Active Power Filter based on Cascaded Transformer Multilevel Inverter

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Abstract

The widespread increase of non-linear loads nowadays, significant amounts of harmonic currents are being injected into power systems. Active power filters (APF) have proved to be an interesting and effective solution to compensate current harmonics and reactive power in power distribution systems. In this paper, operation of APF based on asymmetric cascaded multilevel converter to compensate current harmonics, unbalance currents and reactive power in power distribution systems is discussed. Power quality improvement with proposed power electronic transformer has been verified by the simulation results with MATLAB/SIMULINK.

1. Introduction

The widespread increase of non-linear loads nowadays, significant amounts of harmonic currents are being injected into power systems. Harmonic currents flow through the power system impedance, causing voltage distortion at the harmonic currents' frequencies. The distorted voltage waveform causes harmonic currents to be drawn by other loads connected at the point of common coupling (PCC). The existence of current and voltage harmonics in power systems increases losses in the lines, decreases the power factor and can cause timing errors in sensitive electronic equipments. The use of grid connected power electronic converters to improve power quality in power distribution systems represents the best solution, in terms of performance and stability, for the elimination of harmonic distortion, power factor correction, balancing of loads, and voltage regulation. The most common example of this type of equipment is the active power filter (APF) which has two main configurations: the shunt connected active power filter is placed in parallel with a non-linear load (NLL) and controlled to cancel the current harmonics created by it; its dual, the series active power filter, is employed for voltage correction and is connected in line with the NLL [1-7].

The traditional method of current harmonics reduction involves passive LC filters, which are its simplicity and low cost. However, passive filters have several drawbacks such as large size, tuning and risk of resonance problems. On the contrary, the 4-leg APF can solve problems of current harmonics, reactive power, load current balancing and excessive neutral current simultaneously, and can be a much better solution than conventional approach. The three-phase four-wire system is now being widely used in different areas including industry, office and civil buildings and power supplies for cities and factories. This configuration results in problems with harmonics in addition to the potential unbalance of the three phases. Active power filters may be used to effectively compensate the harmonic and reactive power on a three-phase four-wire grid. In the former the fourth leg is used to compensate the neutral wire current directly [5].

One of the APF has been designed based on asymmetrical cascaded multilevel converter in recent years [7]. This type presents an active power filter implemented with multiple single-phase cells connected in series. Each cell is composed by a dc capacitor and a full–bridge single–phase PWM voltage–source inverter. The cascaded topology requires a separate dc-link capacitor for each cell, requiring a complex control strategy to regulate the voltage across each capacitor [8,9]. Recently cascaded transformer multilevel topology is proposed. Cascaded transformer multilevel has the advantage of having single storage capacitor for all its cells. Therefore, the dc voltage across each cell is equal. This topology has much significance for higher rated converters used for high or medium voltage distribution system, as they require transformers to increase the inverter output voltage at the distribution level [10, 11].

In this paper, we propose an APF based on cascaded H-bridge multilevel converter which employs one single dc input power source and isolated single-phase low-frequency transformers. By the proposed circuit configuration, a number of dc-link can be reduced, compared with traditional APF based on cascaded H-bridge multilevel converter. With this type of topology, higher voltage levels can be achieved, making the proposed topology suitable for compensation of medium and high voltage power distribution systems. A simple control scheme is used for the correct operation of inverter and compensation demands. The current reference required can be obtained allowing the generation of the total compensating current and the absorption of the needed active power to compensate converter losses and to keep the dc voltages constant. Simulated results carried out by Matlab/Simulink program for steady-state and transient operating conditions prove the compensation effectiveness of the proposed scheme.

2. Basic Configuration of Case Study

The basic configuration of case study is shown in Fig. 1. The APF is used to provide an effective current control. This APF generates the compensating currents to compensate the load currents, in order to guarantee sinusoidal, balanced, compensated currents drawn from the AC system. The circuit diagram of the three-phase four-wire active power filter with four-leg converter is presented in Fig. 1. The fourth leg is used to compensate the neutral wire current while legs 1, 2 and 3 generate the compensation currents for phases A, B and C, respectively. The basic principle of a shunt active power filter is shown in Fig. 1 as:

