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Review of Digital control schemes for Active Power Filters

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ABSTRACT: *Most of the pollution issues created in power systems are due to the non-linear characteristics and fast switching of power electronic equipment. The use of the power electronic devices in power distribution system gives rise to harmonics and reactive power disturbances. The harmonics and reactive power cause a number of undesirable effects in the power system. Active Power Filters(APF) have been developed over the years to solve these problems to improve power quality .This paper presents a comprehensive review of Active Power filter configurations, control strategies and the Total Harmonic Distortion(THD) for different control strategies both in analog and digital(DSP, FPGA) environments.*

Keywords *- FPGA, Harmonics, p-q theory, PWM, THD,*

I. INTRODUCTION

In recent years both power engineers and consumers have been giving focus on the “electrical power quality” i.e. degradation of voltage and current due to harmonics, low power factor etc. “Harmonics” means a component with a frequency that is an integer multiple (where n is the order of harmonic) of the fundamental frequency; the first harmonic is the fundamental frequency (50 or 60 Hz). The second harmonic is the component with frequency two times the fundamental (100 0r 120 Hz) and so on. Nearly two decades ago majority of the loads used by the consumers were passive and linear in nature, with a few non-linear loads thus having less impact on the power system. However, due to technical advancement in semiconductor devices and easy controllability of electrical power, non-linear loads such as SMPS, rectifier, chopper etc. are mostly used. The power handling capacity of modern power electronics devices such as power diode, silicon controlled rectifier (SCR), Insulated gate bipolar transistor (IGBT), Metal oxide semiconductor field effect transistor (MOSFET) are very large, so the application of such power semiconductor devices is very popular in industry as well as in domestic purpose. With these advantages, certainly excessive use of power electronic devices leads to a great problem, i.e. generation of current harmonics and reactive power in the power system network. As a result, the voltage at different buses of power system network is getting distorted and the utilities connected to these buses are not operated as designed. The harmonic current pollute the power system causing problems such as transformer overheating, voltage quality degradation, rotary machine vibration, destruction of electric power components and malfunctioning of medical facilities etc.

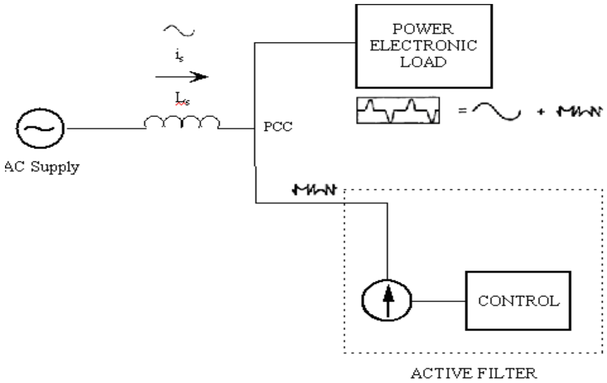

Fig 1: Active power filter

To provide clean power at the consumer-end Power Filter is used. Conventionally, passive filters are available for the elimination of harmonics. But these L-C filters introduce tuning, aging, resonance problems and these filters are large in size and are suited for fixed harmonic compensation. A flexible and versatile solution to voltage quality problems is offered by Active Power Filters (APF). The APF is a popular approach for canceling the harmonics in power system. Digital domain like micro-controller, digital signal processing (DSP) and Field programmable gate array (FPGA) when used to implement an APF, provides a number of advantages compared to analog controllers.

Fig.1 shows an Active Power Filter connected to the power system at the Point of Common Coupling (PCC). Due to use of non-linear loads, the load current is highly nonlinear in nature. The compensating current which is output of the APF is injected at PCC, so the harmonic cancellation takes place and the current between sources to PCC is sinusoidal in nature. Mainly, the harmonics arise due to the use of non-linear loads. The main sources of voltage and current harmonics are due to control and energy conversion techniques involved in the power electronic devices such as chopper, rectifier, cyclo-converter etc. The harmonic sources are energy conversion devices such as power factor improvement and voltage controller devices of motor, high-voltage direct-current power converters, traction and power converters, battery-charging systems, static-var compensators, wind and solar-powered dc/ac converters, direct energy devices-fuel cells, storage batteries which require dc/ac power converters, control of heating elements [1]. The current and voltage harmonics were measured using a dynamic signal analyzer by M.Etezadi-Amoli, and plotted at for different substations [2]. Due to use of non-linear loads like rectifier, chopper etc. the load current gets distorted, which is explained by Robert considering harmonic study [3].

