A Technical Review on Control Strategies for Active Power Filters

Ragam Rajagopal
Research Scholar,
School of Electrical Engg.
VIT, Vellore, India.
ragamrajagopal@gmail.com

Dr. K. Palanisamy
Asso. Professor,
School of Electrical Engg.
VIT, Vellore, India.

Dr. S. Paramasivam
Functional Head, R&D,
Danfoss Drives, Chennai, India.

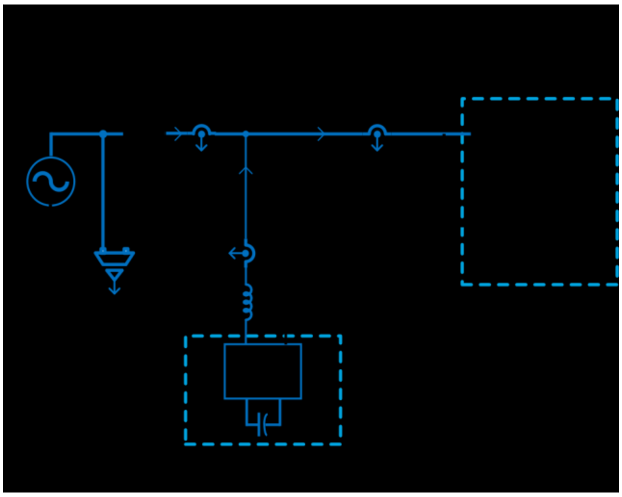
Abstract- **The ever-increasing use of harmonic causing loads in the power system has led to the aggravation of many power quality issues mainly harmonics. The distortions triggered by these power quality issues must comply with the limits set by the international standard organizations. The mitigation of these problems is imperative and active power filters/active power quality conditioners are a practical solution to these issues. The control strategy plays a very significant role in the effective functioning of the APF. The control strategy also determines the performance, efficiency, stability, and reliability of the APF. This paper proposes a comprehensive review on the state-of-art control technologies of active filters highlighting their main features. Various control strategies are studied and investigated based on their characteristics, performance, applicability, and implementation.**

Keywords- active power filter; control strategies; current control; power quality

I. Introduction

The increasing use of power electronics in industrial, commercial and domestic applications has resulted in widespread usage of non-linear load such as power electronic converters, arc furnaces, adjustable speed drives, arc furnace, half and full bridge rectifiers, fluorescent lamps, uninterrupted power supplies . This has led to serious power quality (PQ) issues such as power factor degradation, harmonic injection, reactive current compensation voltage sag and swell, etc. The supply voltage and current become distorted due to the nonlinearity of these loads. To avoid such issues resulting from the usage of non-linear and inductive loads, IEEE-519-2014 and IEC-61000 standards are put in place to regulate the PQ for minimizing or mitigating the adverse effects [1]. Traditionally, passive filters were used for the mitigation of the reactive power and harmonic current disturbances. But due to some major drawbacks like effect of source impedance on performance, resonance problem, fixed compensation characteristics, large size, this solution became less attractive [2]. However, the solution of this problem is also provided by the various custom devices like unified power quality controller, dynamic voltage restorer, active power filter etc. Among all these custom power devices, active power filter provides an effective solution for the mitigation of reactive power and harmonic disturbance problems.

The typical configuration of shunt active power filter (SAPF) is shown in figure 1. It is basically voltage source inverter connected in parallel with the load at the point of common coupling (PCC) through coupling inductor. The SAPF necessitates supply to provide only sinusoidal current with unity power factor maintained at supply side by injecting harmonics and reactive current into the system.



In this paper, section II generalizes the development of the active filter control strategies; section III and IV provides the analysis and comparison in detail of the current reference generation techniques and current control techniques respectively.

II. Active Filter Control Strategies

Ever since the use of APF technology has come into practice, various control strategies are proposed or the existing ones are being improved. The control of SAPF mainly includes dclink capacitor voltage balancing, gating pulse generation for power electronics switches and reference current generation scheme. The control of SAPF can be realised by following three simple steps. Firstly, required voltage and current quantities are sensed by voltage and current sensors like PTs/CTs or hall sensors. Secondly, reference current is extracted from the sensed current and voltage quantity along with *dc*-link voltage regulation. Lastly, gate pulses are generated for the power electronics devices used in APF. High dynamic response, accurate extraction of reference signal, *dc*-link voltage balancing and fast accurate sensing of electrical quantities are the key factors contributing to the efficient operation of the compensating device. To achieve these requirements, researchers have implemented many control techniques with reference current generation, dc-link voltage balancing and fast switching pattern. These methods are discussed below.