$$I_C = I_S - I_L \qquad (1)$$

Where I_C is the compensation input current, I_S is the source current and I_L is the load current, respectively. The main feature of the APF is that the supply current is forced to be sinusoidal and in phase with the supply voltage regardless of the characteristics of the load. Therefore, the shunt APF is harmonics cancellation and reactive power compensation by injecting equal but opposite harmonic and reactive currents into the supply line by means of solid-state amplifier circuits. The APF shown in Fig. 1 may be described as a synchronous rectifier that is connected to a dc-link. In recent years, there has been an increasing interest in using multilevel inverters for high power energy conversion, especially for drives and reactive power compensation. In this paper asymmetric cascaded transformer multilevel converter with single dc-link has been used. This converter has four leg. Four H-bridge modules are connected to the same dc input source in parallel, and each secondary of the four transformers is connected in series. In this configuration, the output voltage becomes the sum of the terminal voltages of each H-bridge module. The amplitude of the output voltage is determined by the input voltage and turn ratio of the transformer. To provide a large number of output steps without increasing the number of DC voltage sources (or transformers), asymmetric multilevel converters (AMC) can be used. The DC voltage sources are proposed to be chosen according to a geometric progression with a factor of two or three. In AMC based on a geometric progression with a factor of two (Binary), all the partial asymmetry factors are equal to two, and the total asymmetry factors are given by a geometric sequence with a factor of two. Another asymmetrical approach is to choose the total asymmetry factors in a geometric progression with a factor of three [8, 9]. In this paper, the partial asymmetry factors are equal to three.

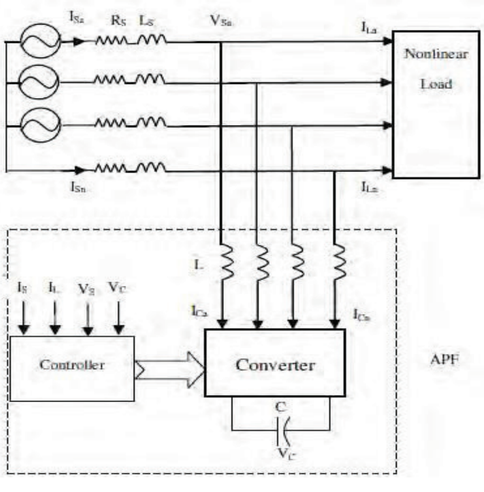

Fig. 1. Basic configuration of case study

One leg of this converter is shown in Fig. 2. It consists of asymmetric cascaded multilevel converter configuration, in multilevel converter with anti-parallel diodes connected to each switch to provide a mechanism for bi-directional flow of compensation current to be either absorbed from or injected into the supply system. The purpose of the filter inductor, L is to regulate the maximum allowable magnitude ripple current flow into the APF, by means of closed-loop control. A proper design of the controller has to be established in order to actively shape the supply current to a sinusoid wave shape.

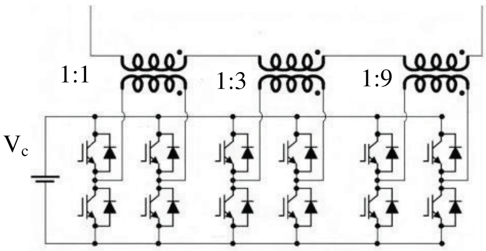

Fig.2. One leg of cascaded transformer multilevel converter

3. Control System

Many control methods are presented for control of input stage in APF, which could be used in proposed system [1-7].The quality and performance of the APF depend mainly on the method implemented to generate the compensating reference currents. This paper presented a method to get the reference current, which is key issue in the control of the APF [1, 2].

The basic operation of this proposed control method is shown in Fig. 1 and equation 1. The three-phase compensating reference current of APF are estimated using reference supply currents and sensed load currents. The compensating currents of APF are calculated by sensing the load currents, dc-link voltage, peak voltage of AC source (Vsm) and zero crossing point of source voltage. The last two parameters are used for calculation of instantaneous voltages of AC source as below:

$$\begin{aligned} V_{Sa} &= V_{Sm}\sin(\omega t) \\ V_{Sb} &= V_{Sm}\sin(\omega t - 2\pi/3) \\ V_{Sc} &= V_{Sm}\sin(\omega t + 2\pi/3) \end{aligned} \qquad (2)$$