II. TOPOLOGY OF ACTIVE POWER FILTER

Active Power filters are basically classified in to three types: Single phase, three phase three wire and three phase four wire systems to meet the requirements of the nonlinear loads in the distribution systems. Single-phase loads, such as domestic lights, TVs, air conditioners, and laser printers behave as nonlinear loads and cause harmonics in the power system [4]. Many configurations, such as active shunt filter [6-7] as shown in Fig 2,the active series filter [5] as shown in Fig.3 , and combination of shunt and series filter as shown in Fig.4 has been developed [8]. This topology has been called the Unified Power Quality conditioner. The above mentioned APLC's either based on a Voltage source inverter (VSI) with capacitive energy storage Fig.5 or Current source inverter (CSI) Fig.6 with inductive energy storage devices. Both voltage source inverters and current source inverters are used to compensate voltage and current harmonics under all the three categories. They are also used for the compensation of reactive power, unbalanced current and voltage, neutral current voltage spikes, voltage flicker and for regulation. The voltage related compensations (voltage unbalance, voltage flicker, voltage regulation, etc) are carried out using series active filters and shunt active filters are mainly used for current related compensations like reactive power, current unbalance, etc,.

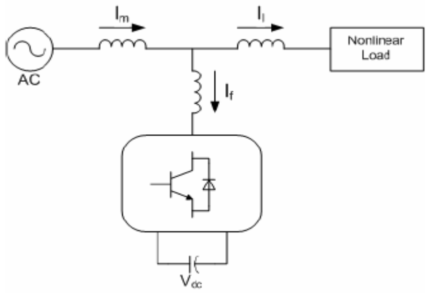

Fig 2: Shunt Active filter

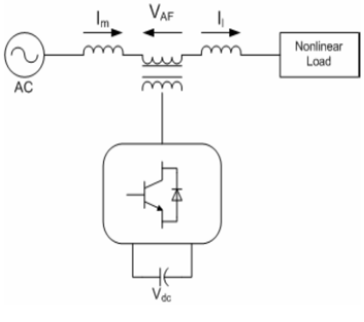

Fig3: Series Active filter

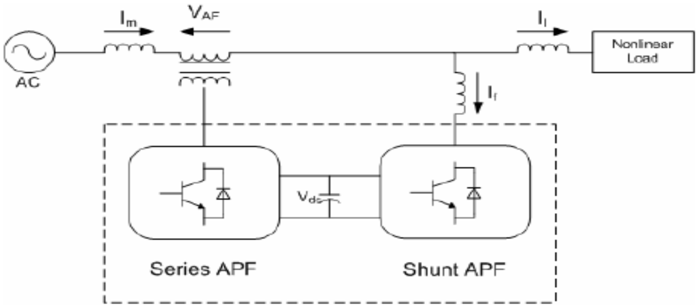

Fig 4: Series-Shunt Active Filters

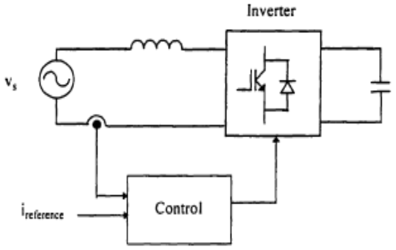

Fig 5: Voltage Source Inverters

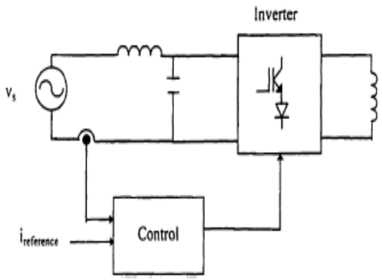

Fig 6: Current Source Inverters

III. CONTROLLING SYSTEM

The main component in the APF is the control unit. Controlling of APF is implemented in *three stages:*

First stage can be called as the *signal conditioning stage*. The essential voltage and current signals could be sensed using power transformers, Hall Effect sensors and isolation amplifiers to gather accurate system information. The instantaneous voltage and current signals are useful to monitor, measure and record various performance indexes such as Total Harmonic Distortion(THD), Power factor, active and reactive power, crest factor, etc,.