Reference Current Extraction Schemes:

Reference current generation plays a crucial role for the operation of compensating device. Reference current can be extracted by either frequency domain techniques or time domain techniques.

a) Frequency Domain Techniques

Frequency domain techniques are based on wavelet analysis, Fourier analysis and applicable for both three phase and single phase systems. The methodologies used under Fourier analysis are Fourier transform, Fast Fourier Transform (FFT) and Discrete Time Fourier Transform (DTFT). The block diagram of frequency domain technique is shown in Fig.2.The basic technique of compensating signal generation is to subtract the fundamental component of signal from the FT and obtain its inverse which is the reference (compensating harmonic) signal in the time domain [3]. The demerit of frequency-domain technique is the increased computational requirements. The number of calculations also increase with the higher order of harmonics to be eliminated. It results in longer response times.

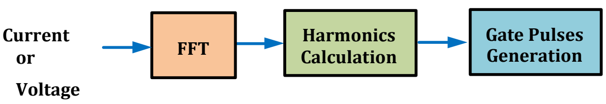


Fig. 2. Block diagram of frequency domain technique

B) Time Domain Techniques

Time domain is the analysis of any function or physical signal with respect to time. In time-domain technique, reference signals in terms of voltage or current are derived instantaneously from the harmonic polluted signals. Some of them time domain approaches are briefly discussed here.

A. Instantaneous PQ theory

The block diagram of implementation of this theory is as shown in Fig.3. Firstly, three phase load currents and supply voltages are converted into stationary α-β frame. Then, stationary α-β frame is converted into p-q frame from which the real and reactive power (includes dc component and oscillating components) of the load is calculated. To generate the compensation reference signal in terms of voltage/current the ac component is extracted by passing through a high pass filter. Lastly, these stationary quantity of reference current is again converted into three phase quantity. This method is applied only for three phase balanced supply systems. Akagi [4] proposed 'p-q' theory and it was amended later by Marshal [5]. To make the p-q theory viable for 3-phase, 4wire systems with unbalanced source voltages and unbalanced NL loads, modification/extension of the same was proposed by Nabae et al [6].

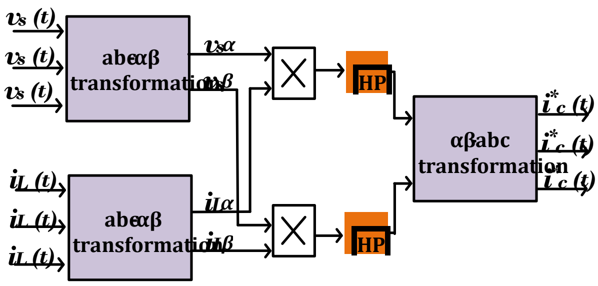


Fig. 3. Block diagram of calculation of p-q method

These modifications are known as modified p-q theory [7] extended p-q theory [8] and p-q-r theory [9].

B. Synchronous Reference Frame method

Fig.4 shows the block diagram of SRF method which is also known as d-q method. This method is used for harmonic component extraction.

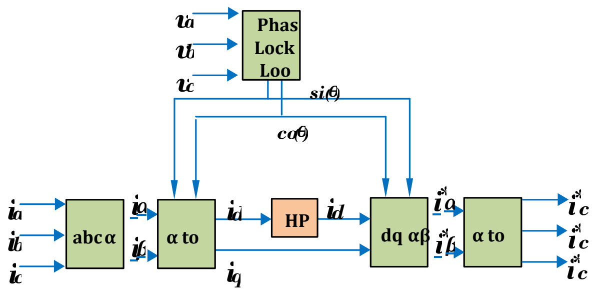


Fig. 4. Block diagram of SRF method

The first step is to convert three phase source currents to two phase stationery reference frame (αβ-0). Next step deals with the conversion of stationery two phase currents to two phase rotating frame (d-q-axes). PLL is utilised for UVT generation i.e., cos θ and sin θ. The currents in d-q axes is comprised of both ac and dc components. On transformation, dc part represents fundamental active component of load current and the ac part indicates the harmonic components of the load current. Extraction of harmonic components is done by HPF as indicated in Fig 4. Since q axis current is composed of reactive component of fundamental and harmonic components, it is utilised for compensation reference current generation. On applying inverse transformation to d-q axes currents it is converted to (αβ-0) frame. Last step involves the conversion from (αβ-0) to three phase frame to obtain the 3 reference compensation currents i_{ca}*, i_{cb}* and i_{cc}*. The d-q theory can be extended to single phase systems creating an imaginary variable by rotating the original signal by 90 deg. The original signal along with the imaginary signal represents the load current in d-q coordinates [10].

