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Analysis and Specifications of Switching Frequency in Parallel Active Power Filters Regarding Compensation Characteristics

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Abstract

The switching frequency of a power device is a very important parameter in the design of a parallel active power filter (PAPF), but so far, very little discussion has been conducted on it in a quantitative manner in previous publications. In this paper, an extensive analysis on the effects of the switching frequency on the performance of a PAPF is made, and a specification of the switching frequency values with different compensation results is presented. A first-order inertia element and a second-order oscillation element are considered as approximate models of a PAPF, respectively. The compensation characteristic for each order of harmonic current is obtained at different switching frequencies. Then, the THDs of each model for the system loads of a rectifier with resistance and inductance loads are proposed. The compensation results of a PAPF controlled as a first-order inertia element are better than those of a PAPF controlled as a second-order oscillation element. With two types of system loads which are rectifier with resistance and inductance loads and rectifier with resistance, inductance and capacitance loads, the THDs of the source current after compensation are presented with different switching frequencies. The compensation characteristics for the most widely used digital control system are investigated. The situation with an analog control is the theoretical characteristic and it is the best situation. The compensation characteristic of the digital control is worse than the compensation characteristic of the theoretical characteristic. Based on these analyses, the specifications of compensation characteristics with different switching frequencies are quite straightforward. Finally, a practical design example is studied to verify the application.

Key Words: Compensation characteristics, Digital control system, Harmonics, Parallel active power filter, Switching frequency

I. Introduction

A parallel active power filter (PAPF) is an advanced harmonics current compensator which has been gaining wide attention in recent years [1-4]. A three-phase voltage source converter with switching devices is widely employed in PAPFs. The choice of the PAPF switching frequency is very important. In previous studies, the discussions about switching frequency were a significant part of the PAPF research. In general the higher the switching frequency, the better the compensation result. For example, with a switching frequency set at 10 kHz, they have good compensation characteristic because of the high switching frequency [5]. A transformerless 2-level inverter based Static Var Generator with multiple functions in medium voltage application was presented with satisfactory compensation result at 3 kHz [6].

"For the design process, three criteria were presented for choosing a switching frequency: the switching losses of semiconductor devices; the electromagnetic compatibility (EMC); and the radiation of the acoustic noise [7]. These methods are very useful for choosing a switching frequency. In [8], practical issues, including the switching frequency of the shunt active power filters were discussed. The factors determining the switching frequency were analyzed. Two papers were based on the switching frequency and losses. However, the compensation characteristic was not considered as one of the choice methods. Since the maximum inverter switching frequency is limited, especially at high power levels, the relationship between the switching frequency and the compensation result needs a detailed quantitative analysis.

In [9], a method for a voltage source inverter to reduce the switching frequency or the current harmonics for sinusoidal PWM with a constant switching frequency was proposed. It was found that the bigger the bandwidth, the better the compensation results. A number of methods which attempt to reduce the switching frequency and increase the bandwidth have been reported [10],[11], but these methods were a little too complicated. In [12], a non-linear digital control was used to break the bandwidth limitations. Since digital control affects the bandwidth, many digital control strategies have been proposed, such as predictive control, dead-beat control, repetitive control, and so on [13],[14]. In [15], a method to reduce the switching frequency was obtained. These control methods are valid, but the relationship between the switching frequency

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Fig. 1. Main circuit of the PAPF.

Fig. 2. Single-phase equivalent circuit.

Fig. 3. Phasors diagram.

Fig. 4. k_{hn} and switching frequency.

and the compensation characteristic must be analyzed before using these digital control strategies. Then the conclusions about whether these digital control strategies were needed and which kind of digital control strategy should be chosen were obtained. In order to reduce the switching frequency, many topologies have been applied to decrease device switching. Multi-level inverters have been paid a lot attention. In [16], a novel switching sequence design for five-level NPC/H-Bridge inverters with an improved output voltage spectrum and a minimized device switching frequency was presented. This method can reduce the device switching frequency and obtain a high inverter equivalent switching frequency. However, the relationship between the compensation characteristics and the inverter equivalent switching frequency was not proposed in detail. In [17], the paper investigated the harmonic content and the frequency response of multimodulator converters. Multilevel converters can reduce the device switching frequency, and guarantee a good compensation characteristic. However, these papers did not mention the method used in choosing the switching frequency regarding the compensation characteristics.

