Research on Low-Order Harmonic Suppression Strategy for Single-Phase Pwm Rectifiers

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Abstract. Single-phase Pulse Width Modulation (PWM) rectifiers are widely utilized in electrified railway systems and other power equipment. Yet, Single-phase PWM rectifiers generate low harmonics during operation, which leads to additional losses in power equipment and affects the grid quality seriously. The suppression of lower harmonics is the core to improving the performance of the power system. To effectively suppress the content of lower harmonics, this paper reviews the current progress of research on the suppression of low harmonics in single-phase rectifiers. In this paper, several commonly used control strategies are analyzed, such as the harmonic current suppression method of the voltage outer loop, the sliding average harmonic suppression algorithm, and the harmonic suppression algorithm based on feedback linearization. The outcome indicates that these algorithms have significant effects on the suppression of harmonic currents. By comparing the plus side and downside of various control strategies, this paper summarizes the effectiveness of existing methods in suppressing lower harmonics and the content of circuit Total Harmonic Distortion (THD) and puts forward the prospects for future research.

Keywords: Single-Phase Pwm Rectifier, Low Harmonics, Control Strategies

1 Introduction

Transistors are arguably one of the most widely used electronic devices in the 21st century. The transistor dates back 78 years to the discovery made by John Bardeen and Walter Brattain on the fourth floor of Bell Labs Building 1 in Murray Hill, New Jersey [1]. The rapid development of transistors has improved the efficiency of people's use of energy. Stihi proposes a single-phase pulse-width modulation (PWM) rectifier composed of transistors. It has the advantages of high energy density and a two-way flow of energy [2]. As an electronic device with a wide range of applications in the current power system, the single-phase PWM rectifier is widely used in the field of electric motorized AC transmission in the electrified railway system and is used in the common electronic devices in people's lives. However, with the large investment and application of electronic devices such as transistors and rectifiers, a series of problems have also arisen. Among them, the problem of serious low-order harmonic pollution caused by single-phase PWM rectifiers in the electrified railway system is particularly prominent. Low harmonic pollution will not only cause additional losses to the power

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equipment of the electrified railway system but also have an impact on the energy quality of the power grid in the power system. Traditional control algorithms for single-phase PWM rectifiers, such as d-q decoupling, convert active and reactive power to the rotating d-q axis. Although this method is supposed to reduce the content of second harmonics effectively in the current reference value (IREF), due to its complex parameter control, the calculation of the system is slow, and it is not suitable for the requirements of instantaneous change of current reference value in the railway system. Therefore, there is an urgent need for new suppression strategies to optimize single-phase PWM rectifiers. Therefore, to systematically sort out the low-order harmonic suppression of single-phase PWM rectifiers in academic circles, this paper introduces some related concepts of single-phase PWM rectifiers, fundamental waves, harmonics, and the causes and conditions of low-order harmonics and summarizes the harmonic current suppression methods of voltage outer loop, sliding average harmonic suppression algorithm and harmonic suppression algorithm based on feedback linearization.

2 Single-Phase PWM Rectifiers

The basic topology of a single-phase PWM rectifier has two adjustment modes: unipolar modulation and bipolar modulation [3]. Therefore, this article focuses on single-phase PWM rectifiers with unipolar modulation. For the convenience of the following text, the single-phase PWM rectifier is now referred to as PWM. Figure 1 shows the basic topology of a single-phase PWM rectifier.

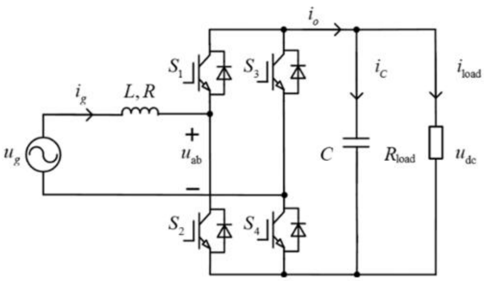

Fig. 1 Basic topology of single-phase PWM rectifier [4]

3 Fundamental and Harmonics

Assuming that the frequency of the required signal is f, the fundamental wave is the component of the sine wave equal to the longest period of the oscillation in a complex periodic oscillation, and its frequency is f. Harmonics refers to the components that are greater than integer multiples of the fundamental frequency obtained by Fourier series decomposition of periodic non-sinusoidal alternating quantities. And nth harmonics are other waves with a frequency of n*f. Where the fundamental frequency is the signal of frequency f. Therefore, the fundamental wave is also known as the first harmonic. Due to the loss of low harmonics on power equipment and the impact on the quality of the power grid, it is particularly important [5]. Therefore, the following strategies for the suppression of lower harmonics are introduced. Figure 2 shows the time-domain images of the 3rd harmonic and fundamental signals.