The basic function of the proposed shunt APF is to eliminate harmonics and compensation of current unbalance and reactive power of load. After compensating the AC source feeds fundamental active power component of load current and loses of inverter for regulating the DC capacitor voltage. Therefore the peak of source reference current (Ism*) has two components. The first component is corresponding to the average load active power (Ismp*). In order to compensating the current harmonics and reactive power of load the average active power of AC source must be equal with average power of load. With considering the unity power factor for AC source side currents the average active power of AC source can be calculated as bellow:

$$P_s = \frac{3}{2} V_{sm} I_{smp}{}^* = P_{Lav} \qquad (3)$$

From this equation, the first component of AC side current can be obtained and named Ismp*. Fig. 3 shows system that calculates Ismp*.

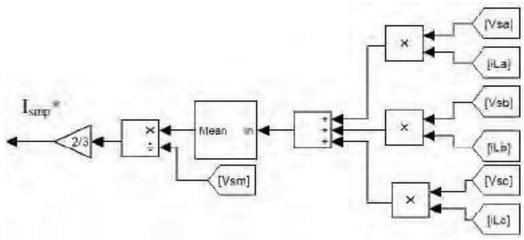

Fig.3. Calculation of Ismp*

The second component of AC source current (Ismd*) is obtained from DC capacitor voltage regulator as Fig. 4.

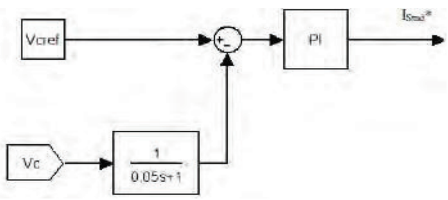

Fig.4. DC –link voltage regulator

The AC source currents must be sinusoidal and in phase with source voltages. Therefore the desired currents of AC source can be calculated with multiplying peak source current to a unity sinusoidal signal. The desired source side currents can be obtained from system that is shown in Fig. 5. The desired value for natural line current is zero.

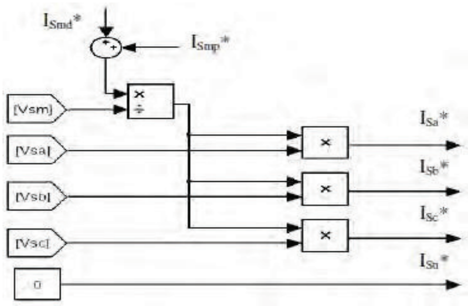

Fig.5. Desired source side currents

The reference currents of APF can be obtained as equation 4.

$$
\begin{aligned}
i_{ca}* &= i_{sa}* - i_{La} \\
i_{cb}* &= i_{sb}* - i_{Lb} \\
i_{cc}* &= i_{sc}* - i_{Lc}
\end{aligned}
\qquad (4)
$$

The reference signals (REF_A, REF_B, REF_C and REF_N) for converter switching are obtained from comparison between reference currents of APF and currents of APF. Calculation of signals for multilevel converter switching is shown in Fig. 6.

The control of the multilevel converters is to choose a series of switching angles to synthesize a desired sinusoidal voltage waveform. Several modulation strategies have been proposed for multilevel converters. Among these methods, the most common used is the multi-carrier sub-harmonic pulse width modulation (PWM). The principle of the multi-carrier PWM is based on a comparison of a sinusoidal reference waveform, with vertically shifted carrier (triangular or direct line) waveforms [8,11]. In this paper we use a closed loop multi-carrier PWM technique for tracking the computed currents by APF.

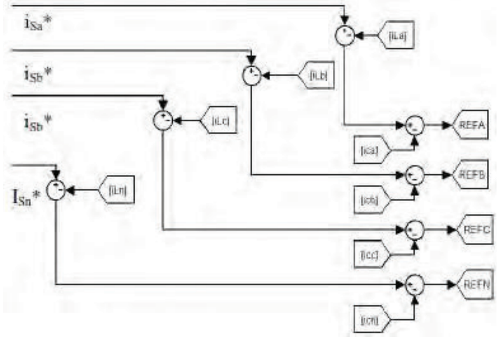

Fig.6. Calculation of signals for multilevel converter switching

4. Simulation Results

A number of simulation results with different operating conditions were developed. In Fig. 1, APF is connected in parallel with nonlinear load. Then, the three-phase controlled rectifier with RL load has to be compensated by the APF.