This paper focuses on the relationship between the switching frequency and the compensation characteristics. Then, it presents a design method for the switching frequency with a given requirement of compensation characteristics. In section III, the compensation characteristic for each order of harmonic current is presented at different switching frequencies. Then, the THDs for each model of the system load of a rectifier with resistance and inductance loads are proposed. The THDs of the source current after compensation are presented with different switching frequencies by using figures for both an analog control and a digital control. After that, both simulations and hardware experimental results are carried out to verify the analysis and specification in section IV. Then, section V presents an example to illustrate a design application. Finally the last section provides conclusions.

II. System Configuration and Analysis Method

Fig. 1 shows the main circuit diagram of a PAPF, where u_k $(k = a, b, c)$ is the phase source voltage, i_{LK} is the load current, i_{sk} is the source current, and i_{ck} is the output current. Assume that the system is balanced, then the single-phase equivalent circuit is shown in Fig. 2, where u_s is the source voltage, u_{L1} is the voltage of the inductor, i_c is the output current, u_c is the output voltage of the converter, and $Z = j\omega L_1$ is the impedance of the inductor.

The phasors relationship diagram of each order of harmonic is shown in Fig. 3, where $\dot{I}_{\rm hn}$, $\dot{I}_{\rm cn}$ and $\dot{I}_{\rm sn}$ are the load harmonic current, the output current and the source current, respectively.

The nth order harmonic of the load is expressed as (1) and the output current is obtained as (2).

$$i_{\rm hn}(t) = I_{\rm mn}\sin(n\omega t + \theta) \tag{1}$$

$$i_{\rm cn}(t) = k_{\rm hn}\cdot I_{\rm mn}\sin(n\omega t + \theta - \varphi_{\rm n}) \tag{2}$$

$$m_{\rm n} = \sqrt{2}I_{\rm sn}\Big/I_{\rm mn} \tag{3}$$

where, k_{hn} is the amplitude ratio and φ_n is the phase shift of the reference current and the output current. In $m_{\rm n} = \sqrt{1 + k_{\rm hn}^2 - 2k_{\rm hn}\cos\varphi_{\rm n}}$, the parameter mn reflects the compensation characteristic. From the equations, if k_{hn} and φ_n are

Fig. 5. φ_n and switching frequency.

Fig. 7. k_{hn} and switching frequency.

Fig. 6. Compensation characteristics.

Fig. 8. φ_n and switching frequency.

known, m_n can be found, that is, the compensation characteristic is obtained. When k_{hn} equals one and φ_n equals zero, it is a full compensation.

III. Switching Frequency Analysis and Specification

In [18], a model for PWM was presented, and the PWM was considered as a proportion and a first-order inertia element with a $T_s/2$ time delay (T_s was the switching period). The time delay was discussed in detail in [19]. The model mentioned above was based on the synchronously rotating reference frame. There were coupled parts in the control, and a decoupled control was presented in [20]. In [21], the coupled parts can be ignored when the cut-off frequency was much bigger than the frequency of the fundamental current. In [20, 22], the influences of the coupled parts on the control were analyzed. In this paper, the coupled parts are ignored. In the *abc* frame, the current loop is considered as a first-order inertia element (P regulator) and a second-order oscillation element (PI regulator). In [23], the bandwidth of a PAPF was usually selected as 1/5 of the switching frequency and it was easily realized [20, 24]. This cut-off frequency is in common use and can be realized. Therefore, in this paper, the cut-off frequency is chosen as 1/5 of the switching frequency.

A. Compensation characteristics for each order harmonic

When a PAPF is controlled as a first-order inertia element, the transfer function of the PAPF is shown in (4), where 1/T is the cut-off frequency. In Fig. 4 to Fig. 6, the compensation characteristics are shown.

$$G(s) = \frac{1}{1+Ts}. \tag{4}$$

From these figures, with the increasing of the switching frequency, the compensation characteristic becomes satisfactory. If an acceptable compensation result for each harmonic is known, the switching frequency can be chosen according to the figures.

