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A Comprehensive Study on Current Control Method of Multi Level Voltage Source Inverter Based Shunt Active Power Filter

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Abstract- *The shunt active power filter is promising solution for compensation of harmonics which are injected by non-linear loads. This paper describes different current control techniques for multilevel inverters based shunt active power filter. The hysteresis current control method for multilevel inverters are studied and evaluated for the application. The performance of Hysteresis Current Control methods such as MOBMH, Modified MOBMH, MBMH, TBMH and improved TBMH are presented in the context of SAPF. Various aspects of current control methods such as switching frequency, speed of response, complexity of control and delay time are compared.*

Keywords: Hysteresis Current Control Technique, Multilevel Inverters, Shunt Active Power Filter.

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1. Introduction

With the development of power electronics technology, use of semiconductor switches based equipments like adjustable speed drives, UPS, SMPS has increased. In addition to this, Power Converter based heating applications has found popularity among industrial consumers[1-3]. This solution provides improved utilization of energy and enhances controllability at the end user side. However, the time domain control of equipment creates power quality problems such as poor power factor and harmonics in the distribution systems as well as supply system. For instance, applications such as oil rigging in off-shore applications still use thyristor converter fed DC drive and generates harmonics on source side which creates problems for local DG sets. Similarly, cross-modulation effect in induction melting furnaces being fed by thyristor converters produces inter-harmonics on the supply side[4]. Conventionally, two level voltage source inverter based shunt active power filter(SAPF) are used for mitigation of current harmonics at the point of common coupling. The configuration of shunt active power filter is as shown in Figure 1(a) where harmonic in the load side (i_{Lh}) are compensated by shunt active power filter restoring sinusoidal behaviour of the source current. The experimental results shown in Figure 1(b) suggest that the harmonics present in the load current (Trace-2) due to non-linear load are not reflected on the source side (Trace-4). In other words, it can be said that harmonics are compensated by injecting compensating current (Trace-3 in Figure 1(b)) synthesized by SAPF. The quantitative measure of load current and improved source current is shown in Figure 1(c) and (d) respectively. Unlike the passive filters, which can target specific pre-

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defined frequencies to which they are tuned, an SAPF can eliminate selective harmonics or a range of harmonic frequencies. Three-phase voltage source inverter based SAPF's are widely used for compensating the load current harmonics, improving the power factor for

