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Design and Implementation of a Shunt Active Power Filter Using SVPWM Technique

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Abstract: This paper presents a control method for shunt active power filter using Space Vector Pulse Width Modulation (SVPWM). In the proposed control method, the Active Power Filter (APF) reference voltage vector is generated instead of the reference current, and the desired APF output voltage is generated by SVPWM. A MATLAB code is developed to generate the SVPWM switching pulses fed to the two-level inverter topology. The entire power system block set model of the proposed scheme has been developed in MATLAB environment. The developed control algorithm is simple. The APF based on the proposed method can eliminate harmonics, compensate reactive power and balance load asymmetry. Simulation results show the feasibility of the APF with the proposed control method. Also this paper presents a shunt hybrid active power filter application mainly for current harmonic elimination and fixed reactive power compensation. The proposed system filter and a series of LC passive filter connected to each consist of a small rated voltage source active power phase. Besides, no additional switching filter is required for the current ripples. Effectiveness of the system is confirmed by the experimental results obtained from a laboratory prototype.

The filter was designed to work as voltage source and operates as harmonic isolator, improving the filtering characteristics of the passive filter. The control strategy for detecting current harmonics is based on the “ p-q theory ” and the phase-tracking system in a synchronous reference frame phase-locked loop. The dc-link voltage control is analyzed together with the effect of controller gain and delay time in the system's stability. Simulations for this application are displayed and experiments in a 1-kVA prototype, using the aforementioned industrial controller, were tested, validating the effectiveness of this new application. This paper deals with the hysteresis current control based hybrid shunt active filter to reduce the harmonics produced by non linear loads in distribution line. The main harmonic sources of distribution lines are the non linear loads and frequent switching of industrial loads. The non linear loads take discontinuous current and thus it injects harmonics. The switching of loads produces voltage sag and swells which leads to harmonics in the lines. The proposed hybrid shunt active filter is fully characterized by series LC and shunt DC link connected through 3-phase active filter. The disturbances in the supply voltage and load current due to the non linear loads such as rectifiers and converters are observed in the simulation. The same is studied after connecting the designed active filter to the line. The simulation results obtained from the proposed method proves that it gives comparatively better the value.

Keywords: SVPWM, LC Passive filter, harmonic isolator, hysteresis current control and 3-phase active filter.

Introduction:

The implementation of Active Filters in this modern electronic age has become an increasingly essential element to the power network. With advancements in technology since the early eighties and significant trends of power electronic devices among consumers and industry, utilities are continually pressured in providing a quality and reliable supply. Power electronic devices such as computers, printers, faxes, fluorescent lighting and most other office equipment all create harmonics. These types of devices are commonly classified collectively as ‘nonlinear loads’. Nonlinear loads create harmonics by drawing current in abrupt short pulses rather than in a smooth sinusoidal manner.

Harmonic filters are used to eliminate the harmonic distortion caused by nonlinear loads. Specifically, harmonic filters are designed to attenuate or in some filters eliminate the potentially dangerous effects of harmonic currents active within the power distribution system. Filters can be designed to trap these currents and, through the use of a series of capacitors, coils, and resistors, shunt them to ground. A filter may contain several of these elements, each designed to compensate a particular frequency or an array of frequencies.

Filters are often the most common solution that is used to mitigate harmonics from a power system. Unlike other solutions, filters offer a simpler inexpensive alternative with high benefits. There are three different types of filters each offering their own unique solution to reduce and eliminate harmonics. These harmonic filters are broadly classified into passive, active and hybrid structures. The choice of filter used is dependent upon the nature of the problem and the economic cost associated with implementation.

A passive filter is composed of only passive elements such as inductors, capacitors and resistors thus not requiring any operational amplifiers. Passive filters are inexpensive compared with most other mitigating devices. Its structure may be either of the series or parallel type. The structure chosen for implementation depends on the type of harmonic source present. Internally, they cause the harmonic current to resonate at its frequency. Through this approach, the harmonic currents are attenuated in the LC circuits tuned to the harmonic orders requiring filtering. This prevents the severe harmonic currents traveling upstream to the power source causing increased widespread problems.
An active filter is implemented when orders of harmonic currents are varying. One case evident of demanding varying harmonics from the power system are variable speed drives. Its structure may be either of the series of parallel type. The structure chosen for implementation depends on the type of harmonic sources present in the power system and the effects that different filter solutions would cause to the overall system performance. Active filters use active components such as IGBT-transistors to inject negative harmonics into the network effectively replacing a portion of the distorted current wave coming from the load. This is achieved by producing harmonic components of equal amplitude but opposite phase shift, which cancel the harmonic components of the non-linear loads.

