RESEARCH ON CONTROL STRATEGY OF HYBRID ACTIVE POWER FILTER

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Abstract- The construction and working principle of shunt active power filter are introduced, current hysteresis tracking control method, triangular wave modulation control method are discussed in detail. Experimental simulation is carried out in MATLAB environment and its results show that this kind of HAPF has excellent filtering effect under the action of the control strategy.

Key words- hybrid active power filter; MATLAB; control strategy; simulation

I. INTRODUCTION

With the rapid development of modern industrial technology and power electronics technology, the application of different kinds of inverters, converters, switches and reactors keeps increasing together with the harmonic pollution arising therefrom, resulting in serious distortion of grid voltage, affecting the normal operation of instruments, aggravating the wear and tear to power components and imperiling the safe operation of power system. Currently, harmonic has become one of the serious pollutions of power system, so it is particularly urgent to solve harmonic problems in power system. Apart from the traditional methods of using passive filters and changing grid structures, active power filters (APF) are effective devices for treating harmonic. In order to improve APF performance, it is vital to study APF control strategies [1,2].

II. WORKING PRINCIPLE OF APF

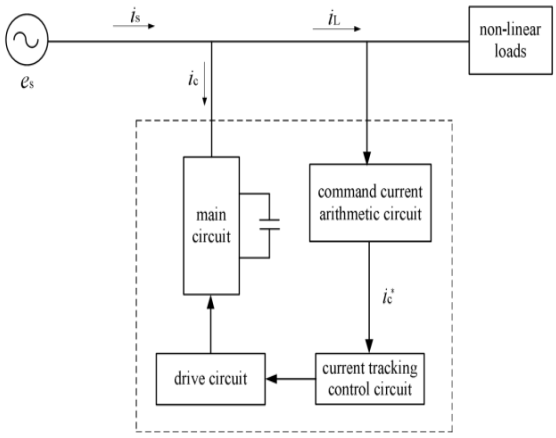


Figure 1 Schematic Diagram of APF

Figure 1 is the schematic diagram of the most fundamental APF system components, with the load as the harmonic source (i.e., compensation object) and APF as the active power filter. According to Figure 1, APF system is composed of two major parts, i.e., command current arithmetic circuit and compensation current generating circuit (consisting of current tracking control circuit, drive circuit and main circuit). The core of command current arithmetic circuit is to detect harmonic and reactive current components in compensation object current, so it is sometimes also called harmonic and reactive detection circuit. The purpose of compensation current generating circuit is to generate actual compensation current according to the command signals of compensation current generated from command current arithmetic circuit. The main circuit currently used is PWM converter [2].

The basic working principle of APF is: detect the voltage and current of compensation object, and calculate the command signal of compensation current through command current arithmetic circuit. This signal will be magnified through compensation current generating circuit to generate compensation current, which is offset by the harmonic and reactive currents, etc. to be compensated in load current, thus getting the expected power current. In Figure 1, set the load current as iL, and the harmonic iLh detected by the command current arithmetic circuit as the command current ic* of APF; the output compensation current ic of compensation current generating circuit will follow the change to the command current ic*, and ic and iLh, will offset each other. Then grid current is=iL-ic=iLf, i.e., equal to the fundamental wave current of load, so that power current becomes sinusoidal wave. If reactive current of load also needs to be compensated, only the component with reverse polarity of load current fundamental wave reactive component needs to be added in compensation current command signal. In this way, the harmonic and reactive components of power current and load current will offset each other, and the power current equals to the fundamental wave active component of load current. Similarly, APF may also compensate the negative-sequence current of asymmetrical three-phase circuit [2-4].

For voltage-type APF, the main circuit uses a voltage-type converter. The main circuit of parallel-type three-phase three-wire system APF is shown in Figure 2 [5].