Second stage is the *derivation of compensation signals* stage. In this stage compensating commands in terms of current or voltage levels are derived based on control methods and APF configurations. Compensations can be done either in time domain or frequency domain. Compensation in frequency domain is based on Fourier analysis of distorted signal. In time domain a number of control strategies such as instantaneous reactive power theory (*p-q* theory)initially developed by Akagi et al. [9], synchronous frame d–q theory [15], synchronous detection method [16,25], notch filter and fuzzy logic controller [17] method , sliding mode controller[12],etc..are used in the development of three-phase AFs .Out of these theories, more than 60% research works consider using p-q theory and d-q theory due to their accuracy, robustness and easy calculation.

The third stage is the *generation of gating signals* to the device of Active filters. The main component of APF is the solid state devices. Earlier BJTs and MOSFETs were used. Now-a-days IGBTs are used for medium ratings and GTOs are used for high ratings. The gating pulses are generated by current control technique like sinusoidal pulse width modulation (SPWM), triangular PWM, hysteresis current control technique [18], Space Vector current controller[57].

Advancement in Microelectronics has motivated new directions for APF design starting from the use of analog and digital components to microprocessors, microcontrollers, digital signal processors (DSP's) [19-20] and FPGA implementation [21-22]. The analog controllers have some disadvantages such as high cost, slow response, large size etc., during real-time implementation. FPGA is given the highest priority as compared to DSP because of its low cost , faster response, and application oriented selection of the bit width for the data resister. In the next section few control strategies have been analyzed and discussed.

3.1 *p-q* theory

In 1983, *Akagi et al.* [9-14] have proposed the Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits, also known as p-q theory. It is based in instantaneous values in three-phase power systems with or without neutral wire, and is valid for steady-state or transitory operations, as well as for generic voltage and current waveforms. The p-q theory consists of an algebraic transformation (Clarke transformation) of the three-phase voltages and currents in the *a-b-c* coordinates to the α-β coordinates, followed by the calculation of the p-q theory instantaneous active and reactive powers components: This scheme is most widely used because of its fast dynamic response but gives inaccurate results under distorted and asymmetrical source conditions.

The main characteristics of *p-q* theory are:

– It compensates dynamically the harmonic currents;
– It corrects dynamically the power factor;
–It compensates dynamically, and instantaneously, the zero-sequence current;
–It balances and reduces the values of the currents supplied by the source to the load;
– It turns the instantaneous three-phase power that source delivers to load into a constant value (the source only delivers conventional active power).

From [24] it is evident that under balanced and unbalanced sinusoidal voltage conditions the THD for *p-q* theory is 2.41% and 7.04 % respectively.

3.2 SRF Theory (i_d-i_q method)

In the synchronous reference frame (SRF) theory proposed by Divan [15], the compensation signals are calculated based on a synchronously rotating reference frame. The synchronous reference frame theory or d-q theory is based on time-domain reference signal estimation techniques. It performs the operation in steady-state or transient state as well as for generic voltage and current waveforms. It allows controlling the active power filters in real-time system. Another important characteristic of this theory is the simplicity of the calculations, which involves only algebraic calculation. The SRF method becomes quite complicated under asymmetrical source and load conditions. From [24] it is evident that under balanced and unbalanced sinusoidal voltage conditions the THD for SRF theory is 2.27% and 5.18 % respectively. Also from [24] it is observed that instantaneous active and reactive current i_d-i_q method always give better result under un-balanced and non-sinusoidal voltage conditions over the instantaneous active and reactive power *p-q* method. Since *p-q* method is frequency variant, on providing additional PLL circuit it becomes frequency independent. Thus large numbers of synchronization problems with unbalanced and nonsinusoidal voltages are also avoided.

3.3 Synchronous Detection Method (SDM)

In SDM, it is assumed the source currents are balanced after compensation. Then the three-phase reactive powers are calculated from the source voltages. Then the three-phase source currents are calculated. Finally the reference currents are calculated for the active power filters Using SDM the THD achieved is 0.41 % from [25]. But the performance p-q theory is much faster than compensation using SDM. In [16] it is proved that p-q theory compensates the undesirable current components within 1st cycle whereas SDM takes about 14 cycles (approximately 0:23 seconds for 50 Hz source). So for faster power quality improvement SDM is not preferable.

