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Research the Design Method of Hybrid Cascade Multilevel Structure for the APFs in Moderate-voltage Grid

***Abstract**. A design method about how to design main circuits of active power filters(APF) with hybrid cascade multilevel structure is proposed in this paper. Through careful research, the combination of these cascade H-bridge modules is properly chosen and the number of high-frequency modules is reasonably selected. Following eight steps described in the paper, a reasonable design process of the combination of these modules can be got easily for a given condition. Through the reasonable combination of hybrid cascaded modules made up of high and low voltage devices, the design method that how to design the main circuit of this APF can be used to different voltage class in moderate voltage grid. Simulation results validate the rightness of the proposed method.*

***Streszczenie.** W artykule przedstawiono zastosowanie hybrydowego kaskadowego wielopoziomowego układu w aktywnym filtrze mocy (ang. Active Power Filter). Opisany został sposób doboru modułów wykorzystanych mostków typu H oraz wyniki symulacyjne układu. (**Projektowanie hybrydowych kaskadowych wielopoziomowych układów dla Energetycznych Filtrów Aktywnych**)*

Keywords: Hybrid cascade multilevel inverter, Design method, active power filter(APF), Moderate-voltage grid
Słowa kluczowe: Hybrydowy kaskadowy falownik wielopoziomowy, metoda projektowania, Energetyczne Filtry Aktywne (APF)

Introduction

Nowadays, hybrid cascade multilevel technology has attracted an increasing concern, especially in moderate-voltage and high-power applications [1]. Different from conventional cascade multilevel structure which consists of several H-bridge modules with the same DC voltage, hybrid cascade multilevel inverter is made up of H-bridge modules with different DC voltage or the modules of different topology such as H-bridge, diode-clamped structure or capacitor-clamped structure. Compared with conventional cascade multilevel structure, hybrid cascade multilevel inverter can synthesize more output levels with the same number of cascaded modules, which will minimize total harmonic distortion (THD) of output voltage and make possible the reduction or even the elimination of output filters[2]-[4]. In addition, because of its hybrid structure, different power electronic devices can be used, higher power cells

using high voltage devices usually operate at low frequency and the lower power cells using low voltage devices switch at high frequency, which combines the advantages of different kinds of devices. It is good for the optimization design of the whole system. Detailed analysis can be found in [5]. Hybrid cascade multilevel structure can be used in many applications, such as motor dirve[6],static var compensator[7], active power filter(APF)[8][9] or renewable energy generation[10]and so on. In this paper, the APFs with hybrid cascade multilevel inverter in moderate voltage grid are discussed.

To meet the objective of power quality at the point of common coupling (PCC) of a distribution system, APFs are widely used and researched in the power engineering field now[11]. But due to the limitation of voltage capability of power devices, it is very difficult to handle nonlinear loads in moderate voltage grid. When the traditional APFs with two-level inverter are used to moderate voltage grid, main drawbacks are related with semiconductor requirements: the necessity of the high voltage stress on switches, the necessity of switching at high frequency in high voltage and large current situation. In this situation, serious *dv/dt* associated to the commutation pattern appears in the system, generating EMI as well as insulation degradation in electronic and electrical systems[9].

Multilevel converters may solve these problems, which decrease *dv/dt* significantly and reduce operating voltage of power electronic devices. Compared with other kinds of multilevel structure, hybrid cascade multilevel structure can synthesize more output levels with the same modules which is good for harmonic current tracking, can combine the advantages of both high voltage and low voltage devices, letting the high power cells operate at low frequency while only the low power cells switch at high frequency to improve the output waveform, which will reduce the switching losses. So it is reasonable to use this structure in controlling harmonic perturbation in moderate voltage grid.