Active Filters are commonly used for providing harmonic compensation to a system by controlling current harmonics in supply networks at the low to medium voltage distribution level or for reactive power or voltage control at high voltage distribution level [2]. These functions may be combined in a single circuit to achieve the various functions mentioned above or in separate active filters which can attack each aspect individually. The block diagram presented in section 3.2 shows the basic sequence of operation for the active filter. This diagram shows various sections of the filter each responding to its own classification.

The block diagram shown in figure represents the key components of a typical active power filter along with their interconnections. The reference signal estimator monitors the harmonic current from the nonlinear load along with information about other system variables.

The reference signal from the current estimator, as well as other signals, drives the overall system controller. This in turn provides the control for the PWM switching pattern generator. The output of the PWM pattern generator controls the power circuit through a suitable interface. The power circuit in the generalized block diagram can be connected in parallel, series or parallel/series configurations, depending on the transformer used

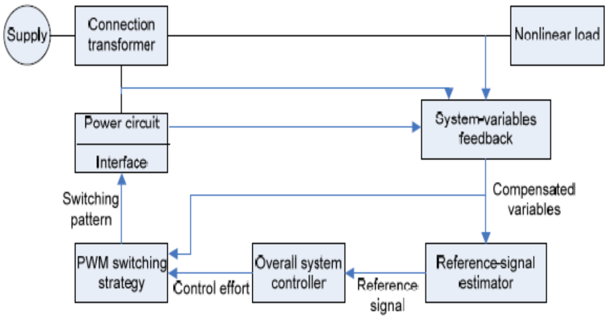


Fig: Generalized block diagram for active power filters

Active power filters according to [2] can be classified based on the following criteria:

1. Power rating and speed of response required in compensated systems;
2. Power-circuit configuration and connections;
3. System parameters to be compensated;
4. Control techniques employed; and
5. Technique used for estimating the reference current/voltage.

SHUNT ACTIVE FILTER WITH PQ CONTROLLER

The objective of shunt active filters is ultimately the same, the primary goal being to compensate for current harmonics in the power system. A variety of active filters also extend upon this initial goal to include reactive power compensation and as an outcome of this power factor correction. The model shown in appendix D is a simplified schematic of a three phase shunt active power filter implementation to a power system network. This active filter model subtly compensates for current harmonics and reduces of the total harmonic distortion.

Current source nonlinear loads such as a six-pulse thyristor converter require harmonics from the generator. Although the demand for current harmonics may only be of a few orders above the fundamental, the generator upstream is compelled to supply this current. This causes the generator to operate at frequencies above the nominal 50Hz or 60Hz and in doing so, also creates a negative phase-sequence component which is undesirable.

A shunt active filter is considered a current source because it injects non-sinusoidal current through the parallel branch of the network in order to compensate for the current harmonic demand of the nonlinear load. The role of the active filter controller is to sense and monitor the load current and to appropriately determine the correct reference harmonic current for the inverter. Once the correct reference harmonic content is determined; this reference current is fed through a suitable current controller which then is sent to the inverter for injection into the network. Appendix D shows the model of the three phase four wire shunt active power filter using a conventional three leg converter.

Critical component operation

DC voltage regulator

The dc voltage regulator is designed to automatically maintain a constant voltage level. It supervises the dc capacitor voltages and provides two control signals, Ploss and ε. The capacitor voltages of C1 and C2 vary by certain conditions caused by the shape of the current reference and the hysteresis bandwidth. If the current references are assumed to be composed from zero-sequence components, the line currents will return through the neutral wire. For a split capacitor inverter topology as shown in figure , the currents can flow in both directions through the switches and capacitors. Therefore, variations in the capacitor voltages can also be caused by a zero-sequence current reference

$$i_{fk} > 0 \; and \; \frac{di_{fk}}{dt} < 0 \; increases \; the \; voltage \; in \; C_1$$

$$i_{fk} < 0 \; and \; \frac{di_{fk}}{dt} < 0 \text{ decreases the voltage in } c_1$$

$$i_{fk} < 0 \; and \; \frac{di_{fk}}{dt} > 0 \; increases \; the \; voltage \; in \; c_2$$