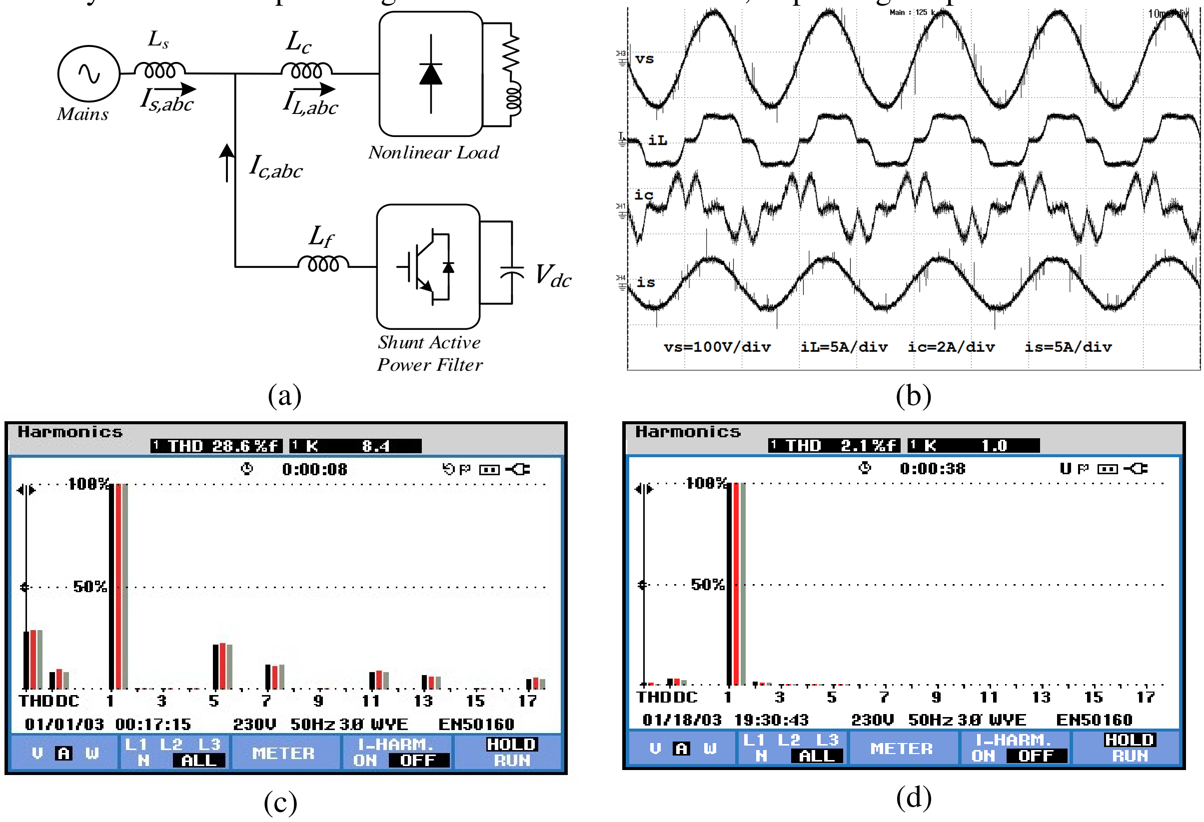


Figure 1. (a) Block Diagram of Shunt Active Power Filter (b) Experimental results of source voltage, load current, compensating current and source current for two level SAPF (c) Load Current FFT Spectrum (d) Source Current FFT Spectrum

nonlinear loads. The overall performance of shunt active power filter depends largely on topology of converter employed, compensation scheme or reference generation scheme and realization of current control algorithm[1-4]. The application of active power filters at medium voltage high power distribution systems are limited by the semiconductor switch ratings used in the VSIs, this limitation is overcome by multilevel inverter(MLI). Minimum harmonic distortion is possible with the use of MLI and high efficiency is achieved with minimum switching frequency operation[5-9]. To give reader a fair understanding of Active Power Filters technology, the solutions from various manufacturers are tabulated in Table 1.

The control of multilevel inverter for effective compensation of current depends largely on the current control method used. This paper reviews different current control methods applicable to multilevel inverters for SAPF application[10]. The paper is organized into following sections. Section II highlights linear current control methods for SAPF applications. Nonlinear current control methods for the SAPF applications are described in section III. Owing to popularity of hysteresis current control method in SAPF applications a separate section which gives insight into various HCC methods for multilevel inverters is presented. The study of multilevel inverter is supported by simulation results which are discussed and compared in Section IV.

Table 1 Active Power Filter Solution by Various Manufacturers

Manufacturer	**Input Voltage**	**Type of Supply**	**Harmonic Compensation Range**	**Reaction Time**	**Response Time**	**Filter Line current**	**Harmonic attenuation factor**	**Control Method / Switching Frequency**
ABB	208-480V 480-690V	3 wire 4 wire	15 to 20 individual harmonics selectable from 2nd to 50th order	<500µsec reaction time 40 ms (10 to 90% filtering)	2 network cycles typically	30 A to 450A	Better than 97% at rated load	NA
Siemens	400V	3 wire	Completely freely programmable filters up to the 16th order	< 25µsec	Less than one power cycle	100A	Better than 95% at rated load	4 kHz THD< 3%
Danfoss	380V - 480V	3 wire	--	<500µsec	Less than one power cycle	190A 400A	Better than 97% at rated load	3 to 4.5 kHz THD< 4%
Amtech	415VAC 600VAC	3 wire 4 wire	Selectable from 3rd to 51st order	<78µsec	Less than one power cycle	30A to 300A	Better than 97% at rated load	Digital FFT HCC 18 kHz
Delta	400V	3 wire 4 wire	harmonics selectable from 2nd to 50th order	<100µsec	Less than one power cycle	50A to 525A	Better than 97% at rated load	60 kHz THD< 5%

2. Linear Current Control Methods for Multilevel Voltage Source Inverter based Shunt Active Power Filter

The methods which are discussed in literature for current control of multilevel inverter based shunt active power filter are categorized as (1) Linear Controller and (2) Nonlinear Controller. The linear controllers attempt to synthesize voltage reference in unit sample time T_s such that the current error at the end of sample time is reduced to nearly zero value. Since the method uses a modulator with constant frequency, it is also known as constant frequency current control technique. The non-linear current controller uses an operator which confines current error within its range and changes its behaviour at every violation of the limit of the operator. Under normal operating conditions, the time taken for subsequent switching events is not fixed and hence results in variable switching frequency. Figure 2 shows the Tree Diagram for Classification of Current Control techniques of SAPF.