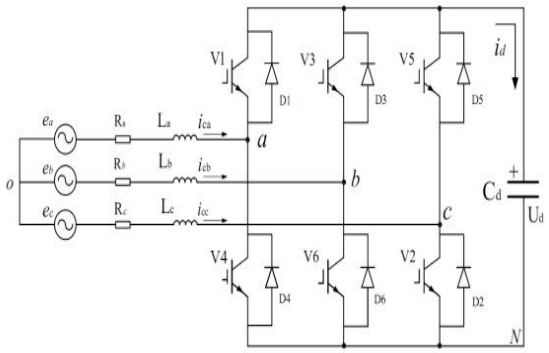


Figure 2 Main Circuit of Three-phase Three-wire System APF

III. APF CONTROL STRATEGIES

The purpose of compensation current control circuit is to get the PWM signals controlling the connection of each device of compensation current generating circuit according to the interrelation between compensation current command signal and actual compensation current, and the control result should follow in real time the changes to the command signal. In order to guarantee good real-time of compensation current, the current control should use tracking-type PWM control method, which currently mainly include hysteresis comparison, triangular wave comparison and dead-beat control [5-7].

A. Hysteresis comparison

Figure 3 is the schematic circuit diagram using hysteresis comparison for control. In this formula, the command signal ic* and the compensation current signal ic actually sent by the inverter are compared, and the deviation of the two is i □ . As the input of hysteresis comparator, it will generate the PWM signal controlling the connection of switching devices in main circuit, and this PWM signal will, after magnification through drive circuit, control the connection of the power devices of main circuit, thus controlling the change to compensation current ic. The output of hysteresis comparator is a series of pulse sequences with relatively large width and irregular distribution, and the hysteresis width has a relatively large impact on pulse width [8].

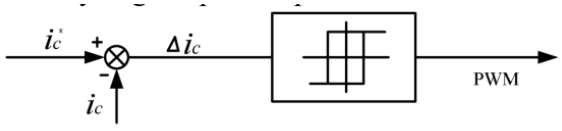


Figure 3 Instantaneous Value Comparison Method of Hysteresis Comparator

It is beneficial to use this control method for APF due to the advantages of hysteresis control such as quick response speed, easy realization and unnecessary understanding of load nature (inductive load or capacitive load). However, this hysteresis control method has a large range of switching frequency change. Particularly, when c i change has a large range, on the one hand, fixed hysteresis width may cause the relative following error of compensation current to be too large with small ic; on the other hand, fixed hysteresis width may also cause the switching frequency of devices to be too high with large ic, which may even exceed the allowable maximum operating frequency of devices, thus resulting in device damage. Large range of switching frequency change indicates that hysteresis control not only has the characteristic of pulse width modulation, but also contains the component of pulse width modulation. It is the combination of the two modulations. For the control over power converter, frequency modulation is usually unwanted. In the hysteresis instantaneous comparison control method, the hysteresis width of hysteresis comparator has a relatively large impact on the following performance of compensation current. When the hysteresis width is relatively large, the switching frequency of power semiconductor switching device is relatively low, thus having low requirement on switching devices; however, the following error is relatively large and the higher harmonic in compensation current is relatively large. On the contrary, when the hysteresis width is relatively small, though the following error is relatively small, the switching frequency is relatively high. Therefore, when the hysteresis comparison control method is adopted, appropriate hysteresis width should be set and

variable hysteresis width should be adopted if necessary, so as to achieve better tracking effect. This control method is featured by relatively simple hardware circuit, which is usually constructed with simulation circuit; since the method belongs to real-time control method, the current response is quick; since carrier wave is unnecessary, the output voltage contains no harmonic components of specific frequency.

