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Three Level Inverter Based Shunt Active Power Filter Using Multi-Level Hysteresis Band Current Controller

***Abstract**. In this paper, a three-level inverter based Shunt Active Power Filter (SAPF) using Multi-Level Hysteresis Current Controller (MLHCC) is presented for solution of power quality problems in distribution system. A simulation model of SAPF is prepared in Matlab/Simulink environment. MLHCC is used for control of SAPF currents. In simulation study, it is considered that SAPF executes two tasks covering compensation of harmonics and reactive power. Therefore, control algorithm is formed to execute two tasks. The Synchronous Reference Frame Method (SRFM) is used to extract the reference currents. Dynamic performance of SAPF is evaluated using two nonlinear loads switched at different times. Some simulation results are given to show performance of a three-level inverter based SAPF using MLHCC. Simulation results show that current harmonics has been kept inside specific recommendation of IEEE-519 and ac grid is approximately kept in unity power factor.*

***Streszczenie.** W artykule przedstawiono bocznikowy aktywny filtr mocy (ang. Shunt Active Power Filter) z trójpoziomowym falownikiem. Sterowanie oparte zostało na wielopoziomowym regulatorze histerezowym prądu (ang. Multi-Level Hysteresis Current Controller). Filtr aktywny spełnia rolę kompensatora wyższych harmonicznych oraz mocy biernej. (**Sterowanie bocznikowego aktywnego filtru mocy z przekształtnikiem trójpoziomowym oparte na wielopoziomowym regulatorze histerezowym prądu**)*

Keywords: active power filters, three-level h-bridge inverter, multilevel hysteresis band current control, harmonics and reactive power compensation
Słowa kluczowe: Aktywny filtr mocy, trójpoziomowy mostek typu H, wielopoziomowy regulator histerezowy prądu, kompensacja harmonicznych i mocy biernej

Introduction

Power electronic devices have been widely used in industrial processes such as arc furnaces, variable motor drives, soft starters, uninterrupted power supplies and so on. These types of loads are called non-linear loads and bring about some power quality problems such as poor power factor and high order of harmonics in distribution and transmission systems [1-2]. Reactive power and harmonics are the most important power quality problems which effect behavior of systems. Presence of harmonics can cause power losses, heat in power transformers and voltage distortion [3]. Conventionally, Passive Filters (PFs) which include reactor and capacitor banks with fixed tuned were used to solve problems of reactive power and harmonics. PFs have some benefits such as low costs and simple designing features but fix characteristics of compensation, large sizes and resonance risks with load are their drawbacks for variable loads [4]. In 1971, Sasaki and Machida investigated basic compensation principle of active power filters (APFs) [5]. In last few decades, as a result of advancement in semi-conductor and micro-processor technologies, APFs have been started to use solving power quality problems. With a suitable control tuning, an APF may solve problems of reactive power and harmonics simultaneously [6]. APFs can be divided to three main topologies according to connection types which are shunt, series and both shunt and series combination (unified power quality conditioners-UPQC). Shunt APFs (SAPFs) are the most common used type of APF because of the ability in harmonics compensation and easy to perform compared to other topologies [7].

APFs generally consist of power circuit and control unit. Power circuit includes DC/AC inverter, its complements and a coupling element which connects the inverter to AC grid. Control unit is divided into two parts. In the first part, reference currents are extracted by sensing current and voltage signals. Second part covers generation of switching pulses for inverter [1].

In application of APF, two types of inverters are used: Voltage Source Inverter (VSI) and Current Source Inverter (CSI). VSIs are more suitable for many applications because of their advantages than its rival CSIs [3].

Conventional two-level VSIs have been widely used in application of APFs [8, 9]. However, multilevel inverter topologies have many advantages such as lower harmonic distortion, lower switching frequency and lower switching losses over conventional two-level VSIs for medium and high-voltage applications. The multilevel inverter synthesizes a desired output voltage from several levels of DC voltages. There are three main topologies of multilevel inverter: diode-clamped, flying-capacitor and cascaded multilevel inverter. The cascaded multilevel inverter requires the less number of components compared with other multilevel inverter topologies. Another advantage of the cascaded is flexible and modularized circuit layout. The number of output voltage levels can also be easily adjusted by changing the number of H-bridge inverters [10].