Now, control of harmonic perturbations by the APFs with hybrid cascade multilevel technology has become a hot topic in the power engineering field[8,9,12-17]. This literature[12] presents a new control strategy for a high performance hybrid cascaded H-Bridge HB multilevel converter with integrated series Active Power Filter Stage APFS. Unequal DC voltage sources are used to energise the converter's HBs. This offers increased number of voltage levels using fewer number of series connected HBs. Simple hybrid stair-case/SVM modulation strategy is proposed to synthesise the converter output voltage waveforms and to guarantee even sharing of power between the converter's HBs. The proposed converter is investigated under different operating conditions and the results show excellent dynamic and steady state performance. In the literature [15], a hybrid shunt compensation system consisting of alternatively a cascaded or a reduced topology multilevel active power filter, and a low rating passive damping filter is presented. The active power filter is controlled by a novel hysteresis current regulation strategy, and both mitigates low-order voltage harmonic distortion along the feeder and provides root mean squared voltage support. Simulation and experimental results are included showing the performance of the filter for both steady state and transient conditions. This literature [17] presents a shunt active power filter implementation based on asymmetrical cascaded multilevel converter. In this paper's control scheme, no transformer is used and the DC voltages are individually controlled. Hence, no DC source is required to maintain the capacitors voltages constant. High switching frequency is used only in the small voltage cell while the high voltage cells operate in low frequency. This makes it more suitable for higher power applications than active filters implemented with common six pulses converters. Simulation and experimental results are provided to validate the proposed scheme.

Evidently, the design of hybrid cascade multilevel structure of the APFs is important to the performance of the filter system. The hybrid cascade multilevel structure decides the harmonic current compensation capability of the APFs. There are many possibilities for setting the DC voltage value of these H-bridge modules when the total DC voltage value is fixed. So it is necessary to development a method to select a proper combination of these H-bridge modules with different DC voltage values within so many combinations. Besides, hybrid cascade multilevel structure includes higher power cells operating at low frequency and the lower power cells switching at high frequency. How to choose the number of high-frequency module and low-frequency module? In the application of the APFs, the number of high-frequency module is directly related with the compensation results of harmonic currents. So it is important to find a way to determine the number of high-frequency cells needed. Furthermore, there are many voltage grades in moderate voltage grid such as 6 kV, 10 kV, 35kV. It is necessary to the researched design method of the hybrid cascade multilevel APF structure that can be applicable to different voltage grades in moderate voltage grid. At present, no literature researches the design problem of hybrid cascade multilevel structure of the APFs in moderate voltage grid yet. In terms of the above-mentioned questions, this paper makes a detailed analysis and proposes a design methodology for this APF with hybrid cascade multilevel structure made up of H-Bridge module in moderate voltage grid. Following eight steps described in the paper, a reasonable design process of the combination of these H-bridge modules can be got easily for a given voltage grade condition.

Design Process

1. According to the design objective, determine the total DC voltage of this APF

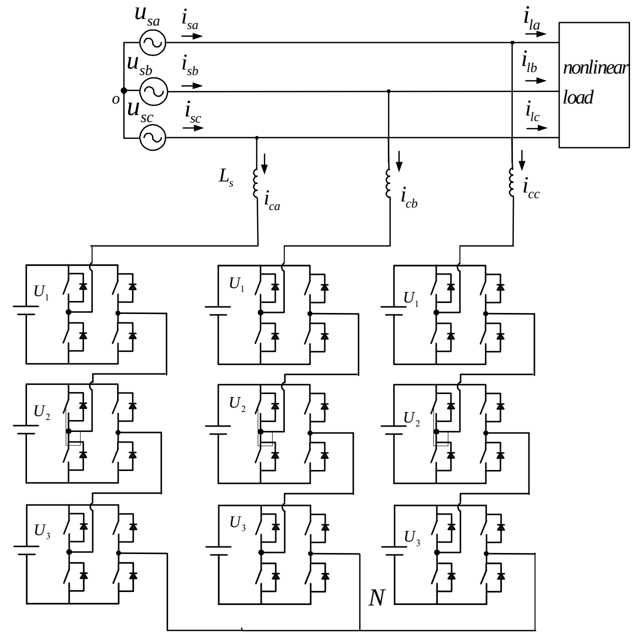

Fig.1 Schematic diagram of the APF with hybrid cascade multilevel inwerter

The structure of this APF with hybrid cascade multilevel inverter is shown in Fig.1. For a given voltage grade in the distribution system, to meet the requirement of harmonic compensation, output command voltage of the APF is our first concern in the design of hybrid cascade multilevel structure of the APFs. According to KVL, output command voltage of this APF can be represented as follows:

(1) $$u_c^*(t) = u_s(t) + L_s \frac{di_c^*(t)}{dt}$$

where $u_s(t)$ is power voltage, $u_c^*(t)$ is output command voltage of the APF, $i_c^*(t)$ is output command current of the APF. From the above equation, we find that as long as power voltage and output command current of the APF are known, output command voltage of the APF can be obtained. After getting output command voltage of the APF, the total DC voltage of this APF can be obtained with the traditional method used in the APF with two-level inverter.