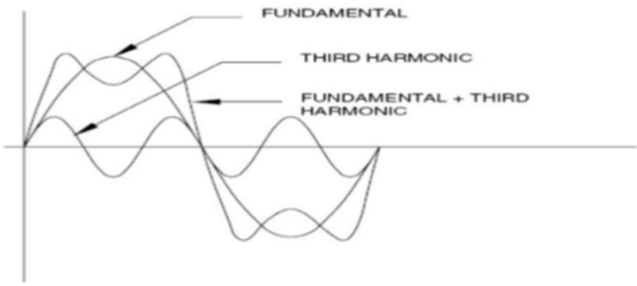

Fig. 2. 3rd harmonic and fundamental signals [6]

The low-order harmonic generation mechanism of PWM. Zhang gave the generation mechanism of the low harmonics of the single-phase PWM rectifier and finally obtained the following conclusions: the low harmonics of the PWM are mainly caused by the following three points:

1) The lower harmonic caused by the secondary ripple voltage generated during the signal acquisition of the AC voltage

2) Under the control of the double closed-loop PI, the low harmonics brought by the current command value Iref

3) In the inner loop of the current, the lower harmonics carried by the current command value gI fundamental

4 Low Harmonic Suppression Strategy of Existing PWM

4.1 Harmonic current suppression method for single-phase PWM rectifier with double closed-loop

Xu proposed a dual-closed-loop control strategy for a traditional PWM, utilizing PI control in the inner loop of the current [4]. PI control is widely applied in the control of the current inner loop of PWM because of its advantages of simple parameter setting, accelerated system response speed, and good stability. However, because it is difficult for PI control to achieve no static error tracking, and the value of iref in the circuit system changes rapidly, it is difficult for the current PI control to achieve the expected effect. Wang compared the advantages and disadvantages of PR control and PI control and pointed out that PR control can achieve static error tracking and Iref tracking without static error [7]. Therefore, PR control is more in line with the operation of electric railway automation. However, PR control of the current inner loop also has certain drawbacks. When PR control is used, the frequency band of the circuit system as a whole is narrowed, and the stability resistance to frequency response fluctuations will deteriorate. Therefore, Zhang proposed a double-closed-loop harmonic current suppression method for PWM: the traditional PI control is changed to PR control in the inner loop of the current so that the AC signal can be tracked without static error [8]. In the voltage outer loop control, the content of low harmonics is reduced by introducing a filter to achieve zero steady-state error. This method effectively suppresses the content of lower harmonics and expands the frequency band to make up for the problem of too narrow a frequency band caused by PR control. Zhang gave a case in which PR-control is used in the inner loop of the current, the method of introducing a f ilter is applied in the outer loop of the voltage, and the two suppression methods are taken at the same time [4]. After the FFT analysis, a comparison of the THD content, the third harmonic content, and the higher odd harmonic content is given. The relevant experimental data show that the above three inhibition methods can effectively reduce the THD content of the circuit system without any inhibition measures, and reduce the THD content of the circuit from 21% to about 8.3%. The suppression of the third harmonic has also changed from 18.43% to 1.05%, 1.12%, 0.16% and 0.10%. Among them, if the third suppression method is adopted, that is, the two suppression algorithms are used at the same time, the content of the higher odd harmonics can be effectively suppressed under the condition of reducing the third harmonic content to a low level. [8]

4.2 Theoretical compensation method and sliding average harmonic suppression algorithm for single-phase PWM rectifier

Now assuming the input voltage and current are pure sine waves and operate at a unit power factor.

$$\mathrm{u(t)} = \mathrm{Um}\sin \omega t \tag{1}$$

$$i(t) = \mathrm{Im}\sin\,(\,\omega t - \varphi) \tag{2}$$

Um, Im are the input voltage and current peaks, respectively, and the φ is the power factor angle.

From equations (1) and (2) above, it could be considered that the instantaneous power on the AC input side can be expressed as:

$$p(t) = \; u(t) * \; i(t)$$

That is, the AC input side power can be expressed as:

$$p(t) = \mathrm{Um} * \mathrm{Im} * \frac{cos\,\varphi}{2} - \mathrm{Um} * \mathrm{Im} * cos\,\varphi * \frac{cos(2\omega t)}{2} \tag{3}$$

The instantaneous power on the DC side is composed of two parts, one is the average power flowing through the load, and the other part is the ripple power when the ripple current flows through the DC output capacitor, and its expression is:

$$p(t) = \mathrm{UdId} + U * C * \frac{\mathrm{d}U}{dt} \tag{4}$$

where Ud and Id are the average output voltage and current, respectively. U is the output ripple voltage.