2.1. Linear Current Controller (Constant Frequency Current Control)

The linear current controllers produce the required amount of reference voltage which is fed to the Pulse Width Modulator. This modulator in turn generates the switching pulses for the solid state switches of the multilevel inverter. The method is parameter dependent which demand for careful tuning with a trade-off between maintaining the system stability over the whole operation range and achieving an adequate dynamic response during transient condition. In constant frequency current control the following controller are discussed in the literature[11-14].

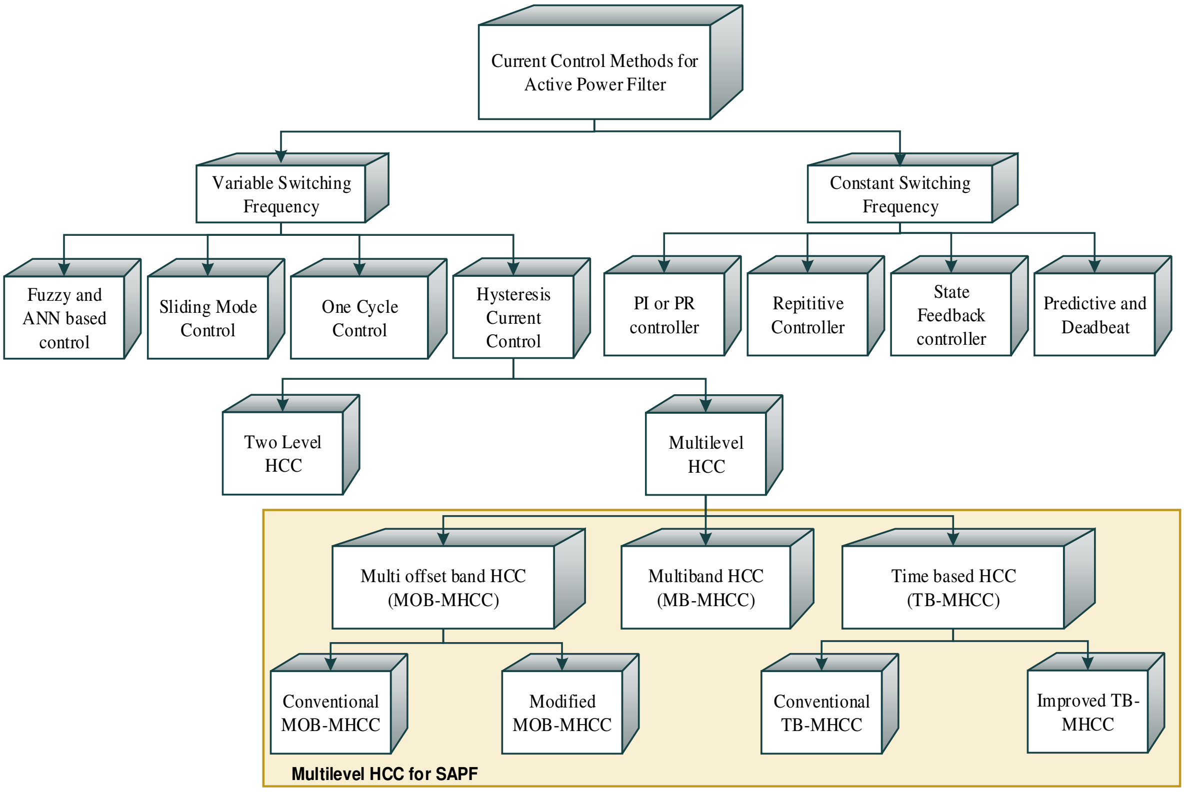


Figure 2 Tree Diagram for Classification of Current Control techniques of SAPF

2.1.1. PI Controller

PI controller is also known as the ramp comparator and it is also known as a Triangle comparison PWM controls (TCPWM). PI controller uses three PI error compensators. In this method, the controller compares the reference voltages obtained from Proportional Integral(PI) or Proportional Resonant(PR) with a sine triangle PWM. Based on the comparison of reference with carrier, a switching signal is generated. The disadvantage of this technique is an output current amplitude and phase error. This limitation can be overcome with the use of a modified ramp comparator[11-14].

2.1.2. Repetitive Controller

The repetitive controller (RC) cancels the steady state error by periodic controlling of the components. Various methods like sliding mode controller[15-18], odd-harmonic repetitive controller[19] and dual-mode repetitive controller[20] are reported to obtain the dynamic response. RC controllers are reported to have slower dynamic response. The performance can be improved by introducing PI controller in parallel. This approach offers the advantages of both, the repetitive controller with excellent steady state characteristics and the PI controller with better dynamic performance.