B. Triangular wave comparison

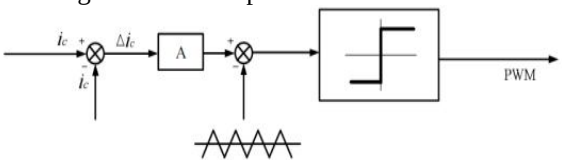


Figure 4 Schematic Diagram of Triangular Carrier Wave Modulation

Figure 4 is the schematic diagram of triangular carrier wave modulation control method, which is different from other PWM control methods using triangular wave as carrier wave in that it compares the deviation c i □ between ic* and ic after amplifier A with triangular wave rather than compares command signal ic* with triangular wave directly. Amplifier A is usually a proportional amplifier or a proportional-integral amplifier. Such control system is designed based on the minimization of c i □ control. Compared with the instantaneous value comparison method, the triangular carrier wave modulation control method has the following characteristics: the hardware is relatively complicated and it is usually

realized by adopting the digital control method with DSP as the core; it has a relatively large following error compared with the hysteresis comparison method; the switch frequency of devices is fixed and equals to the frequency of triangular carrier wave; the current response is slower than that of the instantaneous value comparison method [8,10].

2.3 Phase shift SPWM control of combined converter

In order to realize effective compensation to reactive current and higher harmonic current, switching devices are required to work under higher frequency. However, the switching frequency of high-power sinusoidal pulse width modulation (SPWM) converter will be limited due to the following two reasons: (1) the switching frequency of high-power semiconductor devices (e.g., GTO) is relatively low; and (2) high switching frequency will result in relative large switching loss, thus reducing system efficiency. However, multiplexed power converters have relatively poor regulation performance, which could not fully meet the requirement of modern grid. Therefore, Document [9] proposes the phase shift SPWM technology of combined converter. The essence of this technology is the organic combination of multiplexed technology and PWM technology, which may realize the phase shift SPWM technology of high-power converter under low switching frequency, significantly reduce the harmonic output and improve the output waveform, thus reducing the capacity of wave filters. Meanwhile, phase shift SPWM converter has better dynamic response and relatively higher transmission band, enabling the application of many cutting-edge control means and improving control performance. Current-type converter has the advantages such as direct power supply, reliable operation and simple protection, and is applicable in many high-power applications. For example, grid active compensation devices, if adopting current-type phase shift SPWM technology, may realize the advantages such as simple structure, good control performance, quick response, broad frequency band and strong harmonic elimination capacity. This technology solves the contradiction between high power equipment and low switching-frequency devices, and enables the use of converters composed of super high power devices such as GTO in APF equipment. Therefore, this technology has broad applications in high-power applications such as APF [9].

IV. VOLTAGE CONTROL AT DC SIDE OF MAIN CIRCUIT

As a major part of hybrid APF, compensation current generating circuit is composed of voltage-type PWM converter and other corresponding drive circuits and current tracking control circuits. In order to guarantee good compensation current following performance, the voltage of capacitance at converter DC side should be controlled at a suitable value. The control method of DC side voltage Uc is shown in Figure 5.

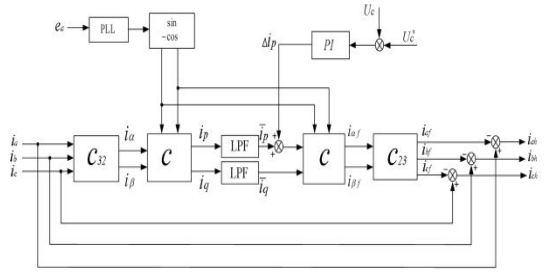


Figure 5 Command Current Operation Containing DC Side Voltage Control

According to the Figure, the difference between the given value and the feedback value of DC side voltage will, after PI regulator treatment, generate the regulation signal □ip, which will be added to overlay the DC component of the instantaneous active current; after operation, the command signal will contain certain fundamental wave active current, and the compensation current generating circuit will generate compensation current according to the command signal and input it into grid, so that the compensation current in APF will have certain fundamental wave active current component, thus enabling energy exchange between DC side and AC side of APF and regulating the DC side voltage to the given value [10,11].

