Grid Active Power Filters using Cascaded Multilevel Inverters with Direct Asymmetric Switching Angle Control for Grid Support Functions

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***Abstract*—This paper presents a new control technique for cascaded multilevel inverters, which can achieve harmonic and reactive power compensation and balance unbalanced load simultaneously. Unlike existing control strategies which work in the time domain and focus on reducing the overall harmonics and reactive power without differentiating individual harmonics, this new method works in the frequency domain and can efficiently compensate individual harmonics and reactive power apart from balancing unbalanced load. The principle of the proposed technique is to compensate harmonics and reactive power and balance unbalanced load with direct asymmetric firing angle and conduction angle control for each H-bridge of multilevel inverter. To verify the effectiveness of this new technique, genetic algorithm (GA) is used to solve transcendental equations and find switching angles of each H-bridge of multilevel inverter. From the simulation results, it can be seen that the proposed technique can not only achieve the same harmonic and reactive power compensation performance with a much lower switching frequency than traditional control methods of cascaded multilevel inverter based active power filter (APF), but also can balance unbalanced loads successfully at the same time.**

I. INTRODUCTION

Nowadays, non-linear components such as diodes/ thyristors, current/voltage source converters, switched mode power supplies and motor drives are very popular in power systems. They generate lots of harmonics and reactive power which greatly degrade power quality [2]. In addition, the presence of large industrial unbalanced loads such as single phase traction systems, electrical furnaces and welding machines can also produce significant current and voltage distortion in power system [11]. There are several deleterious effects of high distortion in the current or voltage waveform and a poor power factor. They increase power loss, cause vibrations and noise in motors and malfunction and failure of sensitive equipments etc [2], [9]. Harmonic currents may also cause resonance between the shunt capacitor and the series inductance of the distribution and transmission lines [9]. Due to these reasons, several limits have been placed on both the consumers and the utilities, such as IEEE-519 [9]. Traditionally, passive filters have been used to compensate harmonics and reactive power, but passive filters are large in size, have aging problems and may resonate with the supply impedance [2]. On the other hand, as more industrial and commercial applications need medium and high voltages, such as the superfast charging station mentioned in reference [5], the implementation of passive filters become harder.

Due to these reasons, multilevel inverter based active power filters, which have the ability to synthesize high voltage with low voltage components, have been designed to compensate harmonics and suppress reactive power simultaneously and numerous control techniques have been proposed by many researchers [1-8]. According to the current reference's generation methods, these control methods of multilevel inverter based APFs can be categorized into ABC-frame current reference generation [1], [6], DQ-frame current reference generation [2], [4], [7] and prediction based current reference generation [8]. ABC-frame reference current generation obtains the reference current based on the currents and voltages in the ABC-frame. DQ-frame current reference generation transforms the ABC-frame current and voltage into the DQ-frame and acquires current reference based on D component and Q component of currents, which is a linear algorithm and is easier to model than the ABC-frame [7]. The prediction based current reference generation proposed in [8] can eliminate the delay inherent in the previous two current reference identification schemes which is caused by performing the digital control algorithm and sampling the measurement signal.

While these control techniques can compensate harmonics and reactive power to some extent, they suffer from several drawbacks. The first one is they can only reduce overall

This work is supported by National Science Foundation.

harmonics and reactive power, but have no control on specific order of harmonics. The second one is only at high switching frequency, can the performance of these control methods be ensured. However, a high switching frequency will increase switching loss and complicate thermal management of the system, especially in high voltage and high power density applications. Additionally, while most of these techniques can compensate harmonics and reactive power simultaneously, few of them can also balance unbalanced loads at the same time.

This paper proposes a new control strategy to control the firing angle and conduction angle of each H-bridge of multilevel inverters. Instead of working in the time domain, this technique works in the frequency domain. Based on the active, reactive and individual harmonic currents drawn by the loads, the firing angle and conduction angle of each H-bridge of multilevel inverters can be derived. By working in the frequency domain, this new technique can control specific order of harmonics to ensure they are in accordance with standards. Also, compared with conventional methods, this new technique can achieve the same compensation effect with a much lower switching frequency, which will greatly reduce switching loss of multilevel inverters. Additionally, unbalanced load can also be balanced with this novel control strategy.

Section II of this paper explains the theory behind this new control technique. Section III introduces genetic algorithm (GA) and shows how to use GA to find firing angles of multilevel inverters. Section IV gives simulation results which include a balanced case, an unbalanced case and a comparison of this new control technique with a control method which uses a similar prediction based current reference generation method to the one proposed in reference [8]. The simulation results validate the proposed technique and its superiority over conventional time domain control techniques.