When a PAPF is controlled as a second-order oscillation element, the transfer function of the PAPF is shown in (5), where 1/T is the cut-off frequency. In Fig. 7 to Fig. 8, the compensation characteristics are shown.

$$G(s) = \frac{1}{T^2s^2+2\xi Ts+1} \quad (\xi = 0.707). \tag{5}$$

From these figures, with the increasing of the switching frequency, the compensation characteristic becomes good.

B. Compensation characteristics for the system load of the rectifier with resistance and inductance loads

When the system load is a rectifier with resistance and inductance loads, which usually occurs in electrical plants, the load current and the output reference current are shown in Fig. 10, where the load current is an ideal rectangle waveform. The Fourier series of the load current from 0 to 2π is shown in (6). And, the THD of the source current (only the harmonic orders from 5th to 19th are considered) is shown in (7).

Fig. 9. Compensation characteristic.

Fig. 11. Compensation characteristic with different switching frequencies.

Fig. 10. Load current and output reference current.

Fig. 12. Single-phase equivalent circuit.

$$i_a = \frac{2\sqrt{3}}{\pi} I_d \sin \omega t + \frac{2\sqrt{3}}{\pi} I_d \sum_{\substack{n=6k\pm1 \\ k=1,2,3,\cdots}} (-1)^k \frac{1}{n} \sin n\omega t \quad (6)$$

$$THD = \sqrt{\left(\frac{1}{5}m_5\right)^2 + \left(\frac{1}{7}m_7\right)^2 + \left(\frac{1}{11}m_{11}\right)^2 + \left(\frac{1}{13}m_{13}\right)^2 + \left(\frac{1}{17}m_{17}\right)^2 + \left(\frac{1}{19}m_{19}\right)^2} \quad (7)$$

where:

$$m_n = \sqrt{1 + k_{hn}^2 - 2k_{hn}\cos\varphi_n}, \ (n=5,7,11,13,17,19).$$

The THD with different switching frequencies can be expressed as Fig. 11.

According to Fig. 11, when the switching frequency is 500 Hz, the compensation characteristic is bad. If the switching frequency is higher than 15 kHz, the THD of the source current becomes lower than 5%. In addition, the THD of the PAPF controlled as a first-order inertia element is lower than that of the PAPF controlled as a second-order oscillation element. The reason is that the phase lag of the second-order oscillation element is bigger than that of the first-order inertia element when ξ=0.707.

C. Influence of the system impedance

The single equivalent circuit of a PAPF is shown in Fig. 12 and the harmonic equivalent circuit is shown in Fig. 13.

For the influence of the source impedance, assume that the load is an ideal current source and that the load impedance is infinite. The control diagram can be carried out as in Fig. 14. The first-order inertia element is discussed as an example. K_p and K_{PWM} are the proportion coefficient and the inverter proportion coefficient. $Z_{sh} = j\omega L_s$.

The transfer function is presented in (8). The cut-off frequencies of each part are shown in (9) and (10).

$$G(s) = \frac{sL_s + K_p K_{PWM}}{s(L_s + L_1) + K_p K_{PWM}} \quad (8)$$

$$\omega_{n1} = \frac{K_p K_{PWM}}{L_s} \quad (9)$$

$$\omega_{n2} = \frac{K_p K_{PWM}}{L_s. + L_1}. \quad (10)$$

From the equations, the value of the source inductor L_s is much smaller than the value of L_1 in practice, so the influence of the source impedance on the bandwidth and the compensation characteristic is small.

For the influence of the source impedance and the load impedance, the load is not an ideal current source and the load impedance is finite. The influence of the source impedance and the load impedance on the bandwidth and the compensation characteristic are hard to obtain, because the load impedance is difficult to determine. When the source impedance is not zero and the loads are of different types, the compensation results are shown by using enormous computer simulations. The source line to line voltage is 380V and the power of the

Fig. 13. Harmonic equivalent circuit.

Fig. 14. control diagram.

load R is 50kW. The per-unit value is presented, and the RMS of the source line to line voltage and power are the based values. Fig. 15 and 16 are the two types of system loads.

From Fig. 11, the THD of a PAPF controlled as a first-order inertia element is lower than that of a PAPF controlled as a second-order oscillation element. So, in practical applications, a PAPF should be controlled as a first-order inertia element.