2.1.3. State Feedback Controller:

The state feedback is another linear current controller which replaces synchronous PI controller. The current regulator works in either the stationary or synchronous rotating frames. Pole assignment approach is used to derive the feedback gains. The method can be applied to non-stiff sources where the grid voltage is distorted due to inverter switching[21].

2.1.4. Predictive and Deadbeat Controller

In this controller, the current error is predicted at the beginning of each of sample period T_s on the basis of the actual error and the converter interfacing parameters. The voltage vector to be generated by PWM during the next modulation period is thus determined, so as to minimize the current error[22]. The technique is promising and has better performances than the current PI regulators which suffer from tuning problems. In comparison to conventional hysteresis control with fixed hysteresis band, the performance of the predictive current control is better[12]. When the voltage vector is decided in such a way that current error becomes zero at the end of the sample period then this predictive control is known as the deadbeat control[22-24]. In conventional digital dead-beat controller, the regulator calculates the phase voltage to make the current error reduce to zero and so it phase current reach its reference by the end of the sample modulation period.

3. Nonlinear Current Control Method for Multilevel Voltage Source Inverter based Shunt Active Power Filter

The hysteresis current control has found popularity in the conventional two level and multilevel inverter based SAPFs. In addition to this, Fuzzy logic based current control and ANN based current control, One Cycle Control and Sliding Mode Control are also reported in literature. Due to popularity of hysteresis current control in multilevel inverters, various methods of multilevel HCC are discussed. The performance of HCC as applied to SAPF is evaluated under given conditions in PSIM® software.

3.1. Hysteresis Current Control

The method compares commanded currents of APF with actual currents on instantaneous basis. When the current error is more than the upper limit of hysteresis band, the upper switch of inverter leg is turned ON. Similarly, when the current error is less than the lower limit of band, the upper switch of inverter leg in turned OFF[11-14]. The hysteresis current controller is more preferable due to its advantage like simplicity in implementation, automatic peak current limitation, fast switching response to transient condition, independence from load parameter variation. Hysteresis current control is classified as two level hysteresis current control and multilevel hysteresis current control.

3.1.1. Hysteresis Current Control of two level inverter

In a two level inverter, the width of the hysteresis band depends upon the maximum permissible switching frequency of the switching devices used in the inverter and the highest permitted levels of current distortion. A lower band size increases the switching losses and a larger band size results in increased level of distortion in the current. Hence, the criteria for the selection of a hysteresis band size are crucial. Although, the conventional practice is to develop analog HCC[25], digital implementation of HCC[26] has also gained attention. The digital implementation facilitates the use of appropriate inverter voltage vector for given current error. This reduces the phase interference effect due to independent control of each leg of the inverter. Figure 3 shows simulation result for conventional two level SAPF with HCC technique, which consist of the current error trajectory and switching pulses for two level inverter[27-34].

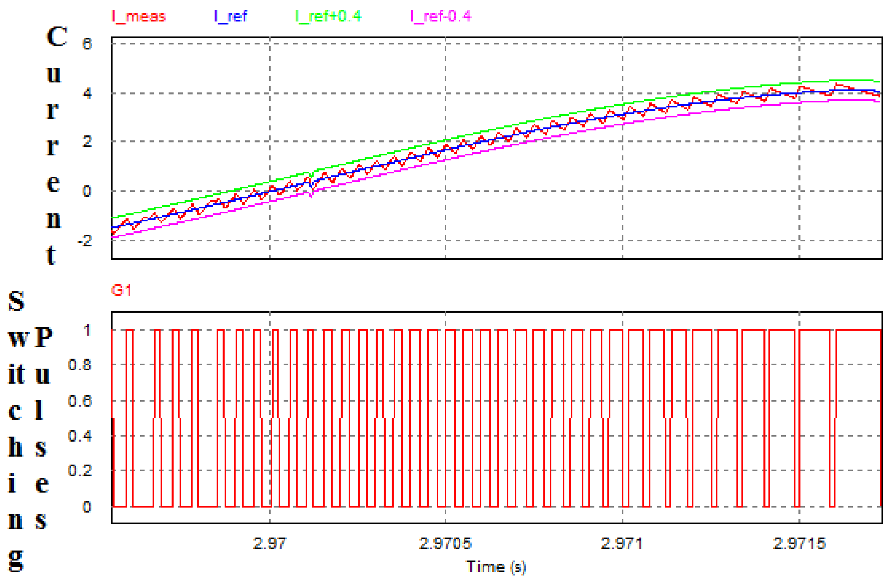


Figure 3 Hysteresis PWM for Two Level Inverter (a) Current error trajectory for one leg of SAPF (b) Switching Pulses

3.2. Delta Modulation Control

The delta modulation current control(DMC) is also based on ON-OFF control and hence the switching frequency is limited by the sampling frequency. In this method a constant voltage applied during the switching period and a variation of the hysteresis current regulator[12, 13]. This method is simple and easy for implementation. DMC was first implemented in single-phase PWM inverters which is reported in[35]. The performance of the delta modulation controller is inferior to HCC for APF application and results in higher THDs[14].