II. DIRECT ASYMMETRIC SWITCHING ANGLE CONTROL OF MULTILEVEL INVERTER

A. *Fourier Series of Voltage Synthesized by Multilevel Inverter*

Fig. 1 shows one phase of a cascaded multilevel inverter, which is composed of m series connected single phase H-bridges. It is modular in nature and can be easily extended to any required number of levels. The separated dc sources may be obtained from batteries, solar cells, ultra-capacitors or high frequency, isolated converters. Each H-bridge can generate three different voltages, $+V_{dc}$, 0 and $-V_{dc}$, as shown in Fig. 2.

The Fourier series of the waveform in Fig. 2 is:

$$v(t) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty}(a_n \cos(\omega_n t) + b_n \sin(\omega_n t)) \tag{1}$$

where ω_n is $n\frac{2\pi}{T}$, a_n and b_n are:

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(\omega t)\cos(n\omega t)d\omega t \tag{2}$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(\omega t)\sin(n\omega t)d\omega t \tag{3}$$

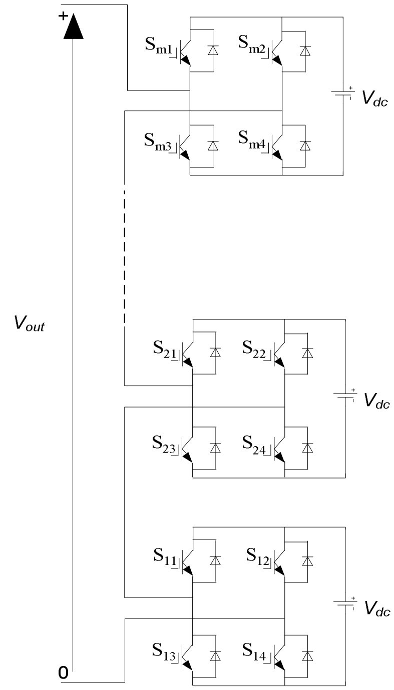

Fig.1 Topology of a cascaded multilevel inverter in one phase

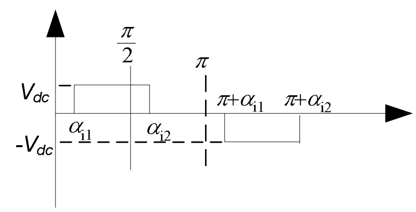

Fig.2 The output voltage waveform of ith H-bridge

It should be pointed out that α_{i1} and α_{i2} in Fig. 2 are asymmetrical to $\pi/2$. However, since the waveform is rotationally symmetric to (π, 0), all even-numbered a_{n_i} and b_{n_i} are zero, and odd-numbered a_{n_i} and b_{n_i} can be expressed as

$$a_{n\_i} = \frac{2V_{dc}}{n\pi}[\sin(n\alpha_{i2}) - \sin(n\alpha_{i1})] \tag{4}$$

$$b_{n\_i} = \frac{2V_{dc}}{n\pi}[\cos(n\alpha_{i1}) - \cos(n\alpha_{i2})] \tag{5}$$

where $0<\alpha_{i1}, \alpha_{i2}<\pi$.

Since there are m H bridges in Fig.1, the odd-numbered a_n and b_n for the total output voltage of the cascaded multilevel inverter are:

$$a_n = \sum_{i=1}^{m}\frac{2V_{dc}}{n\pi}[\sin(n\alpha_{i2}) - \sin(n\alpha_{i1})] \tag{6}$$

$$b_n = \sum_{i=1}^{m}\frac{2V_{dc}}{n\pi}[\cos(n\alpha_{i1}) - \cos(n\alpha_{i2})] \tag{7}$$

B. Principle of the Proposed Control Method

Fig. 3 shows a power system with an APF using a three-phase cascaded multilevel inverter. Z_{grid} and Z_{comp} represent the impedance between grid and the point of common coupling (PCC) and the impedance between APF and PCC respectively.

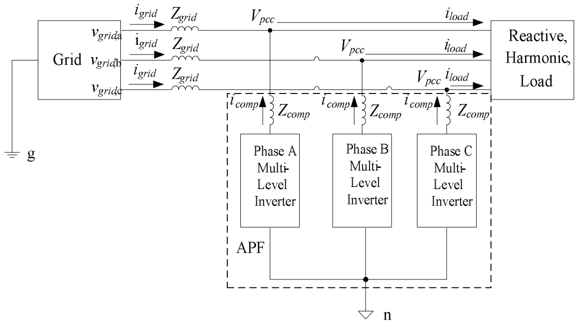

Fig. 3 Topology of a power system with a cascaded multilevel inverter as active power filter