3.4 Sliding mode controller

The sliding mode control has been widely applied to power converters due to its operation characteristics such as fastness, robustness and stability for large load variations. The references for the sliding mode control system are obtained by using the instantaneous reactive power theory. In sliding-mode controllers, either dc-bus voltage (in a VSI) or dc-bus current (in a CSI) is maintained to the desired value and reference values for the magnitudes of the supply currents are obtained. Subtracting load currents from reference supply currents, compensating commands are derived. From [26] the total harmonic distortion in the line currents is less than 2%

satisfying limitations required by international standards. For the generation of gating pulses the commonly used techniques are PWM and Hysteresis Current Control (HCC).

3.5 Pulse Width Modulation

Output Voltage of the Inverter can be modified or controlled by controlling or modifying switching current, or in case of Power Switches, by controlling or modifying Gate current. This control is achieved by PWM control. In one of the methods of controlling inverter output voltage, a fixed DC voltage is given to the inverter and by varying the ON and OFF time of power switches we get a controlled or modified AC output voltage. This method is popularly called as Pulse Width Modulation (PWM) method. The advantages of the PWM control are: (1) PWM control is very simple and requires very less hardware. So they are also cost effective. (2) They can easily be implemented using DSP or FPGA. So this increases the total cost of control. The PWM control signal in Fig.7 , is generated from PWM generator. This PWM signal is logically ANDED with rectangular pulse waveform coming from pulse generator and is fed to power switches S1 and S3. The inverted rectangular waveform is logically ANDED with PWM waveform and is fed to power switches S2 and S4. Thus ON and OFF time of power switches are controlled by this PWM control signal to modulate input DC voltage to required AC voltage. The power switch is usually of MOSFET or IGBT. Since frequency of operation is inversely dependent upon Inverter size so we have to increase the switching frequency to reduce the Inverter size . So we have to look into the frequency aspect of PWM Generator used so that we get optimized size of Inverter by proper selection of frequency of PWM wave.

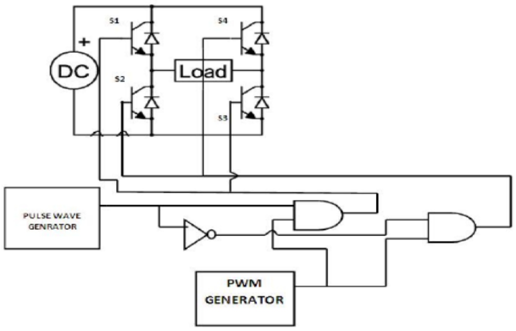

Fig.7 PWM Control of Inverter

3.6. Hysteresis Current Control [HCC]

The hysteresis band current control for active power filter is used to generate the switching pattern of the inverter. There are various current control methods proposed for active power filter configurations; but the hysteresis current control method is proven to be the best among other current control methods, because of quick current controllability, easy implementation and unconditioned stability. The hysteresis band current control is robust, provides excellent dynamics and fastest control with minimum hardware. This work also presents two-level and three-level hysteresis current controller for proposed active power filter and a comparison between them [27-29]. A hysteresis current controller is implemented with a closed loop control system and is shown in diagrammatic form in Fig 8.HCC can be either 2- level HCC or 3-level HCC. From [29] it is evident that the 3-level hysteresis controller reduces the variation of the switching frequency and it indicates improved performance compared to 2-level HCC. Table I shows the comparison of the different control strategies with their THD from [30-34,24].