V.SIMULATION STUDY

Current tracking control circuit is the primary link of compensation current generating circuit, and its purpose is to get the PWM signals controlling the connection of each device of compensation current generating circuit according to the interrelation between compensation current command signal and actual compensation current, so that the compensation current will track the change to the command signal.

A. Hysteresis control

Comprehensive comparison analysis on APF could be performed though the model established, with non-linear load adopting thyristor three-phase bridge fully-controlled rectifier circuit

The detailed parameters are as follows:

DC side voltage U_{dc} =1000V
Output inductance L_0 =0.8mH
Hysteresis width $\delta = 9$
Second-order low-pass filter frequency f_c =30Hz
Non-linear load resistance R_d =4Ω, Inductance L_d =20mH
Non-linear load line parameter R_L =0.05Ω, L_L = 0.01mH
Three-phase voltage source U=220V, f=50Hz
Three-phase power side line parameter Rs =0.05Ω, Ls =0.015mH
Thyristor firing angle $\alpha = 30°$, 45° and 60°
Simulation time $t = 0.1\ s$

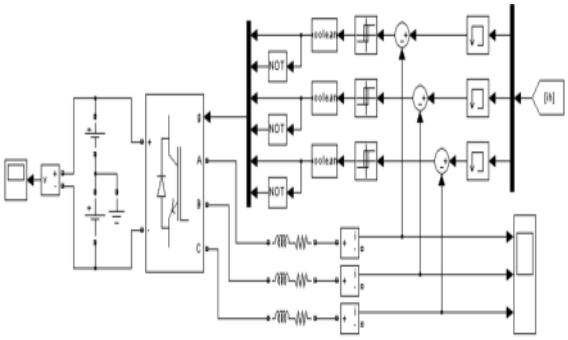


Figure 6 Simulation Model of Hysteresis Control Circuit

(1) Thyristor firing angle $\alpha = 30°$

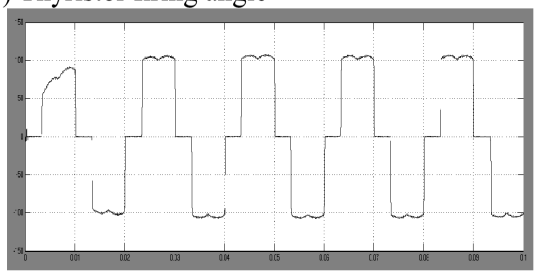


Figure 7 A-phase Current Waveform before Compensation