In this paper, a three-level VSI based APF using Multilevel Hysteresis Current Controller (MLHCC) is investigated for reactive power and harmonic compensation. For this purpose, a simulation model is built in MATLAB/Simulink environment. The model covers three-level inverter, ac-grid, nonlinear loads and control unit. In simulation study, reactive power and harmonics caused by two nonlinear loads are compensated through three level inverter based SAPF. The load-1 is connected to system during all simulation whereas load-2 is switched at 0.3s. Further, APF is taken in to operation at 0.15 s. The Synchronous Reference Frame Method (SRFM) is preferred for reference current extraction due to simplification of filtering the dc components. Some results obtained from simulation model are given to show effectiveness of proposed APF. The results indicate that the APF can approximately keep AC grid in unity power factor and harmonics in source current are also reduced in specific recommendation of IEEE-519 standards.

Basic Operational Principle and Mathematical Model of Shunt Active Power Filter

In general, the working principle of APF is based on injecting a current to the point of common coupling (PCC) in which it is same in amplitude with harmonic component of load current but inverse in phase angle [4]. Thus, the harmonic pollution in the source current is eliminated and almost pure sinusoidal current wave is drawn from source.

SAPF consists of a VSI and dc capacitor supplying dc voltage to VSI, a coupling inductance for connection to PCC and control unit. Control unit processes sensed inputs (source currents and / or voltages / load currents) and extracts reference currents to generate switching signals for VSI. Using Kirchhoff's current law, current equation for PCC can be written as follows:

$$I_s = I_L + I_f \tag{1}$$

In Equation 1, I_L is load current which includes harmonics and dominated reactive power, IS is source current and I_f is current of SAPF.

Because of its harmonic components, I_L may be formulated as in Equation 2:

$$I_L = I_{L1} + I_{LH} \tag{2}$$

Equation 2 defines IL with two components where IL1 is fundamental component and ILH is harmonic component. If SAPF generates If as in the same amplitude but inverse phase angle of ILH, the relation between these currents will be defined as:

$$I_f = -I_{LH} \tag{3}$$

As a result, combining above equations, source current can be determined as:

$$I_s = I_{L1} + I_{LH} - I_{LH} \tag{4}$$

It is seen in Equation 4, load draws only fundamental component from AC grid if SAPF generates harmonic content of load current. In this case, non-linear loads draw pure sinusoidal current from source.

Power Circuit of Three-Level Inverter Based SAPF

In the APF applications, the VSIs act a current controlled voltage source. Traditionally, shunt APFs are implemented using VSI based two-level inverters. Such APFs use a transformer to meet desired voltage profile [11]. The transformer leads to increasing the losses in the system and it may saturate once the load draws any DC current. Further at higher power, long tail current associated with the device characteristics prohibits high frequency operation and the efficiency of the APF is lower due to significant switching losses.

Recently, multilevel VSIs have been applied to active power filters for medium voltage applications because of their advantages such as directly connection to medium voltage without a coupling transformer, generating output voltages with very low distortion, reducing dv/dt stress high power conversion capability and achieving a high equivalent switching frequency effect at rather low device switching frequency [12]

Basically, multilevel inverters have been developed for applications such as ac motor drives and static Var compensation. In such applications, the multilevel inverter is desired to generate an almost sinusoidal output voltage. However, multilevel inverters must be able to generate an output current that follows the respective reference current which contains the harmonic and reactive component required by the load [13]. In addition, multi-level inverter structures allow for a lower dc voltage operation. The power circuit topology of a three-level inverter based SAPF is shown in Fig. 1. An H-bridge is used in each phase: a total of three H-bridge and each H-bridge has four main switches with freewheeling diodes. These H-bridges are connected in parallel through a coupling inductance with internal resistance to the ac grid. In addition, each H-bridge is terminated by a capacitor supplying dc voltage to H-bridge. The three output voltage levels as +Vdc, 0 and -Vdc can be synthesized using suitable combination of the switches.

