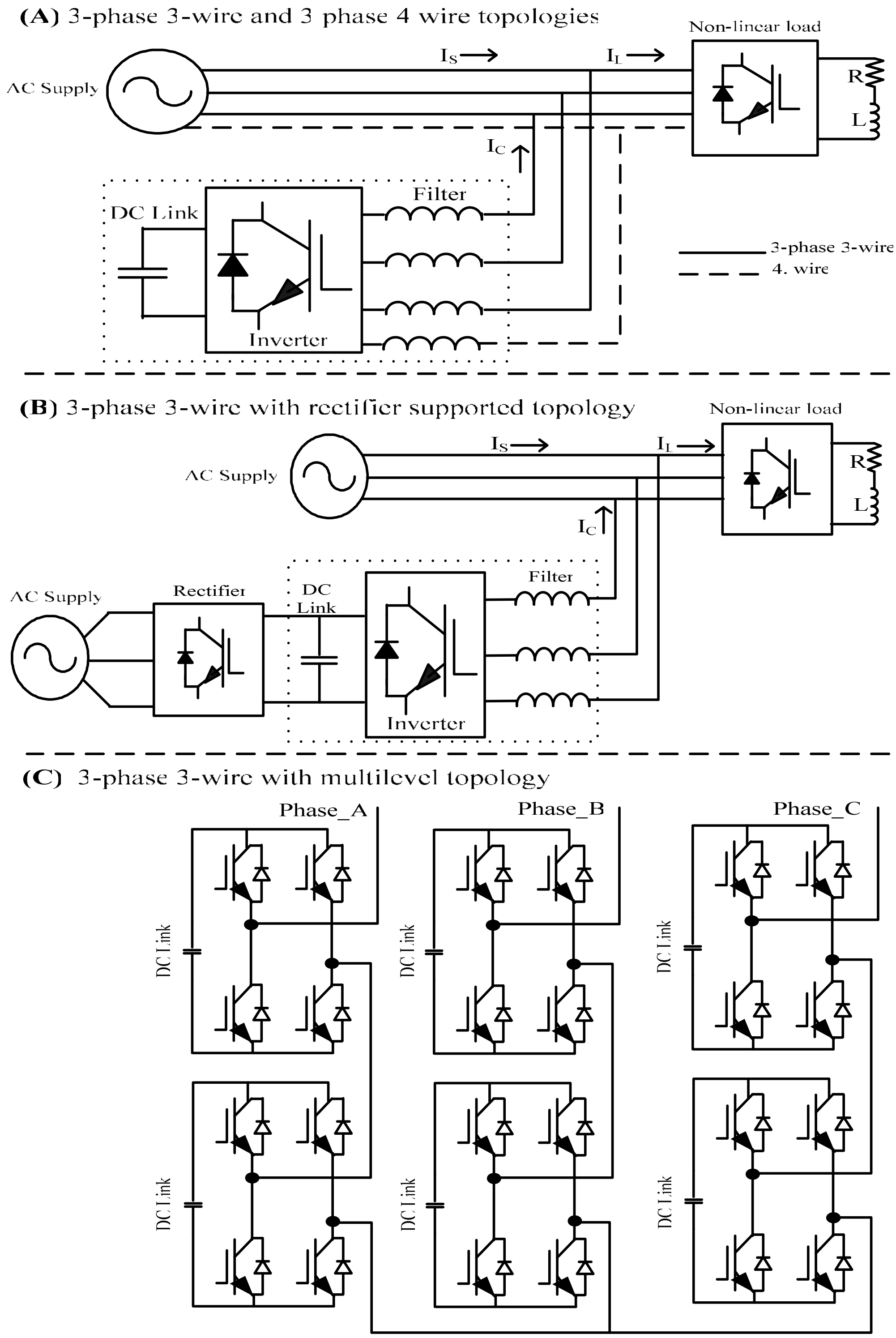

Figure 2. Various power circuit topologies of APF

The examined combinations are combination of both parallel and series active filters, combination of series active and parallel passive filters, combination of parallel active and passive filters [17] and active filter in series with parallel passive filters [18]. Seven-level APF configuration is also examined in [19-20]. Multilevel three-leg center-split VSIs are more preferable in medium and large capacity applications due to lower initial cost and fewer switching devices that need to be controlled [21]. The series-stacked-multilevel-converter topology, which allows standard three-phase inverters to be connected with their DC busses in series is chosen in [22]. This converter has both regenerated energy generation and active power filtering capabilities.