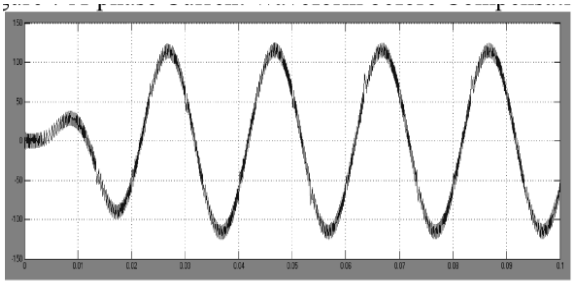


Figure 8 A-phase Current Waveform after Compensation

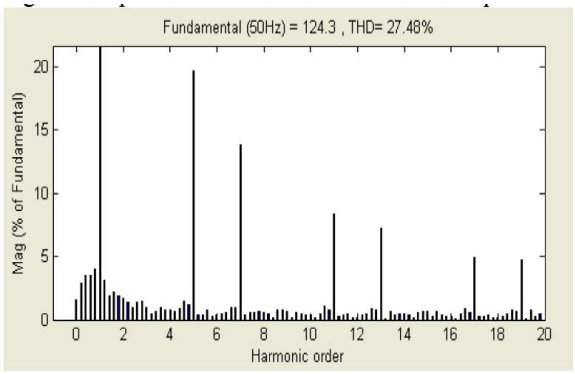


Figure 9 A-phase Current Spectrogram before Compensation

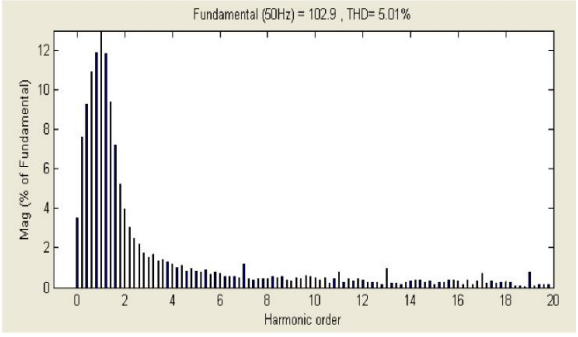


Figure 10 A-phase Current Spectrogram after Compensation

TABLE 1 Comparison of Grid Side Current Harmonic Content before and after Compensation When the firing angle is 30°

Harmonic number	five	seven	eleven	thirteen	Seven-teen
Content before compensation	20.77 %	13.08 %	8.95%	6.95%	5.58%
Content after compensation	0.83%	1.17%	0.75%	0.93%	0.72%

(2) Thyristor firing angle $\alpha = 45°$

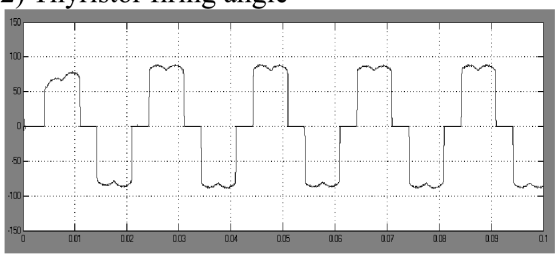


Figure 11 A-phase Current Waveform before Compensation

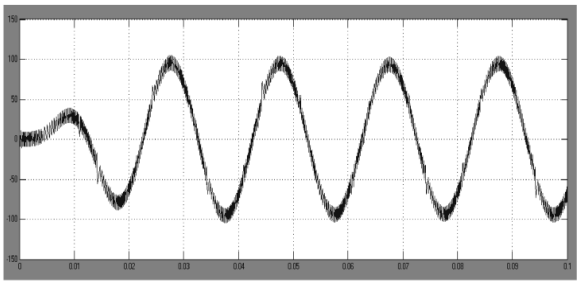


Figure 12 A-phase Current Waveform after Compensation

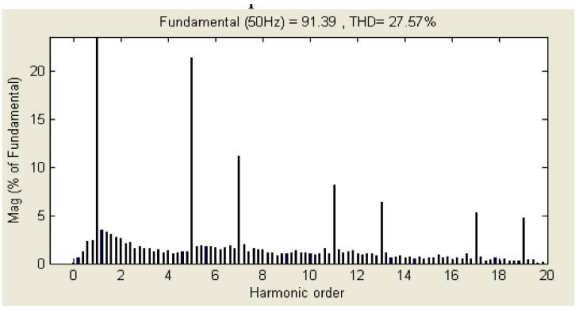


Figure 13 A-phase Current Spectrogram before Compensation

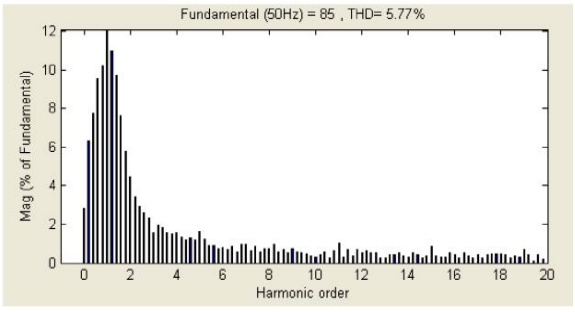


Figure 14 A-phase Current Spectrogram after Compensation

TABLE 2 Comparison of Grid Side Current Harmonic Content before and after Compensation When the firing angle is 45°

Harmonic number	five	seven	eleven	thirteen	Seven -teen
Content before compensation	21.43 %	11.16%	8.14%	6.36%	5.24%
Content after compensation	1.64%	0.94%	1.01%	0.23%	0.40%