2. Determine the number of cascade H-bridges needed

After getting the total DC voltage, we want to know how many H-bridges needed to synthesize this DC voltage. For the APF application, output voltage of the cascade H-bridge inverter is expected to have as more level as possible and the adjacent level should always be modulated so that good compensation results can be obtained.

Suppose that there are n modules in a phase, DC voltage of the jth module is U_j , and DC voltage of each module follows the undermentioned inequality:

(2) $$U_1 \le U_2 \le ... \le U_j \le ... \le U_n (j = 1,2,...,n)$$

Normalize each module's DC voltage relative to the first module, the jth module's normalized DC voltage value is:

(3) $$\sigma_j = \frac{U_j}{U_1} (j = 1,2,...,n)$$

For predigesting research process, we only research this situation that the normalized DC voltage value of each module is an integer equal to or larger than one. When the level of output voltage of the cascade inverter is continuous, the number of the level can be expressed as:

(4) $$m = 1 + 2\sum_{j=1}^{n} \sigma_j = 1 + 2\frac{U_{dc}}{U_1}$$

From the above equation, we can conclude that the number of output voltage level is only related to the total DC voltage U_{dc} and DC voltage of the first module.

For hybrid cascade multilevel converters, to synthesize a full PWM output voltage waveform, DC voltage of the jth module must satisfy the following equation [1]:

(5) $$U_j \le 2\sum_{k=1}^{j-1} U_k (j = 2,3,...,n)$$

Suppose the total DC voltage is already calculated out, if DC voltage of each module is the same, the maximum number of module required to synthesize the total voltage can be calculated easily. The minimum number of module can be calculated when DC voltage of the jth module meets the following relation too:

(6) $$U_j = 2\sum_{k=1}^{j-1} U_k (j = 2,3,...,n)$$

To sum up, the following two steps can be taken to determine the number of cascade H-bridges:

(a) Determine the number of levels

Using the equation (4), the level number can be easily calculated. Here U_{dc} is got in step 1, and U_1 is usually chosen according to voltage capability of power electronic devices for practical application of the APFs.

(b) Determine the value range of modules required

When DC voltage of each cascade H-bridge is the same, the relationship of the number of levels generated and the number of module per phase can be written as:

(7) $$m = 1 + 2n$$

where m is the number of output voltage level, n is the number of modules. When DC voltage of each module meets the relationship described in equation (6), the following equation can be obtained through calculation:

(8) $$m = 2 \times 3^{n-1} + 1$$

Using the equations (7) and (8), the number range of modules needed per phase is:

(9) $$ceil(1 + \log_3(\frac{m-1}{2})) \le n \le \frac{m-1}{2}$$

where ceil represents round up sign.

3. Enumerate all the existent combinations of DC voltage

Having known the total DC voltage and the number of module needed to synthesize the whole voltage, we can list all kinds of existent combinations of DC voltage conveniently according to the following two principles:

(a) The normalized DC voltage value of each module meets the following relationship:

(10) $$\sigma_1 + \sigma_2 + ... + \sigma_j + ... + \sigma_n = \frac{U_{dc}}{U_1}$$

(b) The normalized DC voltage value of the jth module should satisfy the following inequity[18]:

(11) $$\sigma_j \le 2\sum_{k=1}^{j-1} \sigma_k \, (j = 2,3,...,n)$$

4. Choose reasonable DC voltage combinations considering voltage capability of power electronic devices.

Step 3 just gives us all possible combinations of DC voltage. But for a practical system, these combinations are not always reasonable based on voltage capability of power electronic devices. At present, the rated voltage of IGBT mainly includes 1700V, 3300V and 6500V. Considering the safety margin, their withstanding voltages are usually 1000V, 2000V and 4000V respectively. As for IGCT, which is usually used in high power conditions, its rated voltage is 4500V,6000V and 6500V. Considering the safety margin, they can be used in 2800V,3300V and 4000V .For the convenience of theory analysis, the voltage grades of these devices are simplified be 1000V,2000V,3000V and 4000V.In other words, if we choose 1000V as DC voltage of the first module, the normalized DC voltages are 1,2,3,4.