This control technique is based on the assumption that the load current of adjacent fundamental cycles is the same in steady state. From the sensed current drawn by the load, i_{load} of last cycle; the active current, i_{act}, reactive current, i_{ract}, and harmonics current, i_h, can be derived through Fourier analysis. If the system is balanced, to compensate reactive power and harmonics, the grid needs to provide the active current ($i_{grid}=i_{act}$) and APF should provide the reactive and harmonic current ($i_{comp}=i_{ract}+i_h$). Based on the grid voltage, V_{grid}, the active current that needs to be provided by the grid, i_{act}, and the grid impedance, Z_{grid}; the PCC voltage (V_{pcc}) can be expressed as

$$V_{pcc} = V_{grid} - i_{act} Z_{grid} \tag{8}$$

Then the voltage reference of fundamental frequency for the multilevel inverter $V_{1\_reference}$ can be derived from V_{pcc}, i_{ract} and Z_{comp}, as equation (9) shows.

$$V_{1\text{-}reference} = V_{pcc} + i_{ract} Z_{comp} \tag{9}$$

If the grid only provides active current, i_{act}, V_{pcc} only has the fundamental frequency component. Therefore, the voltage references for the multilevel inverter to compensate each order of harmonics, $V_{n\_reference}$ (n>1) can be obtained based on i_{h_n} and Z_{comp}, which can be seen from equation (10).

$$V_{n\text{-}reference} = i_{h\text{-}n} Z_{comp} \tag{10}$$

After the voltage reference, $V_{reference}$, for the multilevel inverter is obtained, $a_{n\_reference}$ and $b_{n\_reference}$ for the multilevel inverter can be acquired from $V_{reference}$. Since the system is balanced, triple-n orders of harmonics are zero. Therefore, the harmonics to be mitigated are odd, non-triple-n harmonics (5, 7, 11, 13, 17·····). To remove low order harmonics and compensate reactive currents, a_n and b_n generated by the multilevel inverter should equal $a_{n\_reference}$ and $b_{n\_reference}$. Thus, the firing angles α_{i1} and α_{i2} of each H-bridge in the cascaded, multilevel inverters are given by equation (11).

$$\begin{aligned}
&\frac{2V_{dc}}{\pi}\left[\sin(\alpha_{12})-\sin(\alpha_{11})+\sin(\alpha_{22})-\sin(\alpha_{21})\cdots\sin(\alpha_{m2})-\sin(\alpha_{m1})\right]=a_{1-reference}\\
&\frac{2V_{dc}}{\pi}\left[\cos(\alpha_{11})-\cos(\alpha_{12})+\cos(\alpha_{21})-\cos(\alpha_{22})\cdots\cos(\alpha_{m1})-\cos(\alpha_{m2})\right]=b_{1-reference}\\
&\frac{2V_{dc}}{5\pi}\left[\sin(5\alpha_{12})-\sin(5\alpha_{11})+\sin(5\alpha_{22})-\sin(5\alpha_{21})\cdots\sin(5\alpha_{m2})-\sin(5\alpha_{m1})\right]=a_{5-reference}\\
&\frac{2V_{dc}}{5\pi}\left[\cos(5\alpha_{11})-\cos(5\alpha_{12})+\cos(5\alpha_{21})-\cos(5\alpha_{22})\cdots\cos(5\alpha_{m2})-\cos(5\alpha_{m1})\right]=b_{5-reference}\\
&\vdots
\end{aligned} \tag{11}$$

In equation (11), the left side is the voltage references for the multilevel inverter in the frequency domain and the right side is the voltages synthesized by the multilevel inverter, which are also in the frequency domain. As equation (11) shows, since the references and actual value for the fundamental component and each order of harmonics are separated, reactive power and each order of harmonics can be controlled individually. Ideally, if the exact solution of equation (11) can be found, the low order harmonics and reactive current can be eliminated and the highest order that can be eliminated is a function of m. For a balanced, three phase system, if m is odd, this order is (3m-2); if m is even, then the order is (3m-1).

If the system is unbalanced, the control principle is similar to the balanced case. However, there are two differences between balanced case and unbalanced case. The first one is the active currrent, reactive current and harmonics current drawn by the loads are different between the three phases. To balance the system, the active current that the grid need to supply should be first chosen, which is the same for the three phases. Then, $a_{n\_reference}$ and $b_{n\_reference}$ can be derived using a similar method as balanced case. However, since the reactive and harmonics current drawn by the loads of the three phases are different, the calculated voltage reference $a_{n\_reference}$ and $b_{n\_reference}$ for the multilevel inverter are different for different phases. Thus, they need to be calculated separatedly. In addition, since the system is unbalanced, triple-n orders of harmonics are non-zero, which should also be taken care of. Thus, the harmonics that need to be mitigated in the unbalanced case are all odd harmonics. Equation (12) shows how to compute the firing angles α_{i1} and α_{i2} of each H-bridge in the cascaded multilevel inverters of phase A. For the other two phases, only the voltage reference need to be changed and equation (12) can still be applied. From equation (12), it can be see that the highest order of harmonics the cascaded multilevel inverter can compensate is (2m-1) in unbalanced case.