C. Synchronous detection method

In instantaneous p-q theory, the source needs to be balanced. But, in pragmatic distributions, it is difficult to get balanced source voltage. Hence, considering unbalanced source voltage, harmonic separation becomes a difficult task.

Synchronous detection method is a method that works on phase by phase basis i.e. the calculations for compensating currents generation are done on every phase. Three different control strategies which is based on the same approach are discoursed in [11]-[12]. Hence this method is otherwise known as equal current distribution method. Here the active main current tracks the voltage waveform and it will maintain an in-phase/locked relationship with mains voltage. And the real power is equally distributed among all three phases. Voltage harmonics of the mains will affect the accuracy of this method.

D. Notch filter method

A notch filter basically attenuates the signal of a particular frequency band and allows a signal at frequency outside the band. In this method notch filter is designed in such a way that the fundamental component of a current signal is diminished by passing through a notch filter and the resultant signal is used for generating the compensating signal [13]. For a better performance of a notch filter, the frequency of a signal should remain constant. A notch filter under variable frequency conditions, should essentially be able to track the frequency changes by appropriately changing the notch frequency, Reference [14] has reported an adaptive notch filter for the harmonic current mitigation.

E. Flux based control method

In this method, reference voltage is generated directly by using a current regulator [15] by utilising the linear relation between the flux and current in a linear inductor. The load current harmonic components are generated using d-q transformation method. Inverter switching is done by means of a carrier less PWM method which can contribute to increasing bandwidth.

F. Adaptive detection method

In adaptive detection method, firstly, UVT is generated using undistorted supply voltage. Now, this UVT is taken as a reference signal while source current is taken as an input signal and error is generated. By the ability to continuously self-study and update from start to end, square of the error is minimalized and reference compensating current is generated [16].

G. Soft Computing Techniques

Soft computing belongs to the category of optimization techniques used to model real world problems and find their solutions, which are otherwise very difficult to model mathematically. Optimization techniques are used to find minimum or maximum of a process/given function. Combinatorial optimization problems are classified into exact, and approximate methods. Approximate method is sub-divide into heuristic and meta-heuristic methods. Metaheuristic methods are widely being used to find solution for the above mentioned problems. The main areas under soft computing techniques include fuzzy logic, artificial neural networks, genetic algorithm etc. which are being utilised for the control of APFs.

Artificial Neural Networks (ANN) are widely used for the implementation of APFs for more than a decade [17].

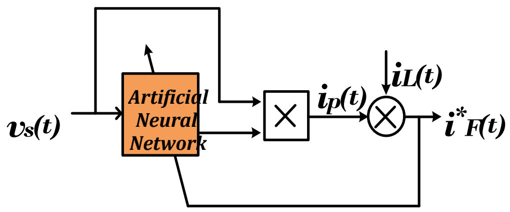


Fig.5. Artificial Neural Controller

Its variants include back propagation [18] based ANN, conductance estimation [19] using ANN, decoupled adaptive neural network [20] and the adaptive neuro-fuzzy inference system (ANFIS) [21]. Sindhu et al [22] has put forward a new shunt auto-tuned passive filter with ANN based controller for hybrid filter configuration, thereby eliminating the problems offered by the conventional shunt passive filter. [23] proposed a firefly algorithm based RNN for optimal performance of UPQC thereby eliminating PQ problems like voltage sag.

Echo state network techniques [24] (computes fundamental components of load current) based on recurrent neural network (NN) has got higher training speed, accuracy in tracking and good dynamic response has made it popular for real time applications of APFs compared to other type of ANNs.

Fuzzy logic controllers (FLC) are used in many applications [25] because of the varied features exhibited like robustness, accurate mathematical modelling is not required, input can be distorted and the ability to work with non-linear loads [26]. The basic process in FLCs are fuzzification, generation of knowledge base, inference system and defuzzification [27].

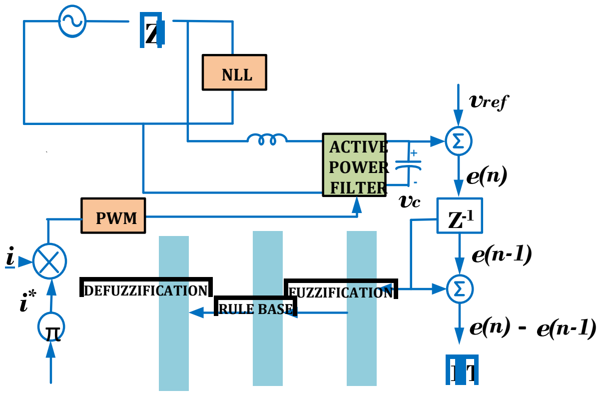


Fig. 6. Fuzzy logic controller

Panda et al [28] have proposed a 3 phase 4 wire buck APF based adaptive hysteresis fuzzy logic controller which can eliminate shoot through in the converter, reduce harmonics and thereby bring down THD to less than 5%. Reference [29] has proposed a self-tuning filter based FLC for harmonic control of a five level APF. In [30], a dwell time allocation algorithm based FLC is proposed to reduce the neutral point voltage deviation of a three phase NPC inverter based APF.