$$i_{fk} > 0 \text{ and } \frac{di_{fk}}{dt} > 0 \text{ decreases the voltage}$$

Variation conditions for the capacitor voltage Vc1 and Vc2

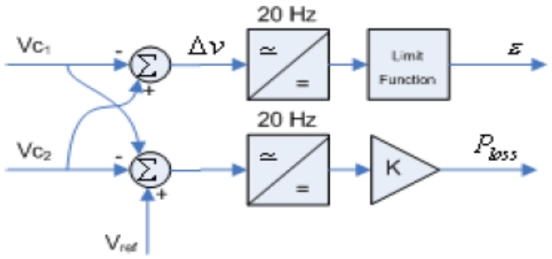


Fig: DC voltage regulator schematic

The inputs to the dc voltage regulator are the two capacitor voltages and an internal fixed reference voltage. The capacitor voltage difference from the reference input is filtered using a lower pass filter with a cutoff frequency at 20 Hz to render it insensitive to the fundamental frequency voltage variations which appear when the active filter compensates the fundamental zero sequence current of the load. The voltage is then amplified using a proportional-integral (PI) controller which outputs signal Ploss. Ploss aims to compensate for losses in the PWM converter which tends to discharge the dc capacitors and thus neutralise the dc bus voltage variations. This gives rise to a negative feedback loop.

The second output from the dc voltage regulator is the dynamic offset level. This offset level is dynamic because it changes accordingly as to ensure that the difference in dc capacitor voltages 21(Vc2-Vc1) stays within an acceptable tolerance limit. The capacitor voltage difference is filtered and then sent along with the reference voltage to a limiting function which is used to determine the appropriate limits.

The limit function must adhere to the following limits:

$$\text{E=}\Leftrightarrow \Delta \boldsymbol{V} < -0.005\boldsymbol{V}_{\boldsymbol{ref}}$$

$$\boldsymbol{\varepsilon} = \frac{\Delta \boldsymbol{v}}{\mathbf{0.05}\boldsymbol{v}_{\boldsymbol{ref}}} \Leftrightarrow -\mathbf{0.05}\boldsymbol{v}_{\boldsymbol{ref}}$$

$$\boldsymbol{\varepsilon} = 1 \Leftrightarrow \Delta \boldsymbol{V} > 0.05\boldsymbol{V}_{\boldsymbol{ref}}$$

Active Filter Controller

Positive-sequence voltage detector

The active filter controller suitably determines reference currents by integration of an appropriate control theory. This model incorporates the PQ theory. The input to the controller monitors the load current waveform and the source voltage waveform and calculates power based upon these parameters. Since the shunt active filter is designed predominantly for current harmonic mitigation, the harmonics present in the power waveform can be assumed to be attributed solely by the current harmonics demanded by the nonlinear load. If one assumes that the voltage waveform is perfectly sinusoidal and free from all harmonics then this condition becomes true. If the three phase voltage input to the controller is unbalanced or high distorted, then the reference currents calculated would not completely filter the current harmonics demanded by the nonlinear load. This situation gives rise for the need of a positive sequence voltage detector.

The positive sequence voltage detector shown in figure derives the positive sequence fundamental signal from a three phase voltage signal carried by the power line. The PLL control circuit tracks the positive sequence voltage at the fundamental frequency of highly distorted and unbalanced three phase signals. The synchronizing circuit determines accurately the fundamental frequency of the system voltage and phase angle of the measured signals which may be unbalanced and contain harmonics.

The PQ Theory

The p-q theory formally known as “The Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuit” was first developed by H. Akagi in 1983. [10] 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 known as a Clarke transformation of the three phase input voltages and the load harmonic currents in the a-b-c coordinates to the 0αβ—reference frame followed by the calculation of the real and reactive instantaneous power components.

Figure shows a diagram of the interactions of each of the power components within the power system and how each relates to one another. 0pis the average value of the instantaneous zero sequence power. This corresponds to the power which is transferred from the power supply to the load through the zero sequence components of voltage and current.

~0pcorresponds to the alternating power of the instantaneous zero sequence power. This relates to the exchanged power between the power supply and the load through the zero sequence components of voltage and current. The zero sequence power only exists in three phase systems with neutral wire.

P is the mean value of the instantaneous real power. This corresponds to the energy per unit time unity which is transferred from the power supply to the load.