$$\begin{aligned}
&\frac{2V_{dc}}{\pi}\left[\sin(\alpha_{12})-\sin(\alpha_{11})+\sin(\alpha_{22})-\sin(\alpha_{21})\cdots\sin(\alpha_{m2})-\sin(\alpha_{m1})\right]=a_{1-reference_a}\\
&\frac{2V_{dc}}{\pi}\left[\cos(\alpha_{11})-\cos(\alpha_{12})+\cos(\alpha_{21})-\cos(\alpha_{22})\cdots\cos(\alpha_{m1})-\cos(\alpha_{m2})\right]=b_{1-reference_a}\\
&\frac{2V_{dc}}{3\pi}\left[\sin(3\alpha_{12})-\sin(3\alpha_{11})+\sin(3\alpha_{22})-\sin(3\alpha_{21})\cdots\sin(3\alpha_{m2})-\sin(3\alpha_{m1})\right]=a_{3-reference_a}\\
&\frac{2V_{dc}}{3\pi}\left[\cos(3\alpha_{11})-\cos(3\alpha_{12})+\cos(3\alpha_{21})-\cos(3\alpha_{22})\cdots\cos(3\alpha_{m2})-\cos(3\alpha_{m1})\right]=b_{3-reference_a}\\
&\vdots
\end{aligned} \tag{12}$$

In the balanced case, if the grid current is equal to the active current drawn by the load, the net power flowing into or out of the APF is zero, and no power flows into or out of a given phase. In the unbalanced case, if the average value of the active current of the three phases drawn by the load is chosen as the active current the grid need to supply, the net power flowing into the APF is still zero while there is a certain amount of power flows into or out of a given phase of the APF. However, the grid current in both balanced and unbalanced cases can be intentionally manipulated to effect a net power flow into or out of the APF. For example, if the maximum active curent of the three phases drawn by the load are chosen as the current that the grid need to supply, then there will be active power flows into the APF of the other two phases with smaller active current drawn by the load. As a result, this technique can also be used to integrate renewable sources such as photovaltaics and wind turbines to the grid while still provide grid support functions.

III. Implementation of Genetic Algorithm

Because the equations in (11) and (12) are transcendental, conventional numerical techniques are not effective because of the large number of unknown variables, multiple local optima and the difficulty in finding good initial values. In this case, genetic algorithm (GA) can overcome the limitations of conventional methods and find the firing angle and conduction angle of each H-bridge in the cascaded multilevel inverters.

GA is a technique inspired by the mechanisms of natural evolution, where individuals are constantly changing in a competing environment in order to survive [13], [14]. It assumes that any potential solution of one problem can be represented by a set of parameters, which are regarded as genes of a chromosome and can be coded as a population of strings. A fitness value, which is positive and highly related with its objective function, is used to reflect the "goodness" of the chromosome. Through generations, it is expected that the quality of the population will tend to improve and the solution of the problem will be optimized [14].

In this application, the chromosomes represent the potential solutions of the switching angles, and each chromosome has a certain number of genes, corresponding to the firing angle and conduction angle of each H-bridge in the multilevel inverter. If the system is balanced, the objective function can be defined as (13) or (14) based on whether the number of H-bridge in the cascaded multilevel inverter is even or odd.

$$\begin{aligned} F_{obj} &= C_1(|a_{1-reference} - a_1| + |b_{1-reference} - b_1|) + C_2(|a_{5-reference} - a_5| + |b_{5-reference} - b_5|) + \cdots \\ &+ C_m(|a_{3m-1-reference} - a_{3m-1}| + |b_{3m-1-reference} - b_{3m-1}|) \quad (m \text{ is even}) \end{aligned} \tag{13}$$

$$\begin{aligned} F_{obj} &= C_1(|a_{1-reference} - a_1| + |b_{1-reference} - b_1|) + C_2(|a_{5-reference} - a_5| + |b_{5-reference} - b_5|) + \cdots \\ &+ C_m(|a_{3m-2-reference} - a_{3m-2}| + |b_{3m-2-reference} - b_{3m-2}|) \quad (m \text{ is odd}) \end{aligned} \tag{14}$$

If the system is unbalanced, the objective function of one phase can be defined as

$$\begin{aligned} F_{obj} &= C_1(|a_{1-reference} - a_1| + |b_{1-reference} - b_1|) + C_2(|a_{3-reference} - a_3| + |b_{3-reference} - b_3|) + \cdots \\ &+ C_m(|a_{2m-1-reference} - a_{2m-1}| + |b_{2m-1-reference} - b_{2m-1}|) \end{aligned} \tag{15}$$

In equation (13), (14) and (15), C_1, $C_2 \ldots C_m$ are weight factors and they usually satisfy $C_1 > C_2 \ldots > C_m$ to prioritize the synthesis of the fundamental and low order harmonics over high order harmonics.