Genetic algorithm developed from evolution theory and natural genetics, is a powerful tool to determine global minimum optimal solution. A FLC is optimised by genetic algorithm for harmonic reduction and thereby THD improvement using APFs is discussed in [31]. Mishra et al [32] have proposed a new technique called bacteria foraging algorithm to estimate optimised gains for the PI controller which is used for the control APF.

Method of Wavelets use a linear concoction of timefrequency signals to create a wavelet controller. The combined time-frequency signals is used for power quality monitoring and conditioning applications. This technique is extended to APFs for generation of reference current to eliminate utility side harmonic problems by proper inverter switching. Extraction of fundamental frequency components is done by Multi-Resolution Analysis [33]-[34]. Firouzjah et al [35] discusses discrete wavelet transform based MRA for harmonic mitigation and power quality improvement in APFs, where computational complexity and dependency on sampling frequency were the challenges. Isaac et al [36] proposed a 2nd order LPF based wavelet control strategy to overcome the above mentioned disadvantages.

The comparison table of different control strategies have been shown below.

Table 1. Comparison of Different Control Strategies

Comparison properties	p-q method	d-q method	Synchronous detection method	Notch filter method
Harmonic distortion effect of the source voltage	Yes	No	No	No
Harmonic Compensati on	Yes	Yes	Yes	Yes
Reactive power Compensati on	No	Yes	Yes	No
Computation Complexity	Complicated	Middle	Middle	Simple
Load Unbalance effect	Yes	No	No	No
Dynamic Response	Fast	Fast	Fast	Slow

III. Gating Pulse Generation Techniques

The last step in APF control is generation of gate signals for triggering of solid state devices in APF by comparing with a reference signal. For open loop systems, PWM/SPWM techniques are used [37]. For closed loop lower order systems, generally hysteresis control is used. For higher order systems, sliding mode controller [38], linear quadratic regulator (LQR) [39], dead bead control [40], Kalman Filter[41] are extensively used. Here three most widely used methods are discussed.

A. Carrier based PWM technique:

In this method, the reference signal (i_{ref}) is compared with the actual signal (i_{act}). The difference is taken as an error (e), i.e. ($e = i_{ref} - i_{act}$). This error drives a PI controller, whose function is to reduce the error to zero. The output of the PI controller is compared with a triangular carrier wave. When PI controller output is greater than triangular carrier wave signal, upper switch in a certain VSI leg is turned OFF and lower switch is turned on which makes the current to decrease. When the PI output is less than carrier, lower switch of a particular VSI leg is turned ON and upper switch is turned OFF. This method offers a merit of fast dynamic response, ease of implementation and constant frequency.

B. Hysteresis band current control technique (HBCC):

HBCC is a switching technique in APF technology which is widely used now-a-days. This method proposes a technique where actual current follows a reference current within a certain defined band around the reference current known as Hysteresis band. When actual current strikes HB upper threshold, lower switch in a certain VSI leg is on and upper switch is off. Eventually current decreases and it strikes lower HB threshold, where lower switch in a certain VSI leg is off and upper switch is on. The main limitation faced by this method is varying switching frequency which creates considerable current distortions in steady state.

C. *Adaptive hysteresis band current-control technique:*

Adaptive HBCC proposes switching signal generation, with almost unvarying switching frequency which was the main shortcoming of HBCC. This is achieved by a variable hysteresis band obtained as a function of slope of reference current and dc link voltage. . References [42]-[44] has reported a formulation of the adaptive HBCC.

IV.CONCLUSION

Power Quality (PQ) issues caused by the inclusion of nonlinear loads in the power system is a problem of major concern as they affect the operation of sensitive equipment's connected to PCC thereby increasing the fault economics. The PQ arena is attaining new dimensions owing to the growing interests in areas like smart grid, PHEV, integration of renewables like PV panels and wind into the existing system and the presence of MLIs for various high power applications. For mitigation of these problems, active power filters/active power quality conditioners belonging to the category of custom power devices is a widely used practical solution. This paper converges on the control techniques to separate fundamental from undesirable components of current arising from harmonic causing loads in the power system. The performance of various control techniques are analysed. Moreover, various gating pulse generation techniques and their performance are also investigated.

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