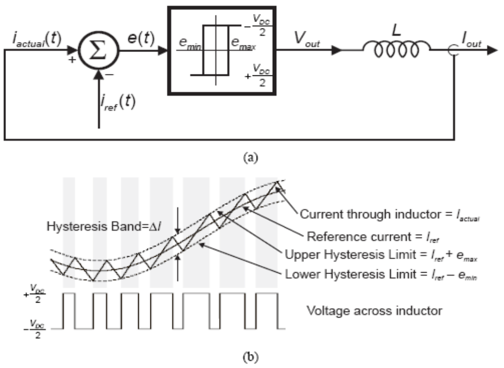

Fig. 8 Hysteresis current controller
(a)Block diagram(b)operational waveform

IV. QUANTITATIVE PERFORMANCE MEASURES

The filter performance should be evaluated in a typical distribution system with different loads, linear and non-linear. The relevant performance indexes will be characterized by the total harmonic distortion (THD) of the mains current, with and without filter, in the following two indexes basis: filter effectiveness index and filter capacity index. The Filtering Effectiveness index (FE) is the relation between the total harmonic distortion of the current supplied by the mains with and without filter in a pre-defined frequency range, according to some standard, e.g. EN 61000-3-2 or IEEE 519.

TABLE 1 Comparison Of The Different Control Strategies With Their THD

Compensation signal Generation method	**Gating signal generation method**	**THD**	**Comments**
SRF	Dead beat control	2.21	Switching losses are reduced
p-q	Sliding Mode	4.13	Good regulation in DC bus for load variation
p-q	PWM	2.41 (Under balanced sinusoidal voltage)	In general, if HCC is used switching losses are reduced.
p-q	PWM	7.04 (Under unbalanced sinusoidal voltage)	
p-q	PWM	9.07 (Under balanced non-sinusoidal voltage)	

SRF	PWM	2.27 (Under balanced sinusoidal voltage)	Under unbalanced non-sinusoidal load SRF is the best method
SRF	PWM	5.18 (Under unbalanced sinusoidal voltage)	
SRF	PWM	3.01 (Under balanced non-sinusoidal voltage)	
p-q	HCC	2.75 (Under balanced load)	HCC , controls the switches in an inverter asynchronously. This is the easiest method to implement
		14.12(Under unbalanced load)	
PID+PLL	HCC	1.49 (Under balanced load)	PID controller maintains the DC side capacitance voltage nearly constant and also settles down early even under unbalanced load conditions
		3.74(Under unbalanced load)	
Artificial Neural Networks	PWM (3-level inverter)	3.91	Multi level inverters reduce the harmonic content generated by the active filter and can reduce the voltage or current rating of the semiconductor.

V. DSP BASED SCHEMES

In [35] a new implementation system based on real-time solution of nonlinear harmonic elimination equations[36,37] using a digital signal processor DSP56001,a 24-bit general propose digital signal processor that features 512 words of full-speed on-chip program RAM and two preprogrammed data ROMs is reported. This system is capable of solving up to 15 harmonic elimination equations within 2.15 ms.

Some of the different current control schemes that have been discussed in [38] are:(i)PI controller in Synchronous Reference Frame (PI-SRF)[39];(ii) Dead-Beat (DB) controller implemented in stationary reference frame [40];(iii) PI controller in Synchronous Reference Frame with Multiple Rotating Integrators (PI-MRI) ;(iv) Stationary Frame controller with Proportional regulator and Sinusoidal Signal Integrators (P-SSI) [41];(v) P-SSI controller with multiple SSI's in Synchronous Reference Frame (P-SSI-SRF) [42];(vi) PI controller with Resonant regulators (PI-RES) in Synchronous Reference Frame [43];(vii)Repetitive Controller [44]. From [38] , the THD for the control schemes are:

TABLE 2 THD for different Control Schemes

Current Control Schemes	THD of main current
PI-MRI	2.51%
P-SSI	2.59%
P-SSI-SRF	2.57%
PI-RES	2.59%
Repetitive Controller	2.42%

Since the performances of all current controllers are rather similar, the choice of the best solution should be strongly influenced by the easiness of the implementation and the execution time. In terms of fixed point DSPs, the repetitive and PI-MRI current controllers appear to be more attractive since they are implemented using the well-known FIR filter structures and integrators, respectively. In addition, the routines for an integrator, rotational transformations or FIR filters can be easily obtained. However, in terms of code generation and execution time, the P-SSI-SRF and P-RES-SRF require less code and they are faster when compared with the PI-MRI since they do not require multiple rotational transformations. The repetitive controller execution time is strongly influenced by the number of coefficients N used by the FIR filter .