~p is alternating value of the instantaneous real power. This corresponds to power which is exchanged between the power supply to the load.

q is the instantaneous imaginary power. This corresponds to the power that is exchanged between the phases of the load. This component is not constructive to the system and is accountable for the undesirable current which circulate between the system phases. The reactive power does not transfer power from the supply to the load nor does it exchange power.

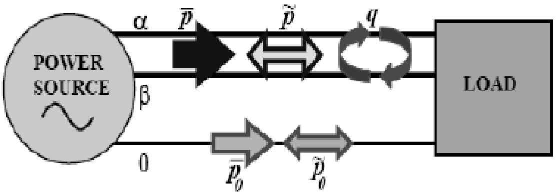


Fig: Power components of the p-q theory in alpha-beta-0 coordinates

From figure, the only component of the power obtained through the p-q theory that is desirable and constructive is the average real power and the average zero sequence power. This is because power is transferred from the supply to the load. The other components of power are less desirable and this can be compensated by the shunt active filter.

Dynamic hysteresis band PWM controller

Current control is implemented through feedback modulation of a dynamic hysteresis band PWM controller. The shunt line current tracks the reference current within a hysteresis band. By comparing the reference currents calculated by the controller with the measured values of compensation currents, the command signals for the inverter semiconductor switches can be produced.

Figure below illustrates the principle of the dynamic hysteresis current controller technique. If the shunt line current exceeds the maximum limit of the hysteresis band, the upper switch of the inverter arm is turned off and the lower switch is turned on. As a result, the current starts to decay. If the current crosses the minimum limit of the hysteresis band, the lower switch of the inverter arm is turned off and the upper switch is turned on. As a result, the current gets back into the hysteresis band. Hence, the shunt line current is forced to track the reference current with the hysteresis band.

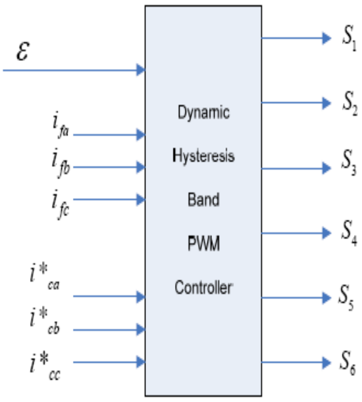
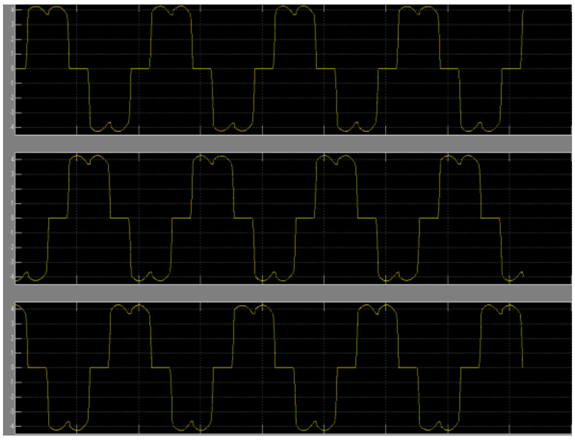
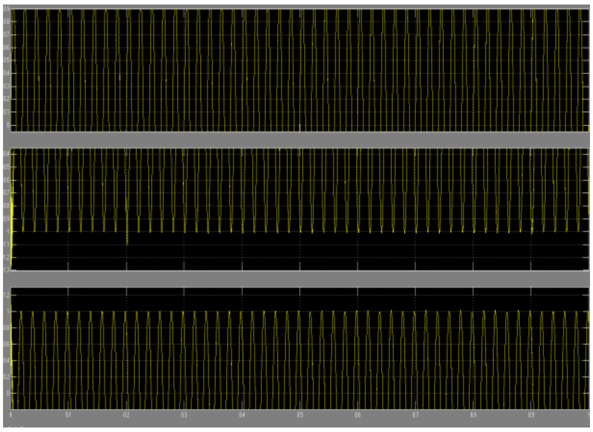