3.3. One Cycle Control

One-cycle Control(OCC) method has shown excellent capability in the harmonic suppression. It has a simple circuitry and robust performance with low cost for the control of three-phase active power filters. OCC is validated with controlled active power filters working with balanced line voltages and balanced nonlinear loads have reported in [36-38]. OCC has advantages of the nonlinear switching converters to achieve instantaneous dynamic control of the average value of a switched variable.

3.4. Sliding Mode Control

In Sliding Mode Control(SMC) algorithm, the compensating current supplied by the APF is controlled in such a way as to tract along a reference given by unity power factor condition at the PCC. The deviation of the actual trajectory from the reference trajectory is detected by the controller and correspondingly changes the switching strategy to restore the tracking[39, 40]. It is a kind of adaptive control which gives robust performance with parameter variation and requires no estimation.

3.5. Artificial Neural Network(ANN) basd Current Control

The ANN based current controller is a non-linear current controller. The main advantage of this method is its capability of the parallel processing and its own learning ability. This method is known for its robustness and generalization. The highest possible inverter switching frequencies is allowed in this method. Digital and Hybrid, analog/digital circuitry can be used in implementation of ANNs[41-45].

3.6. Fuzzy Logic(FL) based Current Control

FL based current controller is advanced technology controller which operates as an alternative of conventional PI controllers, where the PI controllers are self tuned by FL[44, 46] . The FL tuned PI controllers are used to implement for off-line operation. For reducing the tracking error as well as transient overshoot of the PWM current control a FL based current controller are used. The performance of the controller depends upon the design procedure. The dynamic performance can be improved by FL with hysteresis control[47]. FL controllers have some limitations like iteration and redundancy problems.

4. Hysteresis Current Control of Multilevel inverter based Shunt Active Power Filter

Multilevel hysteresis band current control method has been applied to multilevel inverter and is widely reported in[27-34]. These approaches are applied in SAPF application in[48, 49] and distribution static compensator(DSTATCOM) application in[50] This can be mainly classified as:

i. Multi-offset band multilevel hysteresis current control(MOBMH)
ii. Modified Multi offset band multilevel hysteresis current control(Modified MOBMH)
iii. Multiband multilevel hysteresis current control(MBMH)
iv. Time based multilevel hysteresis current control(TBMH)
v. Improved Time based multilevel hysteresis current control(improved TBMH)

4.1. Multi offset band multilevel hysteresis current control(MOBMH)

In MOBMH method the switching signals for inverter are derived from 3-level hysteresis current controller(in case of three level inverter). In contrast to two level hysteresis current control method where single band is used, three level hysteresis modulation employs two bands. There are $(n-1)$ bands for n level inverter and slight offset is provided between each band to get gate signals for switches of multi-level inverter. Figure 4(a) demonstrates the current error and switching states for inverter leg for a three level inverter. There are two