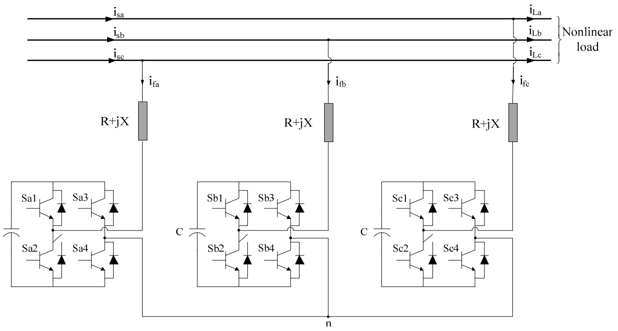


Fig.1. Power circuit of three-level H-bridge inverter based SAPF

Control of Shunt Active Power Filter

Control of APF can be divided into two stages as reference current extraction and generation of gate pulses for switches of inverter. Extraction of the reference current can be carried out by using Time Domain Methods (TDMs) and Frequency Domain Methods (FDMs). In most APF applications, TDMs are preferred because of fewer calculations compared to FDMs and fast response [9]. In this study, SRFM, being one of TDMs, is used to extract the reference currents for compensation of harmonics and reactive power. SRFM is based on dq-transform proposed by Bhattacharya et al. [14]. In this method, three current vectors rotating at ωt are transformed into αβ–components given in Eq.(5), then these components are converted into dq-axes as presented in Eq.(6) [15]. Further, this control method needs a Software Phase Locked Loop (SPLL) to provide synchronization between APF and ac grid.

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \times \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \times \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos\omega t & -\sin\omega t \\ \sin\omega t & \cos\omega t \end{bmatrix} \times \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{6}$$

The fundamental component of load current is transformed to direct current (dc) signal at the plane of dq reference frame rotating in synchronous speed [12]. So both of these dq-axes components of load current have fundamental (dc value) and harmonic polluted (ac value) components as follows:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \tilde{i}_d \\ \bar{i}_q + \tilde{i}_q \end{bmatrix} \tag{7}$$

In Eq.7, it is obviously seen that currents of dq-axes consist of dc and ac components. The harmonics are related to ac components of dq-axes. Therefore, the ac components have to be eliminated for compensation of harmonics. Moreover, dc component of q-axis also determines reactive power of loads. Thus, this component should be only considered in case of reactive power compensation.

The SRFM control algorithm is presented in Fig.2. Where, load current is transformed into dq-axes components by using angular frequency obtained from

SPLL. The d-axis current is passed through a High Pass Filter (HPF) to obtain its ac-component. q-axis current is directly used. Thus, it is aimed to compensate for both harmonics and reactive power. To compensate active power losses in SAPF, dc-link voltage should also be controlled. For this purpose, a Proportional Integral (PI) is used to keep dc-voltage constant in reference value [4]. The output of dc voltage controller is multiplied with dq-axes voltages and multiplied signals are added to respective dq-axes currents. Thus, reference currents for dq-axes are obtained and then these components are converted to abc-coordinate by using angular frequency from SPLL.