(3) Thyristor firing angle $\alpha = 60°$

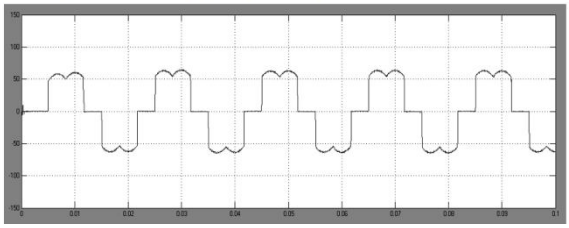


Figure 15 A-phase Current Waveform before Compensation

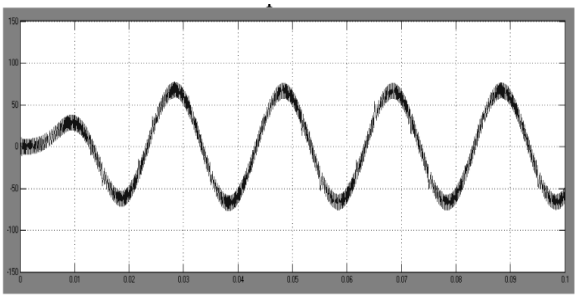


Figure 16 A-phase Current Waveform after Compensation

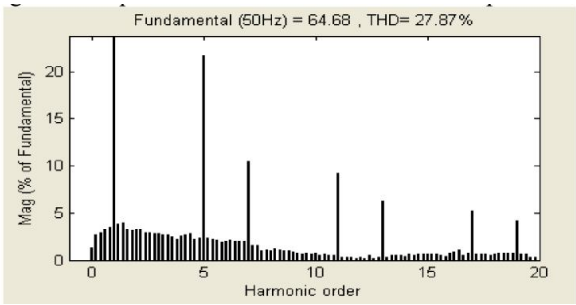


Figure 17 A-phase Current Spectrogram before Compensation

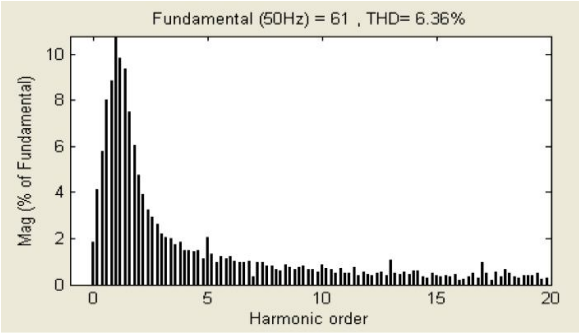


Figure 18 A-phase Current Spectrogram after Compensation

TABLE 3 Comparison of Grid Side Current Harmonic Content before and after Compensation When the firing angle is 60°

Harmonic number	five	seven	eleven	thirteen	Seven -teen
Content before compensation	21.63 %	10.43%	9.19%	6.22%	5.20%
Content after compensation	2.03%	0.32%	0.51%	1.05%	0.95%

From Figure 7 to Figure 18 is the analysis of a-phase current waveform and spectrum before and after APF compensation. Obviously, with the increase of firing angle, the distortion of current waveform becomes more serious. From Table 1 to Table 3, the current before compensation has the highest 5th harmonic content, and the content of major harmonics decreases with the increase of harmonic number. When APF is input, the content of 5th, 7th and 11th major harmonics decreases significantly, indicating that the compensation purpose of APF is effective and significant.

Table 4 Distortion Rate Corresponding to Different Thyristor Firing Angles

Thyristor firing angle	Current distortion rate before compensation THD	Current distortion rate after compensation THD
30°	27.48%	5.01%
45°	27.57%	5.77%
60°	27.87%	6.36%

According to Table 4, when the thyristor firing angle increases gradually from 30°, the current distortion rate will also increase gradually before and after compensation. Therefore, the compensation performance of APF will decrease with the increase of thyristor firing angle.