Table 1 shows the case study parameters. The nonlinear load configuration is described in Fig. 7.

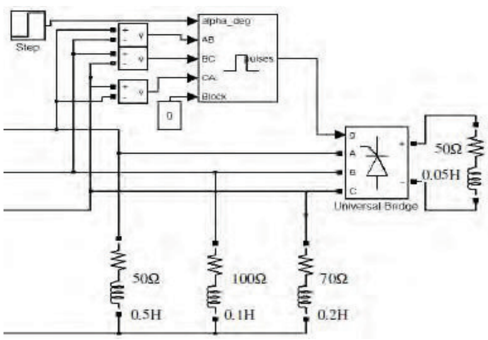

Fig.7. The configuration of nonlinear load

Since the compensation of the APF depends upon the firing angle (α) of the rectifier, two operative conditions have been considered. The rectifier is the first case when α =0, while the second one is the controlled rectifier with firing angle α =90^{O}.

Table 1. Parameters of case study

Parameters	Value
Input line voltage	4160 V
Rs, Ls	0.5 Ω, 3 mH
Power frequency	50 Hz
transformer	50 Hz, 250 kVA
L, C	2 mH, 1000 µF

4.1. Simulation with Firing Angle α =0

The simulation results in steady state operation are presented. Fig. 8 shows the performance of the APF system using PI controller. Current of the non linear load is shown in Fig. 8(a). Fig. 8(b) shows the APF current. APF current consists of harmonic compensation current. Supply current is shown in Fig. 8(c) that is sinusoidal and balance current. Fig. 9 shows the supply and non linear load current superimposed to the supply voltage or power factor correction is shown in this figure. Fig. 10(a) reveals the harmonic spectrum of load current. Fig. 10(b) describes the harmonic spectrum of supply current. It can be observed from the harmonic spectrum of currents that, presented structure is effective to obtain desired harmonic level.

4.2. Simulation with firing angle α =90°

The simulation results in case of steady state operation with static load when α =90o are presented. Fig. 11 shows the simulation waveforms of the non linear current, the APF current and the supply current. The non linear current is unbalanced. APF injects current to balance supply current. These results show that supply currents always remain sinusoidal and balanced. Supply and non linear load current superimposed to the supply voltage (power factor correction) are shown in Fig. 12. From this figure it can be seen that the voltage and current are in phase. Therefore, this figure describes the proper power factor compensation by presented system. The presented simulation results show the validity and effectiveness of presented structure system in power quality improvement by parallel operation of APF to compensate current harmonics, unbalance currents and reactive power in power distribution systems. The source current and neutral wire current waveforms after compensation by the four-leg APF are shown in Fig. 14. a neutral wire current after compensation equal to approximately zero.