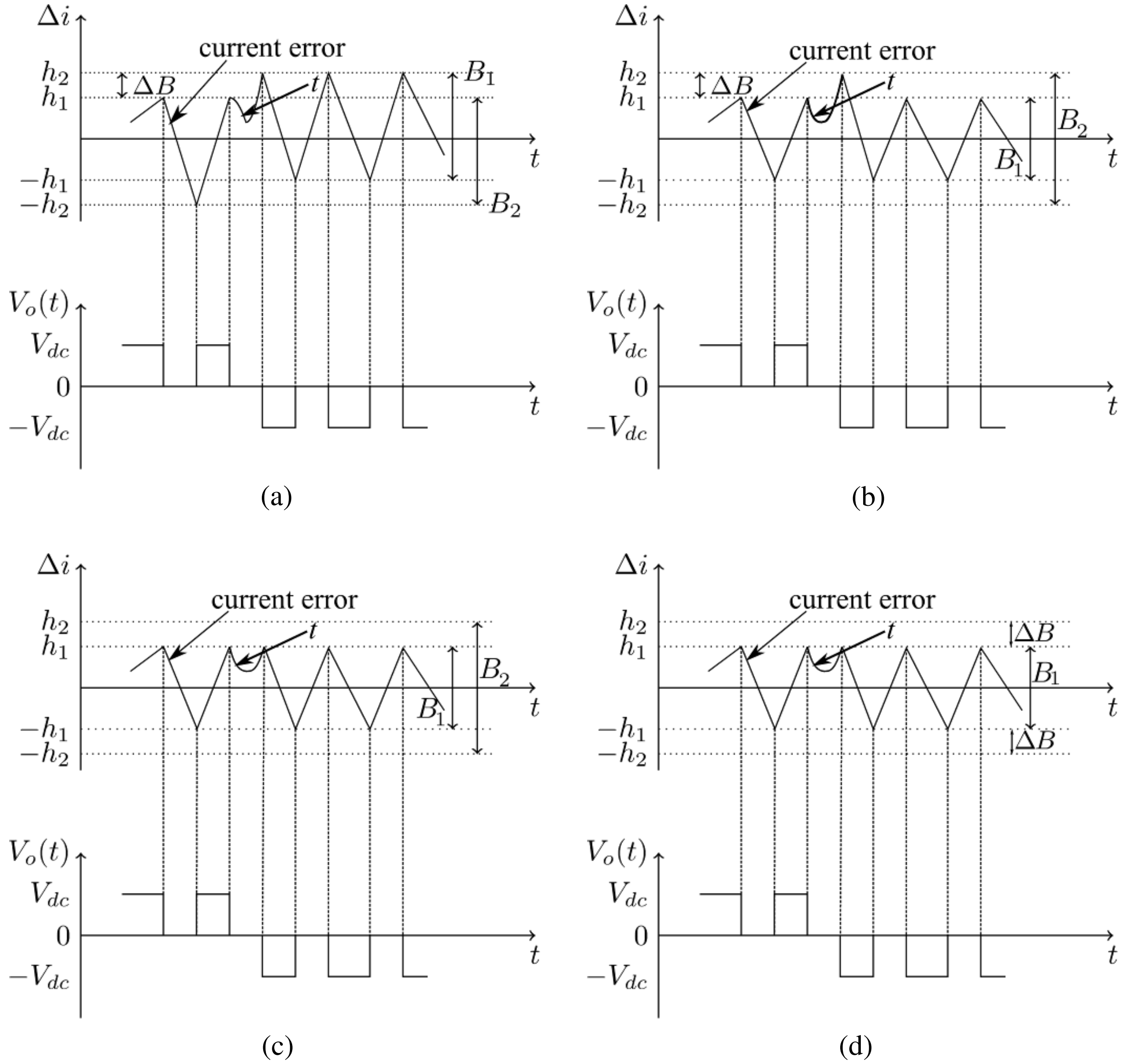


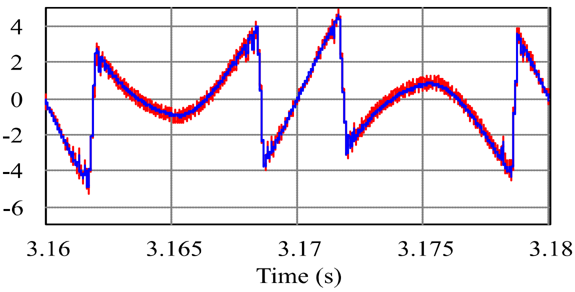
Figure 4 Various schemes of Hysteresis Band Current Control of Three Level Inverter (a) Multi Offset Band Multilevel HCC (MOBMH) (b) Multiband Multilevel HCC (MBMH) (c) Time based Multilevel HCC (TBMH) (d) Improved Time Based Multilevel HCC (Improved TBMH)

explicit bands B_1 and B_2 of current error with the offset of $\Delta B(h_2 - h_1)$ between them. Whenever current error signal crosses the outer most hysteresis band, then output of inverter should be set as positive voltage level or negative voltage level to impose an opposite for current error as shown in Figure 4(a)[33] [51-54].