Genetic algorithm mainly consists of three genetic operators: selection, crossover and mutation and is implemented with the following operations:

Step 1: Randomly generate an initial population between the minimum and maximum limits set by the problem, which are $0<\alpha_{i1}, \alpha_{i2}<\pi$ in this application.

Step 2: Calculate the fitness value of each individual string. The fitness value in this application attempts to minimize the objective function.

Step 3: Select chromosomes from the parent population with a probability proportional to their fitness to form offspring chromosomes. The selection scheme used here is Roulette Wheel selection.

Step 4: Crossover the parents with the crossover probability.

Step 5: Mutate each offspring with the mutation probability.

Step 6: Return to step 2 until the desired termination criterion is met or the maximum iteration count is reached.

After the minimization of the objective function through generations, the firing and conduction angles can be found with the constraints of $0<\alpha_{i1}<\pi$ and $0<\alpha_{i2}<\pi$. If the optimization results for α_{i1} and α_{i2} meet the condition $0<\alpha_{i1}<\alpha_{i2}<\pi$, the i[th] bridge generates $+V_{dc}$ between α_{i1} and α_{i2} and $-V_{dc}$ between $\pi+\alpha_{i1}$ and $\pi+\alpha_{i2}$, as shown in Fig 2. If the optimization results α_{i1} and α_{i2} meet the condition that $0<\alpha_{i2}<\alpha_{i1}<\pi$, the i[th] bridge generate $-V_{dc}$ between α_{i2} and α_{i1} and $+V_{dc}$ between $\pi+\alpha_{i2}$ and $\pi+\alpha_{i1}$.

To efficiently compensate reactive power and harmonics, i_{err}, the difference between the output currents of the APF and the current reference for the APF should be as small as possible. To ensure this, the value of Z_{comp} should not be too large or too small. If Z_{comp} is too small, a small difference between the reference voltage and actual voltage of the multilevel inverter will lead to a large i_{err}. In addition, uncontrolled high order harmonics may also be large. If Z_{comp} is too big, which will increase the voltage reference for the multilevel inverter; there may be no solution for equation (11) and (12). For example, demanding an output voltage higher than the highest voltage that a cascaded multilevel inverter can supply is impossible.

IV. Simulation Results

After the firing angle and conduction angle of each H-bridge of the multilevel inverter are acquired, simulations are carried out based on the Matlab/Simulink model shown in Fig.4. In Fig.4, each phase of cascaded multilevel inverter has four H-bridges (9-level) and their switching frequency is 60Hz.

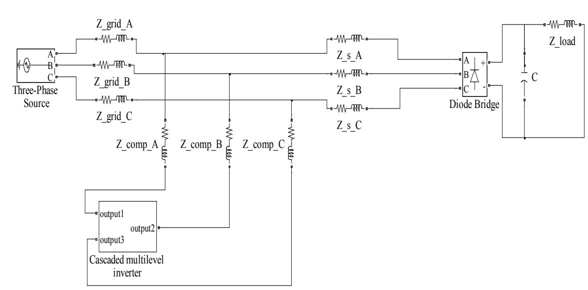

Fig. 4 Simulink model of cascaded multilevel inverter based active power filter (The inverter box contains 4 H-bridges per phase in an ungrounded Y-configuration)

A. Balanced case

In the balanced case, the peak line to line grid voltage is 400V, grid voltage frequency is 60 Hz, grid impedances, Z_{grid}, are all 0.1Ω and 1mH and filter impedances, Z_{comp}, are all 0.1Ω and 2mH, the DC-link voltage for each H-bridge in the multilevel inverter is 100V. The non-linear load includes a diode bridge; a 100 uF capacitor, C; and a 10 Ω resistor in series with a 10mH inductor, Z_{load}. There is also Z_s, a 0.1Ω and 3mH inductor in series, representing the impedance in each phase between the APF and the nonlinear load. Since the currents of the three phases only differ in phases under balanced condition, only the current of one phase is needed to show the characteristic of the grid current. Thus, only the grid current of phase A will be shown below to represent the grid current.