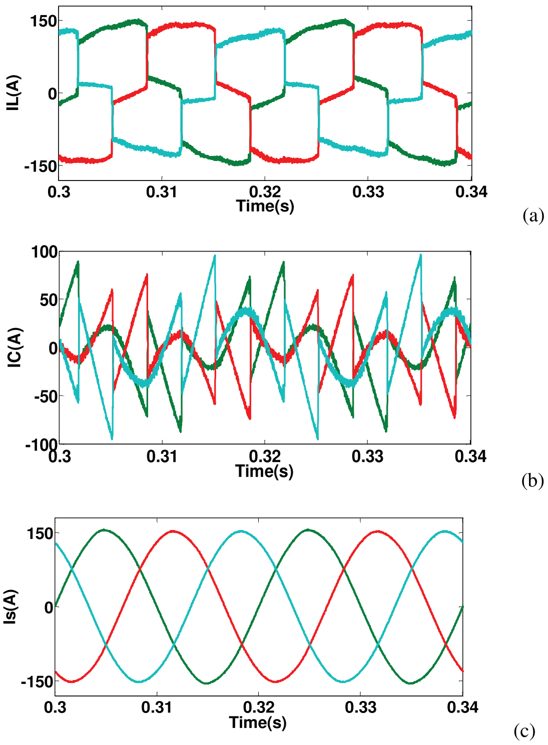

Fig.8. (a) Non linear load current (b) APF current and (c) supply current

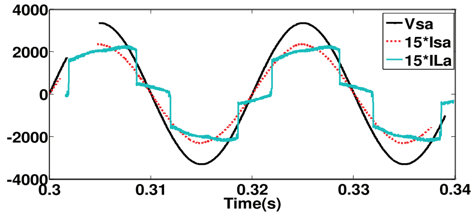

Fig.9. Supply and non linear load currents superimposed to the supply voltage

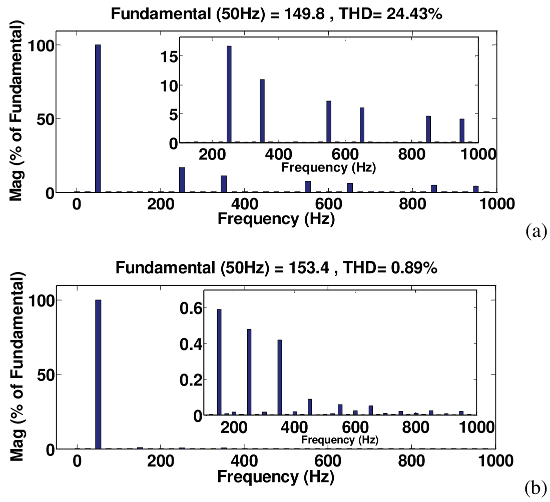

Fig.10. (a) Harmonic spectrum of load current and (b) Harmonic spectrum of supply current

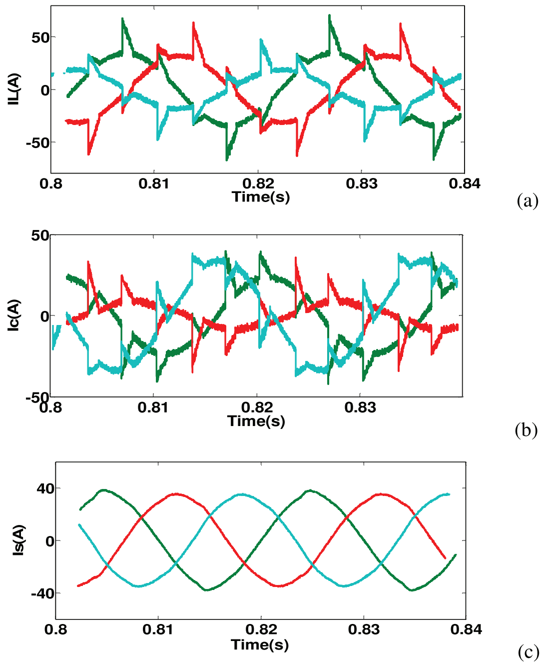

Fig.11. (a) Non linear load current (b) APF current and (c) supply current

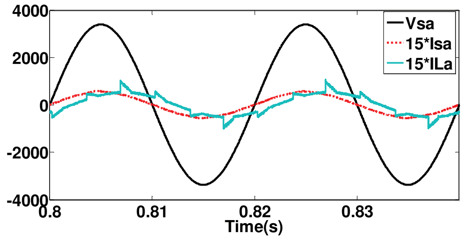

Fig.12. Supply and non linear load current superimposed to the supply voltage

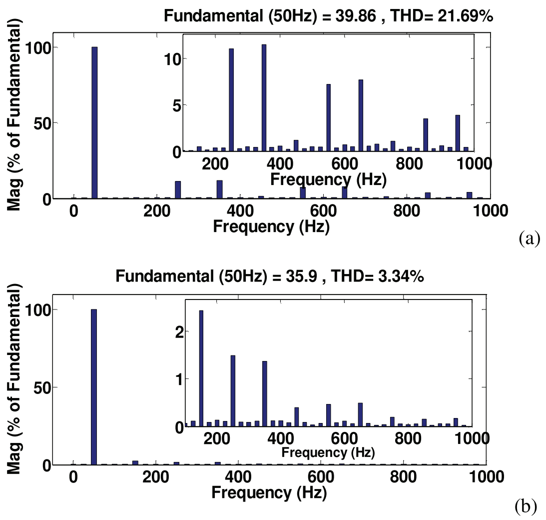

Fig.13. (a) Harmonic spectrum of load current and (b) Harmonic spectrum of supply current