5. Analyze and compare the cost of different combinations, mainly including the cost of the devices and the cost of spare parts, initially identify one combination.

From step 4, we may get many combinations of DC voltage, which one is the best? In terms of the engineering, device cost is an important index to evaluate the power electronics equipment. For different DC voltage combinations, because different devices are used, we can compare their costs to select the most economic combination.

6. Determine the number of high-frequency modules

Since hybrid cascade multilevel inverters consist of different devices, the modulation is different from conventional cascade H-bridge inverters. A hybrid modulation strategy that incorporates stepped synthesis in conjunction with variable pulse width of consecutive steps is adopted [5][19-20].Under this modulation strategy, high power cells operate only at fundamental frequency of the converter output, while the low power cells operate at a higher frequency. The proposed modulation process for high power modules and low power module are illustrated in Fig. 2 and Fig. 3. As to low power module, phase-shifted pulse width modulation is employed.

Evidently, output command voltage of the APF for tracking the command current is non-sinusoidal. Because output command voltage of the APF is non-sinusoidal, the hybrid modulation strategy in [5][19-20] is used to this APF, high power cells will operate at high frequency sometimes. The power voltage is sinusoidal. So the power voltage may be utilized as the output command voltage of the high power cells. The high power cells operate at fundamental frequency to synthesize the power voltage, while low power cells operate at high frequency to synthesize the difference value of output command voltage of the APF and output voltage of high power cells. Evidently, the command voltage of high-frequency module is the sum of inductor voltage produced by harmonic current and the difference value of power voltage and output voltage of high power cells. Output voltages of high power cells and low power cells are added up to the output command voltage of the APF.

The number of high-frequency modules depends on the following two factors:

(a). Inductor voltage produced by harmonic current.

(b). Difference value of power voltage and output voltage of high power cells.

In step 5, this combination of DC voltage has already been known. Using the modulation as Fig.2, modulation waveform of high power cells can be obtained. Based on the difference value of output command voltage of the APF and output voltage of high power cells, the command voltage of low power cells can be got. Then the desired number of low power cells can be determined.

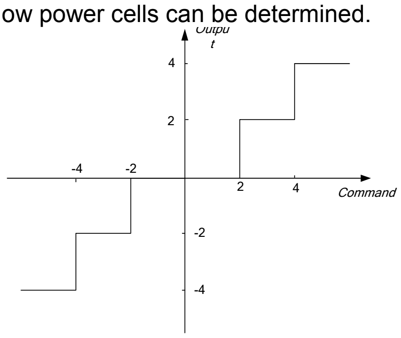

Fig.2. Modulation process of high power module

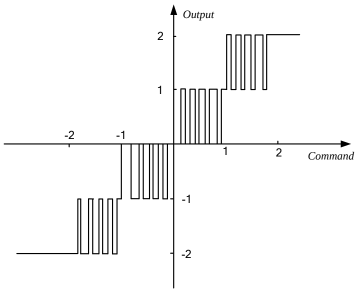

Fig.3. Modulation process of low power module

7. Verify if the number of high-frequency modules match up to the DC voltage combination obtained in step 5.

If the number of DC voltage combination determined by step 5 meets the requirement of step 6, we can go to the next step. Otherwise, we go back to step 5, choose desirable DC voltage combination again until the requirements of both step5 and step 6 is satisfied.

8.Verify the effectiveness of DC voltage combination by simulation.

It seems that we get a set of reasonable combination of DC voltage, whether it can reach our compensation goal or not is not known. Simulation is a good way to prove the effectiveness of our design. Through simulation, we can clearly know the effect of the design. If the result is not satisfactory, we can go back to step 5 to reselect other combinations until a pleasing result is got.