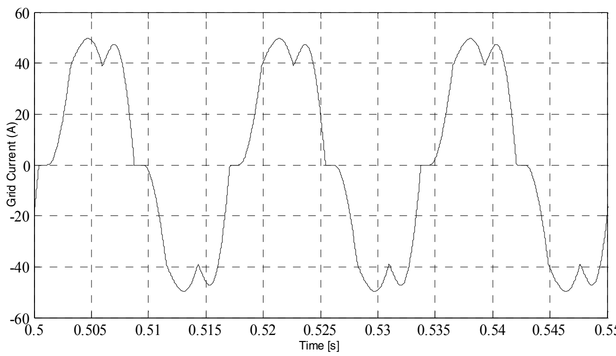

Fig. 5 Grid current before compensation

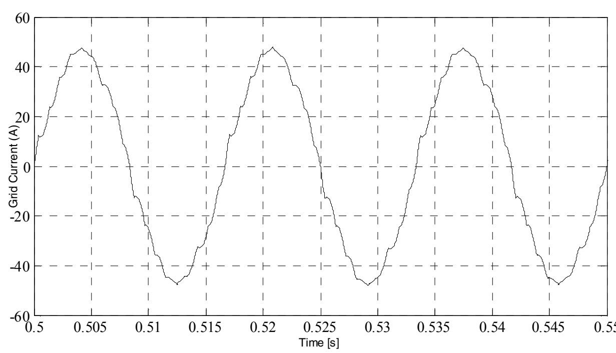

Fig. 6 Grid current after compensation with the proposed technique

The grid current of phase A without compensation is shown in Fig.5. It contains fundamental, reactive and harmonic components. To obtain the firing and conduction angles of each H-bridge of the multilevel inverter, the following parameters are used for the genetic algorithm:

Population: 100
Maximum number of generations: 5000
Crossover rate: 0.8
Mutation rate: 0.1

The objective function is equation (13) with m equal to four. The control angles, α_{i1} and α_{i2}, acquired for the four H-bridges of each phase of multilevel inverter through the genetic algorithm are 0.52 and 2.59, 0.0913 and 2.8524, 1.5812 and 1.6026, 0.8462 and 2.936 (in radians) respectively. Implementing these firing angles can make the multilevel inverter become an active power filter, while each H-bridge switches at 60Hz and can be used to compensate harmonics and reactive power simultaneously. The grid current of phase A after compensation is shown in Fig.6, and compared to Fig.5, it is much more sinusoidal. The spectrums of the grid current including the 60Hz fundamental frequency before and after compensation are shown in Fig.7 and Fig. 8 respectively. As shown in Figs. 7 and Fig. 8, without compensation, the total harmonic distortion (THD) of the grid current is 16.47% whereas the THD of grid current after compensation is reduced to 4.81%. This proves that the multilevel inverter based APF successfully compensates the harmoncs. In addition, the displacement power factor before compensation is 0.8942 and increases to 0.9999 after compensation, which proves that the reactive power is also successfully compensated with the proposed technique. Comparing Fig. 7 and Fig. 8, it can also be found that some high order harmonics are increased after compensation, such as 17^{th} and 19^{th}. The reason is that only fundamental, 5^{th}, 7^{th} and 11^{th} order of harmonics can be controlled when the cascaded multilevel inverter has four H-bridges, which can be seen from equation (11) and (13). However, the higher order harmonics can be easily filtered out by passive filters, especially when the number of cascaded H-bridges is big.

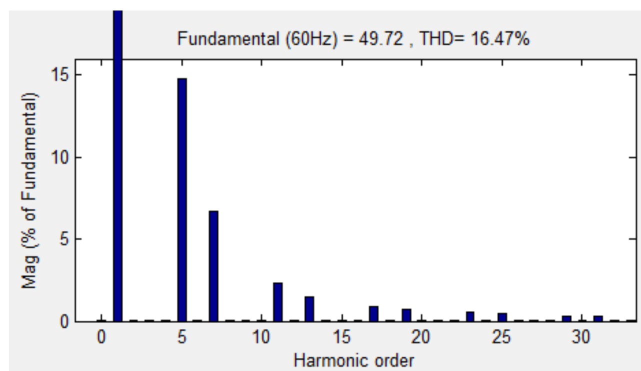

Fig. 7 The spectrums of grid current before compensation

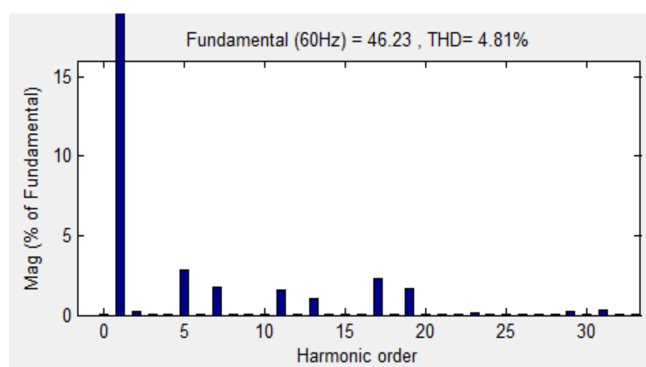

Fig. 8 The spectrums of grid current after compensation with the proposed technique