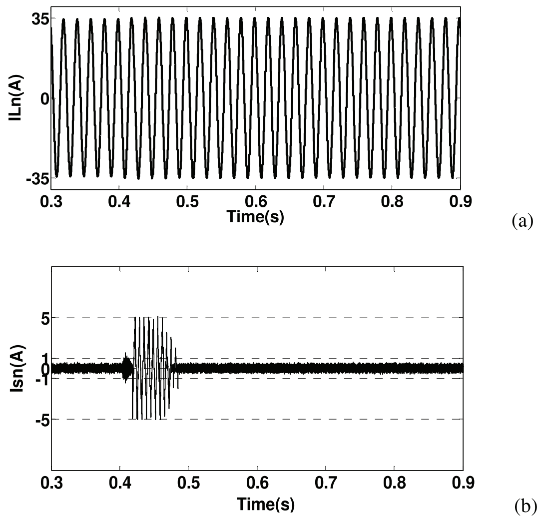

Fig.14. (a) Neutral wire current waveform and (b) Neutral wire current waveform after compensating

6. Conclusions

In this paper an active power filter based on 27- levels multilevel cascaded transformer voltage source inverter has been presented. The principal advantage of the proposed scheme is the straight forward application in medium and high voltage power distribution systems. This structure has one dc-link and control is easy. A simple control system has been proposed and analyzed. Compensating current harmonics, reactive power and current unbalance of nonlinear loads by parallel operation of active power filter have been shown in this paper. Simulation results show the validity and effectiveness of presented active power filter for compensation of harmonic currents, reactive power and unbalance currents.

7. References

[1] A. Ajami and S. H. Hosseini, "Implementation of a Novel Control Strategy for Shunt Active Filter," ECTI TRANSACTIONS ON ELECTRICAL ENG., ELECTRONICS, AND COMMUNICATIONS. Vol.4, No.1, pp. 40-46, February 2006.

[2] M. Ghandchi, A. Ajami and M. Moeini, "A Simple and Low Cost Control Strategy for Multilevel Shunt Active Filters," in Proceeding of International Conference on Control, Automation and Systems 2008 in COEX, Seoul, Korea. pp. 14-17, October 2008.

[3] P. Zanchetta, M. Sumner, M. Marinelli and F. Cupertino, "Experimental modeling and control design of shunt active power filters," Control Engineering Practice, Vol.17, pp. 1126 – 1135, May 2009.

[4] M.George, K. P. Basu, "Three-Phase Shunt Active Power Filter," American Journal of Applied Sciences, Vol. 5, No. 8,pp. 909-916, 2008.

[5] M.C. Benhabib, S. Saadate, " New control approach for four-wire active power filter based on the use of synchronous reference frame", Electric Power System Research, Vol.73 , pp. 353–362, 2005.

[6] C. Yanbo, Z. Fudan, K.W. E. Cheng, "Shunt Active Power Filter – SIMULINK Simulation and DSP-based Hardware Realization," in Proceeding of 2006 2nd International Conference on Power Electronics Systems and Applications, pp. 120-125, 2006.

[7] G. Zhoua, B. Wub, D. Xuc, "Direct power control of a multilevel inverter based active power filter", Electric Power System Research, Vol.77 , pp. 284–294, 2007.

[8] J. S. Manguelle, S. Mariethoz, M. Veenstra , A. Rufer, "A generalized design principle of a uniform step asymmetrical multilevel inverter for high power conversion", in Proceeding of EPE Rec., 2001, CD-ROM.

[9] C. Rech, H. Pinheiro, H. A. Gründling, H. L. Hey, J. R. Pinheiro, "Analysis and comparison of hybrid multilevel voltage source inverters", in Proceeding of IEEE PESC Conf. Proc., pp. 491–496,2002.

[10] E. Barcenas, S. Ramirez, V. Cardenas, R. Echavarria, "Cascaded multilevel inverter with only one dc source ", in Proceeding of VIII IEEE Inter. Tech. Proc. CIEP, pp. 171-176, 2002.

[11] S.J. Park, F.S. Kang, S.E. Cho, C.J. Moon, H.K. Nam, " A novel switching strategy for improving modularity and manufacturability of cascaded transformer based multilevel inverters", Electric Power System Research, 74 (3) , pp.409–416, June 2005.