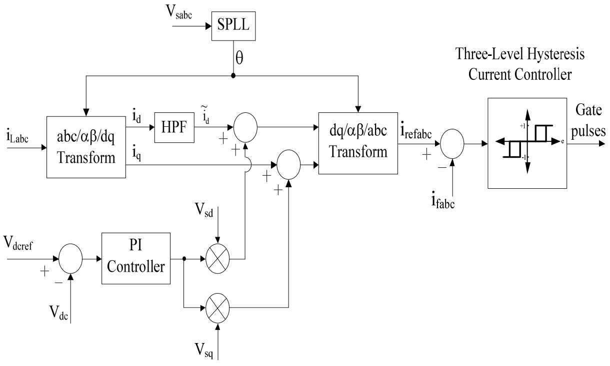


Fig.2 Extraction of reference current using SRFM

Multilevel Hysteresis Band Current Control Method for Three Level Inverter

There are various methods proposed for current control of SAPFs [16]. Among proposed methods, the hysteresis band is used very often because of its simplicity of implementation fast response current and robust structure [17-19]. In hysteresis current control method, the switches of the inverter are controlled so that its output current remains between pre-defined bands.

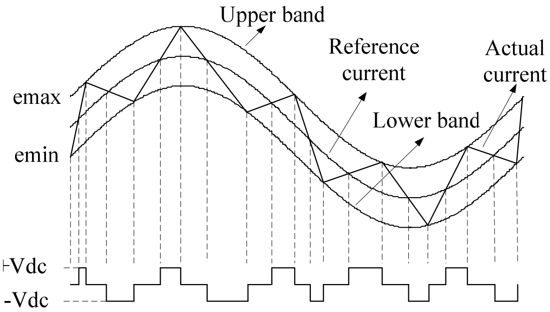


Fig.3. Diagram of three-level hysteresis current control

In literature, the multilevel hysteresis band control method has been applied to multilevel inverter topologies [16, 20-23]. The number of lowest level in multilevel hysteresis band control is three. In this paper, three-level hysteresis band control method is used to control currents of APF. Unlike traditional hysteresis current control method with single band, two bands as upper and lower are defined to obtain gate signals for switches of three-level inverter. Fig.3 shows how output voltage of inverter is obtained using upper and lower bands. As shown in Fig. 3, current error e is obtained by comparing reference and actual current. Whenever error signal reaches out an outer hysteresis limit, then output of inverter should be set as positive or negative to impose an opposite for current error. Correspondingly, error signal reaches an inner hysteresis limit; output of inverter should be set as zero condition so current error will be forced to opposite direction without reaching the other outer limit. If this zero condition does not provide opposite of current error, it will keep forwarding through inner limit to the other outer hysteresis limit. At this time, a reverse polarity of inverter output will be controlled and so current direction will be reversed. [24].

Fig.4 presents three-level hysteresis current control method implemented by using flip-flop circuits for H-bridge of phase-a. The outputs of comparators go into flip-flop. Output of positive inner band limit goes to set input (S) and output of negative inner band limit goes to reset input (R) of Flip-Flop. Outer band behaves opposite of inner band as seen in Fig.4. The inverse of Q1 drives Sa2 in H-bridge while Q1 output of Flip-Flop drives the first leg's upper switch Sa1 in H-bridge [25]. Same processes are carried out for H-bridges of phase-b and c.

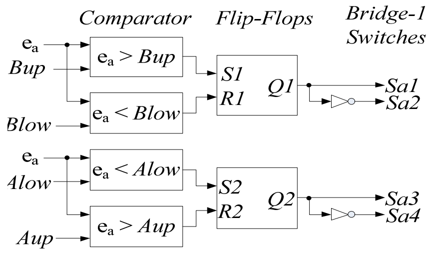


Fig.4 Three-level hysteresis band controller with flip-flop

Simulation *Results*

A simulation model of SAPF is constructed in MATLAB environment. The model consists of three-phase ac source, three-level inverter, coupling inductance, two nonlinear loads, and control unit. Parameters related to simulation model are given in Table I.