2.3. Harmonic Filter

An inductance for output filtering of VSI is used to eliminate the harmonic at different frequencies. The different combinations of L and C filters to attenuate the switching ripple currents are examined in [23]. A rectifier employing phase control with extra low inductance characteristic or load which high-frequency input current, may affect the APF and causing it to malfunction or shutdown. While APF is being applied to this type of load, a reactor (3%~5%) is recommended to install at the input side of the load to reduce the rising rate of load input current [24]. LC passive filter is used in [3] for harmonic elimination and reactive power compensation. LCL-filter presented in [25] gives advantages in costs and dynamic performance since smaller inductors can be used compared to L-filter in order to achieve the necessary damping of the switching harmonics.

3. CONTROL TECHNIQUES OF APF

Active power filters are generally designed to compensate the current harmonics, reactive power, voltage harmonics and to balance the mains current and voltage. Control strategy is based on the overall system control, extraction of reference signal, capacitor voltage balance control and generation of gating signals as shown in Figure 3.

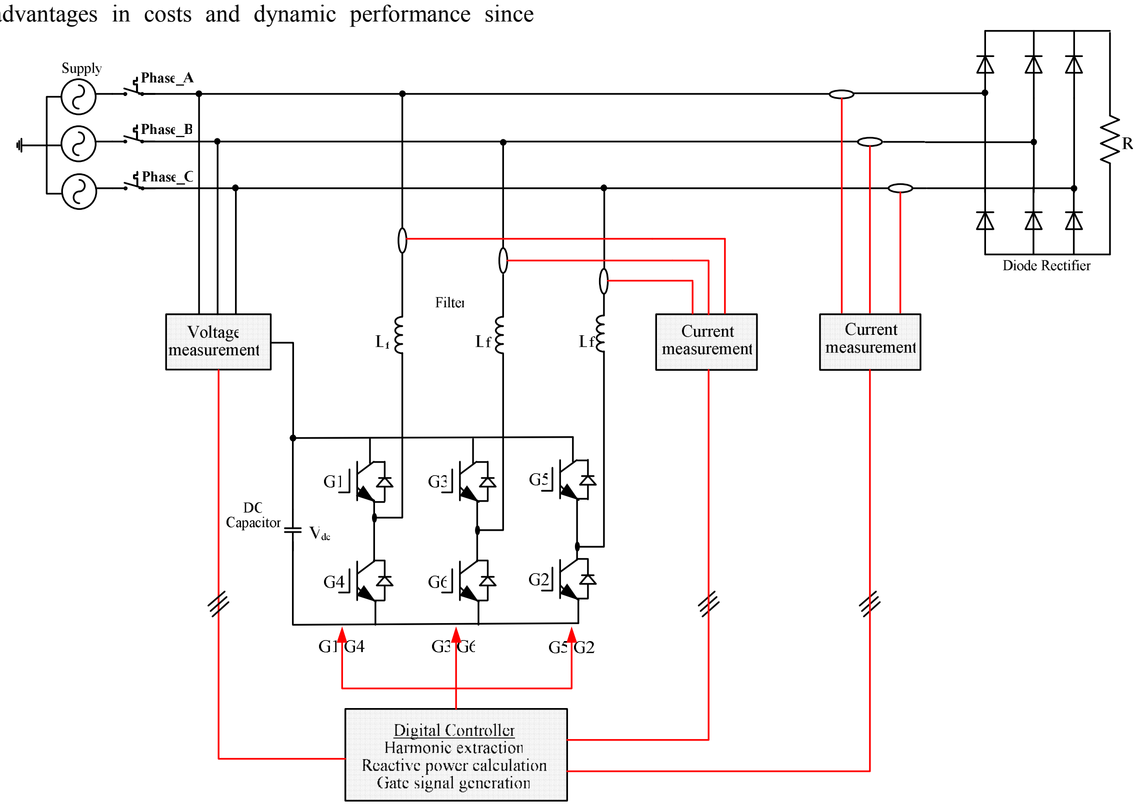

Figure 3. Control unit of APF with a specified power circuit topology

The general control techniques to overcome these power quality disturbances are open loop control system and closed loop control system. The closed loop controls can be further subdivided into other techniques as constant capacitor voltage technique, constant inductor current technique, optimization techniques and linear voltage control technique [4].