Fig: Hysteresis controller

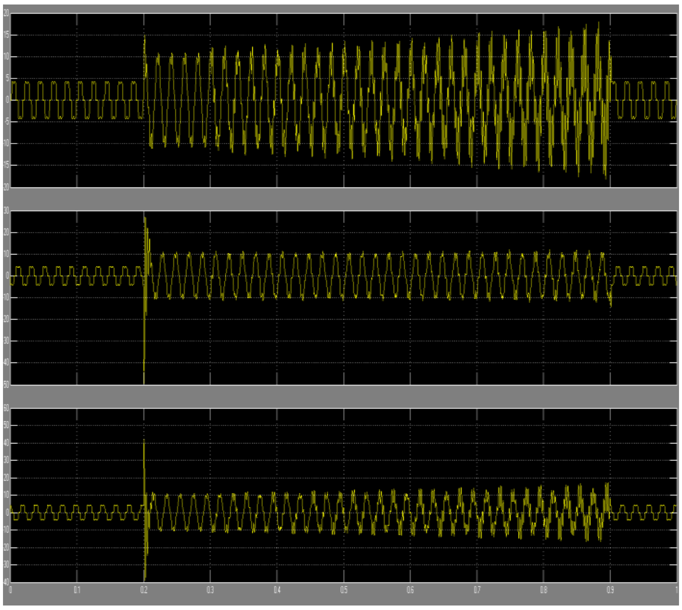
SIMULATION RESULTS



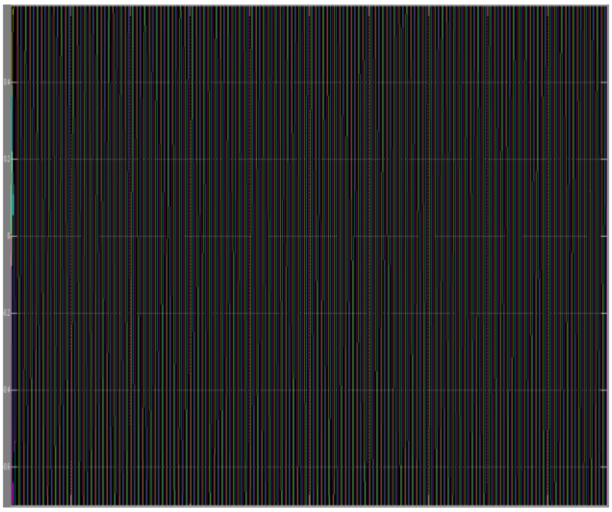
Feedback Control, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Load current (10A/div)



During Start Up, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Filter current (10A/div)



Feedback & Feed forward Control, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Filter current (10A/div)



Feedback Control, C1 DC link voltage (50V/div), C2 Mains voltage (100V/div), C3 Mains current (10A/div), C4 Filter current (10A/div)

CONCLUSION

This paper investigated the analysis and simulation of a shunt active power filter. And it presents a control method for shunt active power filter using Space Vector Pulse Width Modulation (SVPWM). In the proposed control method, the Active Power Filter (APF) reference voltage vector is generated instead of the reference current, and the desired APF output voltage is generated by SVPWM. A MATLAB code is developed to generate the SVPWM switching pulses fed to the two-level inverter topology. The entire power system block set model of the proposed scheme has been developed in MATLAB environment. The developed control algorithm is simple. The APF based on the proposed method can eliminate harmonics, compensate reactive power and balance load asymmetry. Simulation results show the feasibility of the APF with the proposed control method.

Another major strength of this shunt active power filter is the results achieved under the two case study scenarios. For each of the given nonlinear loads, the active filter reduced the total harmonic distortion to below 5%. The strength is the fact that the internal harmonics generated by the inverter remained minimal. This is a definite advantage and adds to the positive outcome to the overall success of the compensation.

Areas of weakness in this project include the efficiency of the major high pass filter, which is responsible for filtering the harmonic component from the real power waveform. In addition, the hysteresis band PWM current controller proves a likely source of errors due to the complexity.

Future Implications

For future research, once might consider designing a higher order high pass filter for within the controller. This filter is responsible for filtering out the harmonic component of the real power. As all filters are not ideal, and thus lack in their ability to filter every component as required, an element of error is introduced in the calculation of the reference currents and thus compensation currents. This error is such that the compensation currents will not exactly match the load harmonic currents and thus harmonic currents will remain in the system. Although the total harmonic distortion will be reduced, designing a filter of a higher order will prove valuable in increasing the filters accuracy and thus efficiency.

The determination of the PI controller values is also another area of interest for future consideration. These values relate to the compensation of the DC voltage regulator maintaining a regulated voltage across the two capacitors such that it will provide voltage to power the inverter. In general the determination of these values is very cumbersome and for this project a trial and error approach was sustained. These values are accurate to the extent of observing output waveforms from the controller and adjusting the parameters accordingly to achieve a plateau curve at time increases.

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