Table I. Parameters related to simulation model

Parameters	
DC-link capacitors	3.3 mF
Reference DC-link voltages	400V
Coupling Inductance	1.2 mH
Source Voltage and frequency	380V/50Hz
Load1 (Diode Rectifier)	(100 +j31.4) Ω
Load1 (Thyristor Rectifier)	(1 +j6.28) Ω
Sampling time	5us

In simulation study, it is assumed that source voltages are balanced. To show dynamic response of SAPF with three-level hysteresis current controller, nonlinear loads are switched at different times. That is, load1 is connected to ac grid at beginning time of simulation while load2 is switched at 0.3s. Also, SAPF is operated at 0.15s. Fig.5 shows one phase source current and voltage in per unit (pu) before start-up of SAPF. From this figure, it is clearly seen that load draws a current with harmonics from ac grid and it also absorb reactive power from source.

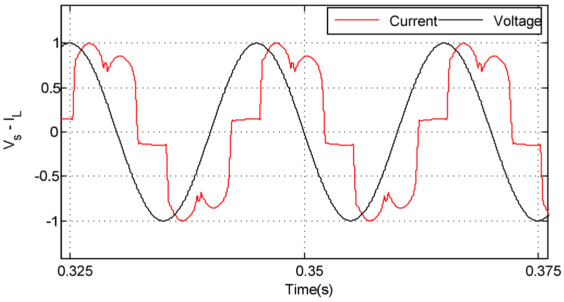
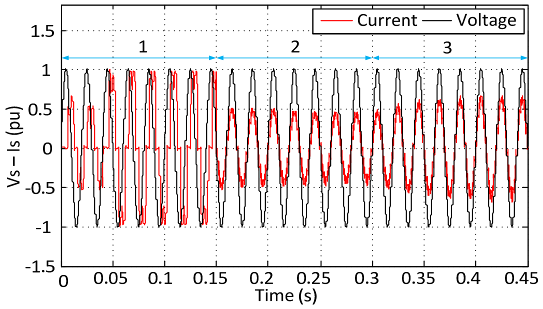


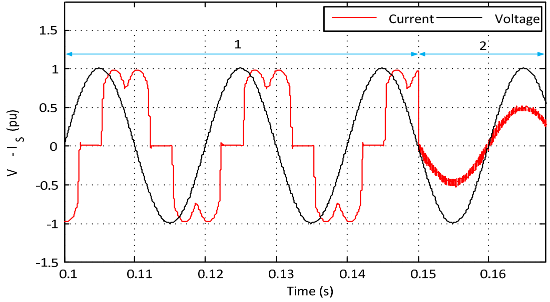
Fig.5 Relation between load current and source voltage before start-up of SAPF

To depict harmonic suppress performance of SAPF, waveforms of single phase source current and voltage in pu are depicted in Fig.6. Simulation study is carried out in three stages as shown in Fig.6. In stage-1, first nonlinear load is connected to ac grid without SAPF. Stage-2 represents operating condition with first nonlinear load and SAPF whereas stage-3 indicates operating condition with first and second nonlinear loads and SAPF. Fig. 6(a) is given as zoomed in Fig.6.(b) and (c) to provide a clear presentation. These figures reveal that the source current returns approximately sinusoidal form as well as in phase with source voltage after three-level inverter based SAPF are switched at 0.15s. It is concluded from these figure that SAPF not only compensates for harmonics but also supplies reactive power to system.

a) Waveforms of single-phase source current and voltage during simulation



b) Waveforms of single-phase source current and voltage during stage-1 and 2



c) Waveforms of one phase source current and voltage during stage-2 and 3

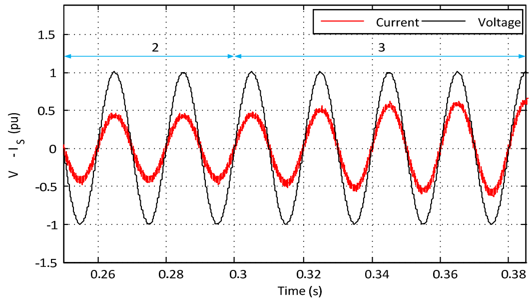
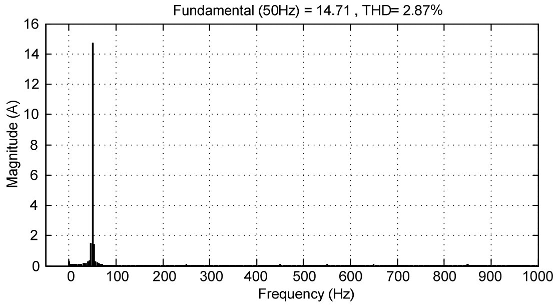