Classification according to current/voltage reference estimation techniques can be made as time domain control and frequency domain control that are processed by the open loop or closed loop control techniques [4]. Control strategy in the frequency domain is based on the fourier analysis of the distorted voltage or current signals to extract compensating current/voltage reference [8]. Frequency domain approaches are suitable for both single and three-phase systems. The frequency domain algorithms are conventional Fourier and fast Fourier transform (FFT) algorithms [26], sine multiplication technique [4] and modified Fourier series techniques [27]. Control methods of the APF'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 [8]. Time domain approaches are mainly used for three-phase systems. The time domain algorithms are neural network [13], constant active power algorithm, constant (unity) power factor algorithm [15], DQ method [26], instantaneous reactive power algorithm (p-q) [28], fictitious power compensation algorithm [29] and synchronous flux detection algorithm [30]. A component that has a frequency between the two frequencies is called an interharmonic. A method for real-time detection and extraction of interharmonic components in a power signal with potentially time-varying characteristics is presented in [31].

The measurements of supply voltage, load current, injected current and capacitor voltage are required for reactive current extraction [28]. However, the measurements of load current, injected current and capacitor voltage is enough for only harmonic current extraction in [32]. In [33], there is no need to measure the load current or power to calculate the reference currents.

The switching signals for the solid state devices of APF are generated using deadbeat [5], hysteresis [7], PWM [19], multiresonant controller [34], space vector modulation (SVM) [35], sliding-mode [36] or fuzzy logic based control techniques [37]. The capacitor voltage balance control is performed using PI [38], Artificial Neural Network based adaptive PI [39], fuzzy [40] and SVM controllers [41] methods. Digital controllers used in APF for field applications are combination of Digital Signal Processor (DSP) and Field Programmable Gate Array (FPGA) [5], processor board [42], DSP [43] and FPGA [44].

4. ACTIVE POWER FILTER IN SERVICE

Applications of shunt active filters are expanding, not only into industry and electric power utilities but also into office buildings, hospitals, water supply utilities, and rolling stock [45-49].

- 48-MVA shunt active filter installed in the Shintakatsuki substation by the Central Japan Railway Company.
- Toshiba-Mitsubishi-Electric Industrial Systems Corporation in Japan has developed a 21-MVA active filter using 4.5-kV, 1.5-kA injection-enhanced gate transistors.
- Medium voltage (31.5-34.5 kV), 5 MVA Active Power Filter has been commissioned at Denizli-2 Transformer Substation by TÜBİTAK (National Power Quality Project, Turkey).
- 1.5 MW inverter and Active Power Filter system for the injection of regenerated energy in a Spoornet Traction Substation (one of South-Africa's largest railway companies).
- Shunt APF of 300kVA, manufactured by Meidensha Corporation, has been installed to compensate for harmonic currents generated by eight adjustable speed drives.
- A shunt APF of 440V 200kVA and a shunt active filter of 210V 75kVA, designed and developed by Toyo Electric- Manufacturing Company, have been installed for harmonic compensation at water supply facilities in Takatsuki-City, Japan.
- Several shunt active filters in a range of 40 MVA to 60MVA have been installed in substations along the Tokaido Shinkansen.

The alternative solution to APF for reactive power compensation can be capacitor banks and thyristor controlled reactors. The alternative solution to APF for harmonic mitigation is passive filters. However, APF provides better power quality than its alternative solutions and it has fast response and fewer transients.

5. CONCLUSIONS

Active Power Filter can mitigate some types of power quality disturbances such as harmonics, reactive power and unbalanced load currents. These disturbances can cause misoperation of highly automated systems and malfunction of sensitive loads connected to point of common coupling (PCC) which increases the economical cost of fault. APF can be very effective solution such a high technology industrial plants or the group of customers having sensitive loads in Custom Power Park or Power Quality Park. This paper has been mainly concentrated on the converter topologies and the control algorithms. A number of APF topologies have been reviewed. With this study, the findings about APF studies in the literature and the application notes of APF in service are presented and thus the trends of APF through the years are clearly observed.

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