In [45],to extract out the harmonic components and reactive part of the distorted load current, "Perfect Harmonic Cancelation (PHC)" control strategy has been used. The single-phase PHC strategy is implemented on a digital controller of the APF and TMS320LF2407A DSP of TI is utilized to implement the control algorithm in real time.Using this method, theTHD level of i_s is reduced from 42.3% (before compensation) to 4.6% (after compensation) which comply with IEEE 519 Std [46].

In [47] a control method for determining the reference compensating currents of the three-phase shunt active power filters based on artificial neural network (ANN) was presented. It is evident that the THD is improved from 24.04 % without the Shunt Active filter to 4.6156 % for using PI controller and 2.9156 % for using ANN control with the SAF. The distortion in supply current with ANN is less than in case of PI controller method. The controller based on synchronous reference frame is discussed in [48].The THD is reduced from 28.6% to 8.4% due to harmonic compensation

VI. FPGA BASED TECHNIQUES

With very large scale integration devices currently available, such as field programmable gate array (FPGA) and application-specific integrated circuit, fully digital controllers can be realized [50], [51]. They are basically interconnection between different logic blocks. Thus, a control system which was previously implemented in an electronic board can now be designed in a single chip [52]. When design is implemented on FPGA they are designed in such a way that they can be easily modified if any need arise in future, by just changing the interconnection between these logic blocks. This feature of Reprogramming capability of FPGA makes it suitable to make our design using FPGA .Also using FPGA the design can be implemented within a short time and the implementation of FPGA-based digital control schemes prove less costly and hence they are economically suitable for all designs.

In [53], a scheme for control of single-phase shunt active power filter based on the sliding-mode control approach devised by Torrey and Al-Zamel [54]is implemented using FPGA by Simulink®, combined with Xilinx® System Generator. The design involves the measurements of source voltage, source current, and filter current, allowing the filter to compensate for multiple nonlinear loads connected to the same distribution bus, since the load current is not directly measured. The generation of the source reference current is based on the computation of average power. The Total Harmonic Distortion of the source current has been obtained from 43.7% to 10.4% with the active filter operation. Additionally, an improvement in the power factor at the source line has been obtained from 0.91 to 0.99.

Using SRF transformation [55], LPF, three-phase phase- locked loop (PLL), and inverter-current control, their dedicated hardware architectures with low computational were designed, and the whole control schemes is integrated into one medium-scale FPGA, and the THD of the source current is reduced to around 2.82%, In [56], a distributed-arithmetic (DA)-based proportional–integral–derivative (PID) controller algorithm is proposed and integrated into a digital feedback control system. This explains how the resources of the FPGA can be used efficiently with the help of a temperature control system.

In[49] , Synchronous reference frame is used for generation of reference current.HCC and advanced HCC are used for the generation of the switching signals. The digital controller is designed using FSMD architecture for three phase shunt active power filter. The THD of the source current for HCC is 3.16% and for AHCC is 2.82% which is less than 5%, the harmonic limit imposed by the IEEE-519 & IEC-6000-3 standard.While implementing in digital domain, the Total Harmonic distortion (THD) is measured for the source current with digital controller using SIMULINK. The digital controller's VHDL code can be written in Xilinx and is dumped in to the FPGA for hardware implementation. In FPGA based implementation ,the Compilation Report should carry :the Selected Device, Number of Slices, No. of Slice Flip Flops, No. of 4 input LUTs, Number of bonded IOBs, Speed, NUMBER OF GCLKS ,Maximum circuit delay time ,Total equivalent gate counts for design. Always keep the logic utilization at 85% of the available resources or below. This makes it easier to place and route the design and allows sufficient room for future design iterations.

VII. CONCLUSION

A brief review about the Shunt active filters was made both in hardware and software domains. Taking the THD as the quantitative measure, it is understood that for the same compensation signal and gating signal generation method the THD is almost the same. Digital techniques are easier to implement than analog techniques. Also they are immune to environmental noise and temperature change. Also they do not suffer component variation and switching losses.. For sophisticated control schemes it is desirable to use FPGAs reduces the overall speed of the system increases. Also they are economically suitable for all designs and avoid unwanted mathematical calculations. While designing with FPGA, the resources are a major factor which should be used properly by effective coding techniques.

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