When a PAPF with an analog control system is considered as a first-order inertia element, in Fig. 17, the THD is presented with a different system impedance when the system load is a rectifier with RL load. Fig. 18 to Fig. 20 show the THDs of the rectifier with a RLC load with different values of L and C when the source impedance is different. From these simulation results, the relationship between the compensation results and the switching frequencies is carried out with different types of system loads.

Digital control systems are used wildly, but they have unique characteristics. In this paper, a digital system simulation is proposed. A harmonic compensation characteristics comparison between a digital system and an analog system with a different switching frequency is carried out. When the PAPF with a digital control system is considered as a first-order inertia element, the computer simulation results are carried out from Fig. 21 to Fig. 24, when the source impedance is different and the values of L and C are different. From these figures, the switching frequency can be carried out according to the values of L, C and the source impedance.

When comparing the compensation results between the analog control and the digital control, the bigger the frequencies are, the smaller the THDs are. Therefore, the compensation characteristics of the analog control are approximately equal to the theoretical characteristics, and the compensation characteristics of the digital control are worse than the compensation characteristics of the theoretical characteristics. The theoretical value is the best situation in terms of zero tracking error, no dead time and no delay time. The diagrams can be used as a reference for the best situation.

Fig. 15. RL load.

Fig. 16. RLC load.

By using these figures, the compensation characteristics are obtained with different switching frequencies and different system impedances.

IV. Simulation and Experimental Results

In order to verify the relationship between the switching frequency and the compensation characteristics, simulations were carried out.

According to Fig. 25, when the switching frequency was 1000Hz, the harmonic current caused by the switching frequency was great and the THD was almost the same as the THD before the compensation using the simulation results. When the switching frequency was 2000Hz, the influence of switching frequency was small. Therefore, when the switching frequency is lower than 1000Hz, other methods should be considered to eliminate the switching frequency harmonics. In this paper, the simulation switching frequency is above 2000Hz. This was also the lowest useful switching frequency for three-leg bridge inverters with an acceptable compensation result.

A. Analog system simulation

In Fig. 26 and Fig. 27, the system load was a rectifier with a RL load, where the source impedance was equal to zero. The simulation results of the 7th order harmonic current were almost the same as the theoretical results, that is, the converter was controlled as a first-order inertia element. Also, the compensation result was shown in Fig. 28, where the THD of the source current was carried out when the switching frequency was known. From these figures, the analysis and the specifications on the zero impedance and the rectifier with a RL load were verified.

B. Digital system simulation

There is a time delay in the AD sample/hold and the PWM. In [25-29], there may be a stability problem due to the digital control. In the simulation system, the source impedance was zero. The system load was a rectifier RL load. The

Fig. 17. THD of RL load with different source impedances.

switching frequency and the frequency of the AD sample/hold were 10 kHz. In Fig. 29 and Fig. 30, the magnitudes of the digital control and the analog control were approximately the same when only the harmonic orders from 5th to 19th were considered. However, the phase delay of the digital control was bigger than the phase delay of the analog control. It was expressed that the time delay of the digital control was bigger than that of the analog control. The compensation characteristics were shown in Fig. 31 and Fig. 32. In the analog control system, the THD was 6.0%, and in the digital control system it was 10%. Therefore, the conclusion can be drawn that the compensation result of the analogy control was better than that of the digital control. In Fig. 33, a comparison between the digital simulation results and the theoretical results was presented. The compensation characteristic of the analog control is approximately equal to the theoretical characteristic, and the compensation characteristic of the digital control was worse than the compensation characteristic of the theoretical characteristic. The theoretical value was the best situation in terms of zero tracking error, no dead time and no delay time. The diagrams can be used as a reference for the best situation.