Design Example

This section presents a practical design example of a hybrid cascade multilevel APF to understand clearly the design steps mentioned above. Parameters of the simulation system are: power voltage is 10kV, design capacity of the APF is 1MVA, the THD of the system current compensated is desired less than 5%. Following the above-mentioned design steps, detail analysis will be made in each step respectively.

1. Determine the total DC voltage

We use three-phase diode rectifier as a typical load. Considering the overload factor as 1.2, the RMS value of desired output current can be calculated as follows:

$$I_c = \frac{\alpha P_N}{\sqrt{3}U_N} = \frac{1.2\times 10^6}{\sqrt{3}\times 10^4} = 69.28A \tag{12}$$

That is to say, the RMS value of the typical load harmonic current is 69.28A. Based on the desired output current, we can draw the waveform of power voltage, desired inductor voltage and desired output voltage of the APF with the equation (1) as the Fig.4. As the Fig.4 illustrates, the peak value of output voltage of the APF is nearly 8500V, so the total DC voltage is selected as 9000V.

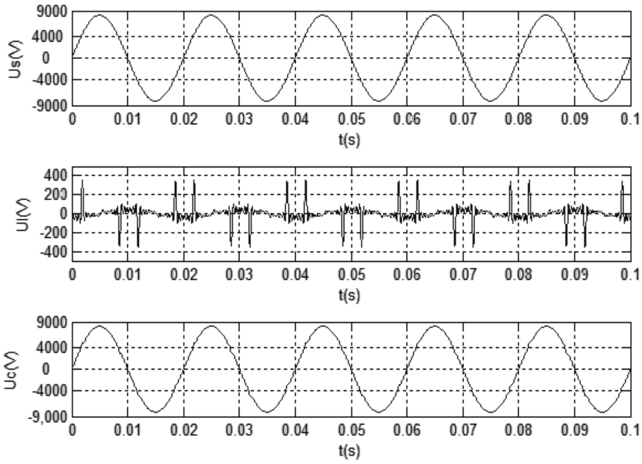

Fig.4 Waveforms of power voltage, inductor voltage and output voltage of the APF

2. Determine the total number of cascade H-bridges

(a).Determine the level number of output voltage

Equation (4) shows that the level number of output voltage is just dependent on the value of total DC voltage and the first DC voltage. In step 1, we've already got the value of the total DC voltage. In step 4, the voltage grades of these devices are simplified be 1000V, 2000V, 3000V and 4000V.We choose 1000V as DC voltage of the first module, the normalized DC voltages are 1,2,3,4.The level number of output voltage is:

$$m = 1 + 2\frac{U_{dc}}{U_1} = 1 + 2\times\frac{9000}{1000} = 19 \tag{13}$$

(b).Determine the number of module needed

Using the equation (9), the value range of modules needed per phase is:

$$3 \le n \le 9 \tag{14}$$

3. List all the combinations of DC voltage.

According to the expressions (10) and (11), we can list all the combinations of DC voltage. Firstly, assume that there is only one module with normalized DC voltage as 1. Using the expression (10) and (11), the following combinations can be got:

$$1:2:6,\ \ 1:2:2:4,\ \ 1:2:3:3,\ \ 1:2:2:2:2$$

Secondly, consider that there are two modules with normalized DC voltage as 1, following the same process, such combinations can be obtained:

$$1:1:2:5,\ \ 1:1:3:4,\ \ 1:1:2:2:3$$

Then, in the same manner, consider that there are three, four... nine modules with normalized DC voltage as1, list other combinations. Table 1 gives us all existent combinations.

Table 1 DC voltage combinations

1	1:2:6 1:2:2:4 1:2:3:3 1:2:2:2:2
2	1:1:2:5 1:1:3:4 1:1:2:2:3
3	1:1:1:6 1:1:1:2:4 1:1:1:3:3 1:1:1:2:2:2
4	1:1:1:1:5 1:1:1:1:2:3
5	1:1:1:1:1:4 1:1:1:1:1:2:2
6	1:1:1:1:1:1:3
7	1:1:1:1:1:1:1:2
8	1:1:1:1:1:1:1:1:1

4.Select practical combinations

Considering voltage capability of power devices, the normalized value of DC voltage of each module can only be chosen as 1,2,3 or 4.From Table 1, we choose practical combinations ,which is not shaded in Table I.