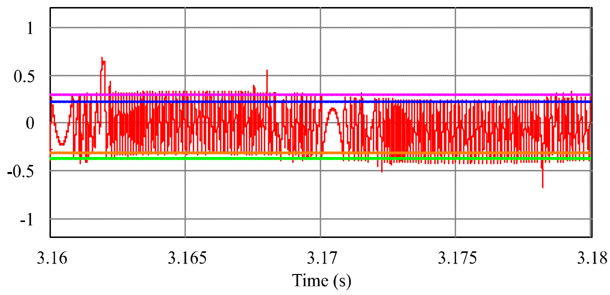
If current error signal reaches to the inner hysteresis band specified by $\pm h_1$, output of inverter attains zero voltage condition and consequently, current error will be forced to change the direction without reaching the outer band. In case, application of zero voltage vector does not force current error to change its direction (as shown with time t), the current error continues to increase and hits the outermost boundary. In such a case, the inverter output voltage polarity is reversed and it will reverse the current direction. The main disadvantage of this technique is that the bands are displaced by an offset and the current error remains in the particular band till next change in detected. This approach leads to steady state tracking error with respect to current error axis. To overcome this, an offset compensation strategy to ensure zero average current error within each switching period is required for improved performance. However, it requires complex analogue circuitry[33] [51-54].

Table 2 Hysteresis Current Control with two level inverter and three level inverter

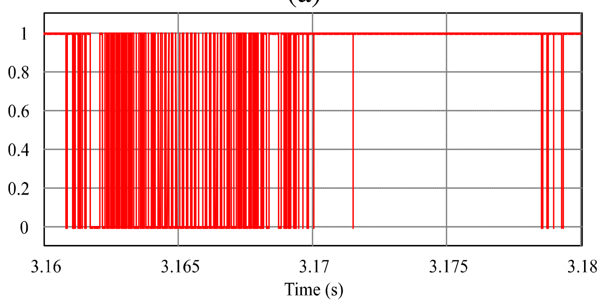
Inverter	% THD	Number Switching per Cycle	Switching Frequency in kHz
Two-Level Inverter	4.41	152	7.6
Three-Level Cascaded H-Bridge Inverter	3.38	76	3.8



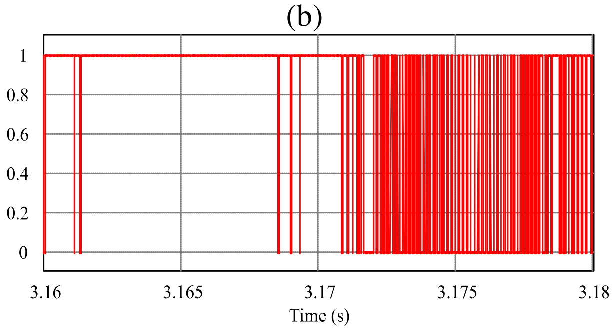
(a)



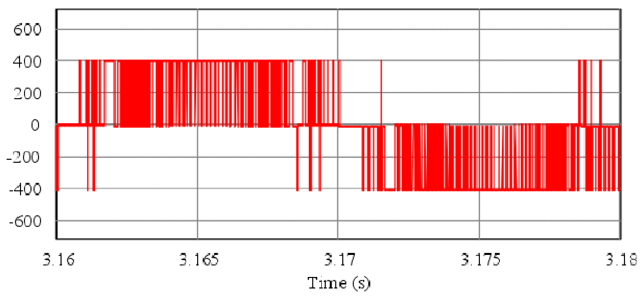
(b)



(c)



(d)



(e)

Figure 5 MOBMH method for Three Level CHB Inverter based SAPF (a) Compensating Current: Commanded and Actual (b) Current Error and Hysteresis Bands B_1 and B_2 (c) Gating Pulses for Upper switch of leg A (d) Gating Pulses for Upper Switch of leg B (e) Output Phase Voltage of CHB inverter

The simulation result with MOBMH method for three level CHB inverter based SAPF is demonstrated in Figure 5 which shows the current error trajectory and switching signals for one leg of inverter. In addition, a comparison of conventional two level HCC for 2-level inverter based SAPF and MOBMH technique based 3-level CHB inverter based SAPF is shown in Table 2 which indicates that the performance is improved with three level HCC.

As shown in Figure 5(a), the commanded current can be effective tracked using MOBMH method. The commanded current of SAPF is quite different than conventional applications where it is sinusoidal in nature. During commutation process of diode, the output current ceases to flow through the phase. This forces the commanded to current to change its magnitude as well as direction. Due to finite coupling inductance, the error crosses the other boundary at a particular instant. This results into opposite voltage vector selection. The phenomena can be well understood from Figure 5(b), (c) and (d). In Figure 5(e), inverter output voltage transits from positive voltage vector $+V_{dc}$ to negative voltage vector $-V_{dc}$. As soon as the current starts following the command value, its original state is attained.