Fig.6 Single-phase source current and voltage in pu

A comparison between harmonic spectrums of two-level inverter and three-level inverter under same load conditions are also given in Fig.7(a) and (b), respectively. Total Harmonic Distortion (THD) of source current is 28.7% without SAPF. THD of the source current is reduced to 6.08% from 28.70% by two-level inverter based SAPF whereas THD of the source current is reduced to 2.87% from 28.70% by three-level inverter based SAPF. When results of harmonic spectrums are compared with each other, it is obviously seen that three-level inverter based SAPF is more effective in terms of harmonic suppression than two-level inverter based SAPF.

a) Two-level inverter based SAPF



b) Three-level inverter based SAPF

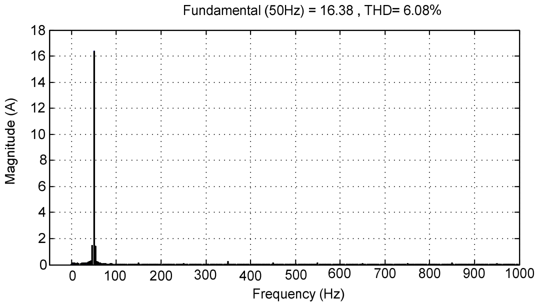


Fig.7 Harmonic spectrums for different inverter topologies

To obtain a good harmonic and reactive power compensation performance from SAPF, inverter has to generate reference current as fast and accurate as possible. Fig.8 shows reference and actual current. It is clearly seen in figure that current generated by inverter has been perfectly tracked its reference value.

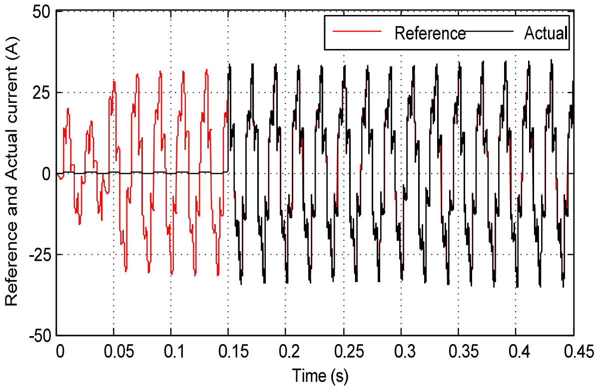


Fig.8 Reference tracking capability of SAPF

Conclusion

Solutions for electric power quality problems are increasingly discussed among electricity manufacturers and consumers because of the need for more efficient use of energy. In this paper, a three-level inverter based SAPF using MLHCC method is investigated to solve the electric power quality problems such as reactive power and harmonics occurred by nonlinear loads in a distribution system. A simulation model including ac grid, nonlinear loads, three-level inverter based SAPF and control unit is prepared in Matlab/Simulink environment. Reference currents are obtained by SRFM whereas three-level inverter is controlled by MLHCC. Performance of proposed SAPF is evaluated by nonlinear loads switching at different times. Some simulation results are given to show efficiency of SAPF in harmonic and reactive power compensation. Further, a comparison in terms of THD between three-level and two level inverters is presented for better validation. For this aim, simulation model of two-level inverter based SAPF is run under same conditions with three-level. Simulation results show that THD of source current is reduced from 28.70% to 2.87% by three-level inverter based SAPF using MLHCC. However, THD of source current is reduced from 28.70% to 6.08% in case of two-level inverter using conventional two-level hysteresis band current control method. It is obviously seen that THD of source current is lower in three-level inverter based SAPF when compared with two-level inverter based SAPF.

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