5. Compare the cost of each combination

(a). Device costs

Considering the cost of 1700V IGBT is a, the costs of 3300V IGBT, 6000V IGCT, and 6500V IGBT are $k_1 \times a$, $k_2 \times a$,and $k_3 \times a$ respectively. Since Each H-bridge has the same four devices, so we compare the cost of module instead. Assuming the cost of 1000V module is 1, the costs of 2000V, 3000V and 4000V modules are k1,k2 and k3 respectively. The cost of combination 1:2:3:4 is:

$$y = 1 + k_1 + k_2 + k_3 \tag{15}$$

We take $k_1 = 1.5, k_2 = 3, k_3 = 4$ as an example, then the cost of each combination can be calculated. Table 2 gives us the list of each combination with their costs.

(b). Spare parts cost

To reduce spare parts cost, DC voltage of each module should be the same as possible. The following combinations may have lower spare parts cost:

1：2：2：2：2
1：1：1：2：2：2
1：1：1：1：1：2：2
1：1：1：1：1：1：1：2
1：1：1：1：1：1：1：1：1

By comparing device cost and spare parts cost of each combination, 1:2:2:2:2 may be the best combination. Its cost is low. On the other hand, only two kinds of modules are needed. Its spare parts cost is very low. So the whole system is suitable.

Table 2 DC voltage combinatios and costs

DC voltage combinations	costs	DC Voltage combinations	costs
1:2:2:2:2	7	1:1:1:2:2:2	7.5
1:2:2:4	8	1:1:2:2:3	8
1:1:1:1:1:2:2	8	1:1:1:1:1:1:1:1:1	8
1:2:3:3	8.5	1:1:1:2:4	8.5
1:1:1:1:2:3	8.5	1:1:1:1:1:1:1:2	8.5
1:1:3:4	9	1:1:1:3:3	9
1:1:1:1:1:4	9	1:1:1:1:1:1:3	9

6. Determine the number of high-frequency modules

The modulation process for high power modules is illustrated in Fig.2. The difference value of output command voltage of the APF and output voltage of high power cells is the command voltage of high-frequency module. The command voltage of high-frequency module includes the difference value of power voltage and output voltage of high power cells and inductor voltage. Fig.5 illustrates that inductor voltage, the difference value of power voltage and output voltage of high power cells and command voltage of high-frequency module. From this figure, we can see that the peak value of command voltage of high-frequency module is larger than 1kV, so we need two high-frequency modules to synthesize the waveform.

7. Combining step 5 and step 6, reconsider reasonable combinations.

In step 6, we demand two high-frequency modules, but the combination only has one low voltage module. So we should go back to step 5 to reselect the combinations. Through comprehensive compare, we select 1:1:1:2:2:2 because it is not only economical but also meeting the requirements of step 6. Owing to needing only two high-frequency modules, one cell of three low power cells in this combination may operate at fundamental frequency to reduce the equipment switch cost.

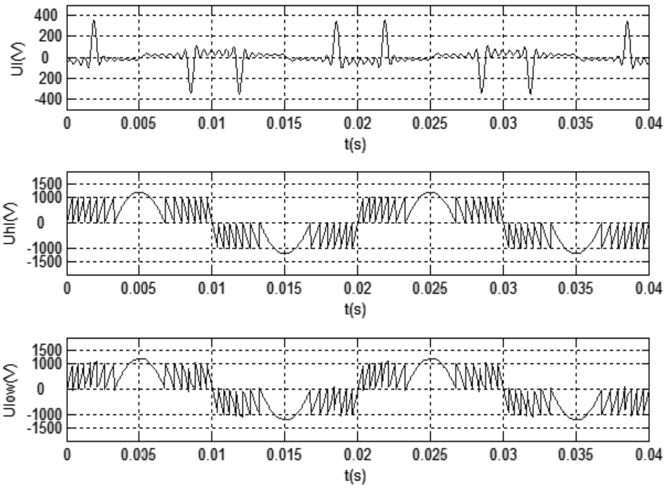

Fig.5 Waveforms of inductor voltage, different value of power voltage and high power cells voltage, reference voltage of low power cells

8. Simulation verification.

To verify the effectiveness of the proposed combination, we establish a model with PSIM. The simulation parameters are listed in Table 3.