Fig. 9 and Fig. 10 show the waveform and spectrum of grid current after compensation with a conventional time domain control method which uses a similar prediction based current reference generation method to the one proposed in reference [8]. The active power filter used is also a four H-bridge cascaded multilevel inverter and the switching frequency is also 60Hz. From Fig. 9 and Fig. 10, it can be seen that this method can only reduce THD to 9.46%. Additionally, the amplitude of the grid current is increased greatly and triple-n-orders of harmonics are induced, which will cause more power losses actually. As for the displacement power factor, it is reduced to 0.773, which means the reactive current is actually be increased rather than decreased. In conclusion, the conventional techniques are not suitable to work at low switching frequency, especially when the number of cascaded H-bridges is small. These simulation results are in accordance with our analysis that the conventional control techniques need high switching frequency to have good performance, which, however, will increase switching loss.

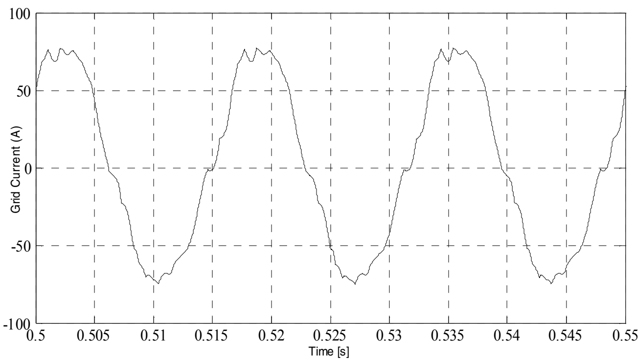

Fig. 9 Grid current after compensation with conventional technique

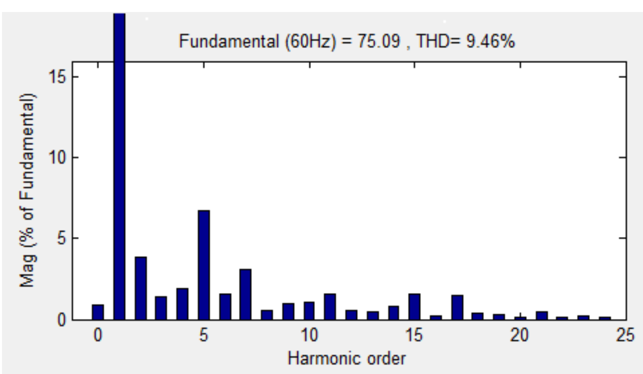

Fig. 10 The spectrum of grid current after compensation with conventional technique

B. Unbalanced case

As for the unbalanced case, the Simulink model is the same as the balanced case while some parameters are changed. Impedances Z_s_A, Z_s_B and Z_s_C are changed to 0.1Ω and 1mH, 1Ω and 5mH, 3Ω and 15mH respectively to generate an unbalanced load. The filter impedance is change to 0.1Ω and 3mH for all three phases. The grid currents without compensation are shown in Fig.11, and obtained detailed information about the grid currents by doing Fourier analysis of grid current is shown in Table 1. From Fig.11 and Table 1, it can be seen that the grid currents not only contain harmonics and reactive components, but also are unbalanced between the three phases.

Here, the active current that the grid need to supply is chosen as the maximum active currents drawn by the load of the three phases. The parameters for genetic algorithm used here are the same as the parameters used in balanced case. The objective function is equation (15) with m equal to four. With the genetic algorithm, the firing angles of the four H-bridges can be obtained, which is shown in Table 2. Fig. 12 shows the three phase grid current after compensation and Table 3 gives detailed information of the three phase grid currents after compensation. Comparing Fig.11 and Table 1 with Fig.12 and Table 3, it can be seen that the multilevel inverter not only compensates reactive and harmonic currents, but also balances the unbalanced load successfully. Since the three phases are unbalanced, there are triple-n orders of harmonics that the APF needs to take care of. Thus, only fundamental, 3^{rd}, 5^{th} and 7^{th} order of harmonics can be controlled. Thus, higher order of harmonics may be increased, which can also be easily taken care of with passive filters.