C. Digital system hardware experiment

A hardware experiment was conducted to verify the conclusions. The switching frequency and the frequency of the AD sample/hold were 10 kHz. When the value of the P regulator was too big, there was a resonant result in Fig. 34. Fig. 35 was the load current before compensation, and Fig. 36 was the source current after compensation. The compensation result was best when there was no resonance. In Fig. 37 and Fig. 38, the current loop Bode diagrams of the transfer functions were presented to illustrate that the theoretical characteristics were the best situations for compensation, and that the analog control and the digital control were worse than it. The compensation results were proposed in Fig. 39. The THD of the source current from the 5th to 19th harmonic orders was 10.7%. From Fig. 21, the THD with digital control at 10 kHz was 10%. Therefore, the experimental result was approximately equal to the value of the digital control. The experimental results verified the compensation characteristics figures of digital control system. Then, the compensation characteristics figures for both the analog control and the digital control can be used as a reference for choosing a switching frequency.

(a) L=0.1 p.u.

(b) L=0.05 p.u.

(c) L=0.02 p.u.

Fig. 18. THD of RLC load with Z_s=0 p.u..

V. Design Example

An example is presented to explain the design of the switching frequency. A rectifier with a RL load is considered as an example, where $Z_s = 0$. If the THD of the source current after compensation must be lower than 10%, the switching frequency should be higher than 6 kHz according to Fig. 17, when the analog control system is used. In Fig. 40, the simulation result is shown with a switching frequency at 6 kHz. The THD was lower than 10%. When the digital control system was used, the switching frequency was higher than 10

(a) L=0.1p.u.

(b) L=0.05 p.u.

(c) L=0.02 p.u.

Fig. 19. THD of RLC load with Z_s=0.02 p.u..

kHz according to Fig. 21. In Fig. 41, the simulation result is shown with a switching frequency at 10 kHz. The THD was also lower than 10%. Therefore, the design method is valid.

VI. Conclusions

In this paper, an extensive analysis on the effects of switching frequency on the performance of a PAPF is carried out, and a specification of the switching frequency values with different compensation results is presented. The following conclusions can be obtained.

(a) L=0.1p.u.

(b) L=0.05 p.u.

(c) L=0.02 p.u.

Fig. 20. THD of RLC load with Z_s=0.05 p.u..

Fig. 21. THD of RL load with different source impedances.

(a) L=0.1p.u.

(b) L=0.05 p.u.

(c) L=0.02 p.u.

Fig. 22. THD of RLC load with Z_s=0 p.u..

(a) L=0.1p.u.

(b) L=0.05 p.u.

(c) L=0.02 p.u.

Fig. 23. THD of RLC load with Z_s=0.02 p.u..

(a) L=0.1p.u.

(b) L=0.05 p.u.

(c) L=0.02 p.u.

Fig. 24. THD of RLC load with Z_s=0.05 p.u..

(a) switching frequency at 1000Hz.

(b) switching frequency at 2000Hz.

Fig. 25. Frequency spectrum of compensation current.

Fig. 26. Relationship between k_{hn} and switching frequency.

Fig. 27. Relationship between φ_n and switching frequency.

1) The compensation characteristic of a PAPF controlled as a first-order inertia element is better than that of a PAPF controlled as a second-order oscillation element with ξ=0.707, when the THD of the source current is considered.

2) The relationship between the output current and the reference current is shown with different switching frequencies. The compensation characteristic is analyzed by using the THD of the source current according to the figures.

3) The compensation characteristics of the analog control and the digital control are analyzed, and the values of the analog control can be considered as the best situation. The compensation characteristics of the digital control were worse than the compensation characteristics of the analog control. The diagrams can be used as a reference for the best situation.

Based on these analyses, the specifications of the compensation characteristics with different switching frequencies are quite straightforward.

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Fig. 28. Compensation characteristic.

Fig. 31. THD of source current with analog control system.

Fig. 29. Current track of harmonics with analog control system.

Fig. 32. THD of source current with digital control system.

Fig. 30. Current track of harmonics with digital control system.

Fig. 33. Comparison between the digital system simulation results and the theoretical results.

Fig. 34. Source current with resonant parts.

Fig. 35. Load current and frequency characteristic.

Fig. 36. Source current and frequency characteristic after compensation.

Fig. 37. Comparison between the digital system experimental results and theoretical results.

Fig. 38. Digital system simulation results, experimental results and theoretical results.

(a) THD of source current before compensation.

(b) THD of source current after compensation.

Fig. 39. Digital system experimental results.

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Fig. 40. Compensation result of analog control system with 6 kHz.

Fig. 41. Compensation result of digital control system with 10 kHz.

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