The simulation results are shown in Fig.6 and Fig.7. Fig.6 shows the load current, the compensated power current and the output current. It is noted that the harmonic current is greatly reduced, the THD of the compensated power current is 3%, which meets the above-mentioned requirement of harmonic current compensation. Fig.7 shows that the reference voltage of low power cells and the total output voltage of the APF. As the Fig.7 illustrates, the reference voltage of low power cells is larger than 1kV, so two high-frequency modules are necessary in accord with the above design. The output voltage which has 19 levels is good for harmonic current tracking. Moreover, the waveform of output voltage is modulated among all adjacent voltage steps, which doesn't generate serious *dv/dt*.

Table 3 Parameters of simulation

Symbol	Values	Parameters
U_s	10KV	RMS value of line voltage
f_s	50Hz	Power frequency
L_s	0.5mH	Output inductor
R_s	0.5Ω	Equivalent resistor of inductor
U_{dc_high}	2000V	Dc voltage of high power cells
f_{high}	50Hz	Switching frequency of high power cells
M	3	Number of high power cells
U_{dc_low}	1000V	Dc voltage of low power cells
f_{low1}	5kHz	Switching frequency of two low power cells
f_{low2}	50Hz	Switching frequency of one low power cell
N	3	Number of low power cells

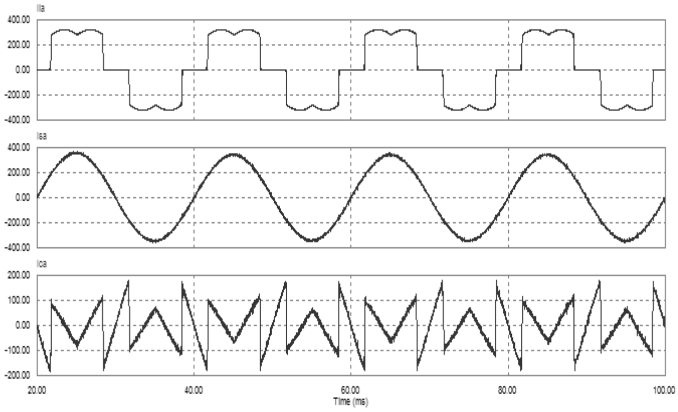

Fig.6 Waveforms of load current, compensated power current and output current of the APF

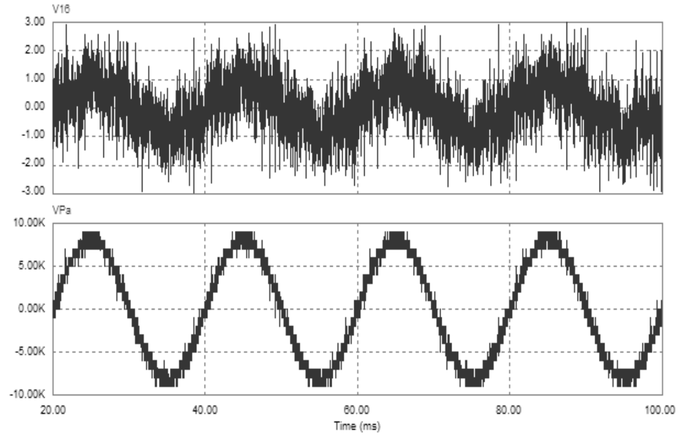

Fig.7 Waveforms of reference output voltage of low power cells and the total output voltage of the APF

Conclusion

This paper proposes a method to design the structure of the APF with hybrid cascade multilevel structure made up of H Bridge modules. Eight steps are taken to complete a design process, including the determination of the total DC voltage, the number of modules per phase, DC voltage of each module and the number of high-frequency modules. Simulation results prove the rightness of this design process. This design method of the hybrid cascade multilevel APF structure in this paper may be not only applicable to 10KV, but also applicable to different voltage grades in moderate voltage grid.

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