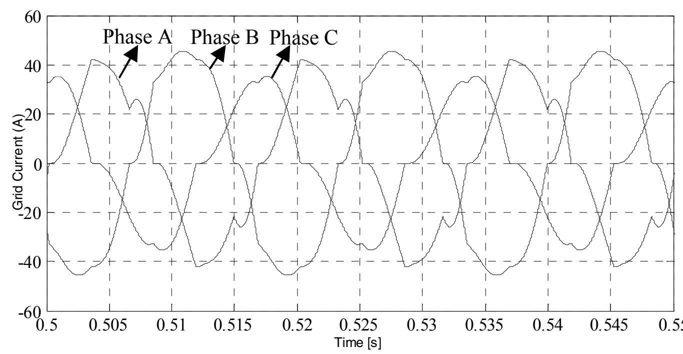

Fig. 11 Grid current before compensation in unbalanced case

Table 1: Information of Grid Current without Compensation in the Unbalance Case

	Phase A	Phase B	Phase C
Peak of fundamental	38.68	47.11	32.78
3^{th} harmonics	8.97%	2.92%	12.94%
5^{th} harmonics	7.41%	3.89%	8.12%
7^{th} harmonics	5.44%	4.68%	1.95%
9^{th} harmonics	4.73%	2.66%	2.02%
11^{th} harmonics	1.36%	1.33%	1.39%
THD	13.9%	7.5%	15.65%
Displacement Power Factor	0.9707	0.8634	0.81

Table 2: Switching Angles of H-bridges

		Firing angles		
		Phase A	Phase B	Phase C
H-bridge 1	α_{i1}	0.903	1.455	0.7365
	α_{i2}	2.922	2.877	2.7925
H-bridge 2	α_{i1}	0.453	0.185	0.1872
	α_{i2}	1.355	2.4	3.0081
H-bridge 3	α_{i1}	1.204	0.6122	1.4523
	α_{i2}	2.316	1.6886	2.4749
H-bridge 4	α_{i1}	0.356	0.7204	0.8823
	α_{i2}	2.924	2.9291	1.7522

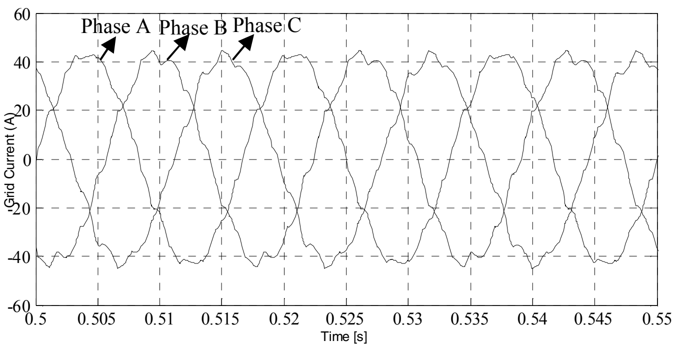

Fig. 12 Grid current after compensation in unbalanced case

Table 3: Information of Grid Current after Compensation in the Unbalance Case

	Phase A	Phase B	Phase C
Peak of fundamental	43.17	42.83	42.18
3^{th} harmonics	0.2%	0.73%	0.79%
5^{th} harmonics	1.03%	2.2%	1.22%
7^{th} harmonics	3.06%	3.45%	1.68%
9^{th} harmonics	1.65%	2.39%	3.67%
11^{th} harmonics	1.53%	3.03%	2.53%
THD	4.44%	6.08%	5.29%
Displacement Power Factor	0.9999	0.9993	0.9998

V. Conclusion and Future Work

In this paper, a new technique using direct, asymmetric switching angle control for cascaded multilevel inverters is proposed. This technique is distinct from existing, time domain control strategies in that it works in the frequency domain. Compared with conventional time domain control methods, this technique can control specific orders of harmonics to ensure they are in accordance with standards. Additionally, it achieves this improved frequency domain performance with a much lower switching frequency than traditional control techniques, which can reduce switching loss and increase the efficiency of the system. Additionally, this novel control technique can balance unbalanced load and, compensate harmonics and reactive power simultaneously. The effectiveness of this technique is successfully verified in both balanced and unbalanced cases through simulations.

To implement this technique in practical situations, several things need to be done to further optimize this control technique. The first thing is to find a more time efficient way to solve these transcendental equations, which is very critical in closed-loop control in a dynamic grid. The second one is to differentiate transient state operation with steady state operation and develop a more robust current reference generation algorithm under the transient state operation. The last one is to combine this control technique with small passive filters to filter out high order harmonics this control technique may induce. If these tasks are accomplished, this technique can be applied to practical power systems and greatly improve the performance of cascaded multilevel inverter based APFs and improve the efficiency of the system.

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