B. Triangular wave control

Triangular wave control model has basically identical parameters with hysteresis control model.

The details are as follows:

DC side voltage $U_{dc}=1000V$
Output inductance value $L_0=0.8mH$
Second-order low-pass filter frequency $f_c=30Hz$
Non-linear load resistance $R_d=4\Omega$, Inductance $L_d=20mH$
Non-linear load line parameter $R_L=0.05\Omega$, $L_L=0.01mH$
Three-phase voltage source $U=220V$, $f=50Hz$
Three-phase power side line parameter Rs $=0.05\Omega$, Ls $=0.015mH$
Thyristor firing angle $\alpha = 30°$
Carrier frequency 2KHz

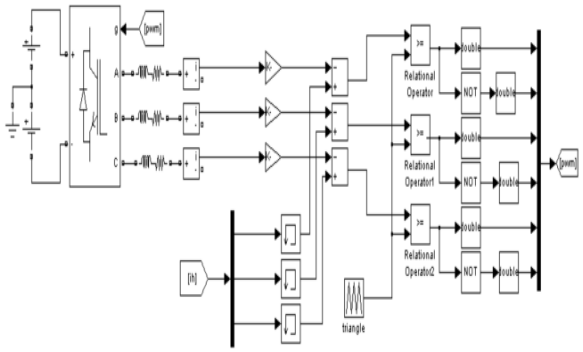


Figure 19 Circuit Simulation Model of Triangular Wave Modulation Control Method

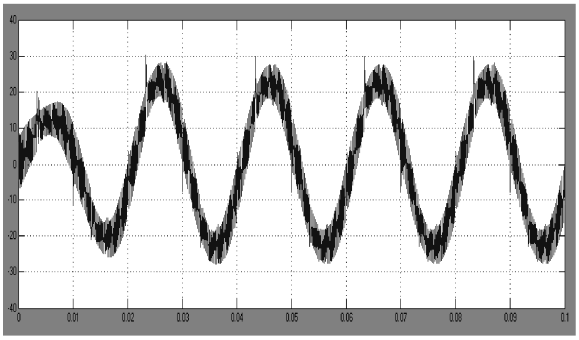


Figure 20 A-phase Current Waveform after Triangular Wave Modulation

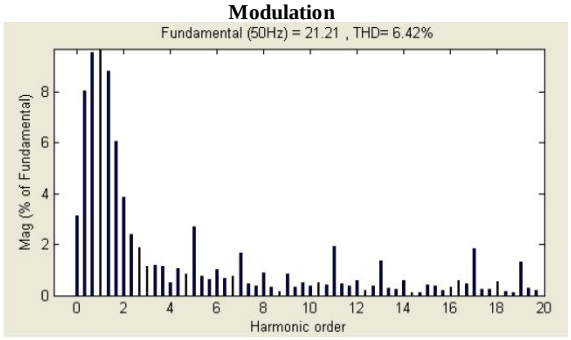


Figure 21 A-phase Current Spectrogram after Triangular Wave Modulation

Figure 21 is the a-phase current spectrogram after triangular wave modulation of APF under the triangular wave control method. According to this Figure, the content of 5th, 7th, 11th and 13th harmonic is 1.15%, 1.68%, 1.94% and 1.36% respectively, while the total distortion rate of a-phase current before compensation is 27.48%. However, the total distortion rate of a-phase current after compensation under the hysteresis control method is 5.01%. Therefore, with same compensation object, hysteresis control method has better compensation effect tan triangular wave control method.

CONCLUSION

This paper analyzes the APF control strategies, including PWM control methods and inverter DC side voltage control principles. PWM control methods mainly include hysteresis comparison, triangular wave comparison and dead-beat control. This Chapter is the simulation comparison analysis on the first two control methods. The experimentation shows that both the methods may effectively restraint harmonic, but the hysteresis control has better tracking performance under same conditions.

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