4.2. Modified Multi offset band multilevel hysteresis current control(Modified MOBMH)

The limitation of MOBMH current control method is overcome by the modified MOBMH current control[33]. In this method, current error is bound between the two bands (B_1 and B_2). For reliable and robust control of the multilevel inverter, additional two offsets of the same width are placed out of bands. So, for n-level inverter, the offsets are required is $(n-2)$ in both the positive and negative current error area. The modified MOBMH current control is more advantageous than the MOBMH current control in which the current follows exact reference with a minimum change in the voltage[33, 54].

4.3. Multiband multilevel hysteresis current control(MBMH)

In this method, $(n-1)$ bands are placed symmetrically with respect to the zero error axis for n-level inverter. The current error is obtained by comparing reference and actual current for three level HCC as shown in Figure 4(b). For a three level inverter, an inner band B_1 and an outer band B_2 are used. If the current error last hits the lower limit of band B_2 then the band B_1 controls the switching between $+V_{dc}$ (lower limit of B_1) and 0V (upper limit of B_1). On the other hand, if upper limit of band B_2 has last exceeded, the band B_1 controls switching between 0V (lower limit of B_1) and $-V_{dc}$ (upper limit of B_1) [55, 56]. Figure 4(b) shows that the current error travel within band B_1 where it is assumed that the lower limit of band B_2 has last exceeded. The inverter switches between $+V_{dc}$ and 0V until time instant t where the zero inverter output is not sufficient to change the current error direction. The current error is increased and hits the upper limit of band B_2 which forces the inverter to switch to $-V_{dc}$ and changes the current error direction. The advantage of multi-band hysteresis current control is that the bands are symmetrical about the zero-current error axis. Therefore no dc tracking error is introduced into the average output current resulting into elimination of offset compensation circuitry[33, 53].

4.4. Time based multilevel hysteresis current control (TBMH)

In this method, the output voltage level is selected one after another and therefore the current error can be controlled through a single band. During the transient condition, the second band B_2 which is usually outer hysteresis band is optionally used to allow for extreme voltage levels switching. Time based logic is developed which checks if there is second occurrence of crossing of same boundary of band B_1. As it can be seen from Figure 4(c), when the inverter voltage vector does not change the direction of the current error after delay time t, next lower or higher voltage vector is switched. This forces inverter to reverse current error direction. For satisfactory operation under different loading conditions and smaller band size, suitable modification is required. The size of the main band depends on the level of current distortion permitted[57]. TBMH method does not create any steady state tracking error[33, 54, 58].

4.5. Improved Time based multilevel hysteresis current control (Improved TBMH)

With certain modifications, the performance of TBMH method can be further improved[59]. For n-level inverter, $(n-2)$ equidistant bands are introduced on either side of band B_1 (Figure 4(d)). These extra bands indicate that if the current error is within the main band and a certain voltage is switched at its boundary, the next voltage level will not be switched until the error touches outer band at the offset ΔB from the main band. In this method, vertical movement of current error is monitored to switch the next voltage level out of the main band. Similar to TBMH, it also considers delay time t for deciding the transition from one voltage level to another voltage level. The Improved TBMH current control method is discussed in detail[33, 54, 58, 60]. This method is also applicable to hybrid multilevel inverters[61]

The comparison of current control methods used for multilevel voltage source inverter based SAPF are given in Table 3.

Table 3 Comparison of Current Control Methods

Current Control Technique	Switching Frequency	Complexity	Speed of Response	Delay Time
PI Controller	Constant	Medium	Fast	No
Repetitive Control	Constant	Simple	Medium	Medium
Predictive Control	Constant	Medium	Medium	Long
Deadbeat Control	Constant	Complex	Medium	Medium
Hysteresis Current Control	Variable	Simple	Fast	No

Delta Modulation Control	Variable	Simple	Fast	No
One Cycle Control	Constant	Simple	Fast	No
Sliding Mode Control	Variable	Simple	Medium	No
Artificial Neural Network	Constant	Medium	Fast	Small
Fuzzy Logic	Constant	Medium	Fast	Small

5. Conclusion

The current controller plays crucial role in performance of Shunt Active Power Filter. Based on the performance requirement, it is desirable to select and employ appropriate current control technique. In this paper, the linear current control techniques such as PI control, Repetitive control, Predictive control and deadbeat control are explored. Owing to popularity of nonlinear current controller for SAPF applications, comprehensive study on Multilevel HCC methods such as Multi Offset Band Multilevel HCC, Multiband HCC, Time Based HCC and Improved Time based HCC for Multilevel inverter is presented. Advantages and limitation of each current control method for SAPF application are reviewed and compared. The simulation study for Multi Offset Band Multilevel HCC is carried out on three level CHB inverter to appreciate the applicability of HCC method in SAPF application.

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