Now assuming that in the ideal state, there is no loss in power transmission, then there must be p(t) = p(t), which can be obtained from the equations (3) and (4).

$$U = -\frac{\mathrm{Um} * \cos\varphi * \mathrm{Im} * \sin 2\omega t}{4 * \omega * \mathrm{C} * \mathrm{Ud}} \tag{5}$$

(5) Above is the mathematical equation for the output ripple voltage. Based on the expression of the mathematical function, Yi first adopts a theoretical compensation method for the expression: that is, the magnitude of the required ripple is calculated from the theoretical calculation, to make ripple compensation to achieve the influence of voltage harmonics on the reference value of the current inner loop Iref. However, experimental simulations show that compared with the traditional suppression algorithms, the THD content is only reduced from 5.827% to 4.347%, and the suppression effect on the lower harmonics is not significant Yi also gave a suppression algorithm for suppressing voltage harmonics--moving average suppression algorithm: that is, the data set of capturing the sampling ripple is adopted, and the size of the sampling ripple is reduced by the method of averaging, to achieve the size of the suppressed sampling ripple, to reduce the downside of voltage harmonics on the current inner loop control. The experimental data show that a sliding window is given to stabilize the ripple component of the feedback voltage when the average will slow down the sampling rate. Experimental simulations show that compared with the traditional suppression algorithm, the moving average harmonic suppression algorithm reduces the THD content from the original 5.827% to 1.852%, and the suppression effect on the lower harmonics is more significant. [9]

4.3 A harmonic suppression algorithm based on feedback linearization for single-phase PWM rectifier

Deng proposed a new control method: a harmonic suppression algorithm based on feedback linearization. Before using the harmonic suppression algorithm for feedback linearization, Deng proved that the PWM has affine nonlinearity by presenting the knowledge of feedback linearization of affine nonlinear systems, thus trying to use a new control strategy: converting the current controller to LFB control. Based on the LFB control, to suppress the harmonic content in the circuit, Deng also filtered the PI control of the outer loop of the voltage: a notch filter was inserted to achieve the second harmonic component of the suppression current reference value iref. However, this filtering of the circuit system will result in a significant reduction in its dynamic performance. To compensate for this shortcoming, it is necessary to increase the proportional factor of PI, but this also causes a surge in current harmonics. Therefore, Deng also made a sliding mode controller for the current inner loop, which suppresses the current harmonics surged by the increase of the PI scale factor and enhances the anti-interference ability of the system. [10] For example, through simulation, the control strategy with a notch filter effectively reduces the size of THD from 6.94% to 4.78% compared to PI control and LFB control alone. On this basis, if the synovial membrane controller is added, the size of the signal THD will be further reduced to 3.0. In addition, the comparison of Deng's three FFT analyses shows that the content of lower harmonics such as the third harmonic can be effectively suppressed by filtering and introducing the inner ring sliding mode controller. Figure 3 shows the procedure of the control system for Deng. Figure 4 shows a flowchart about the ideal performance of a harmonic suppression algorithm based on feedback linearization.

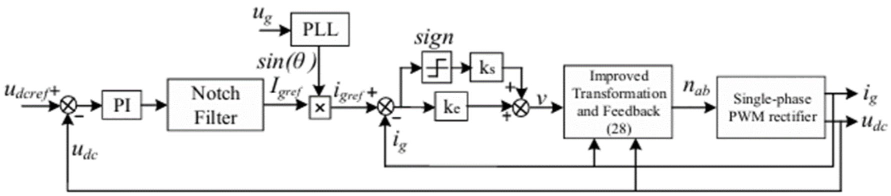

Fig.3. A system structure diagram based on harmonic suppression algorithm based on feedback linearization (Original)

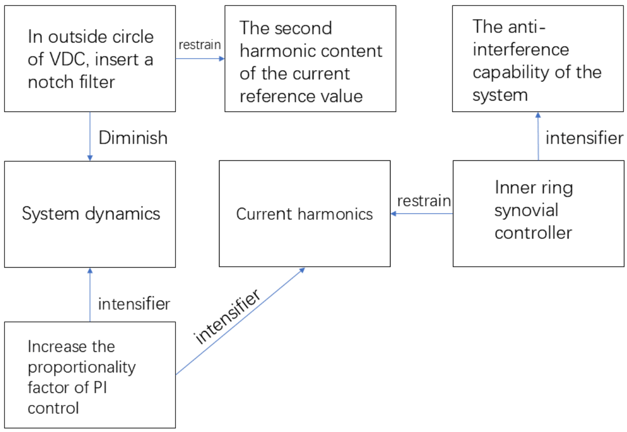

Fig. 4. About the ideal performance of a harmonic suppression algorithm based on feedback linearization (Original)

Given the three strategies given by Zhang, Yi, and Deng, the size of THD was effectively reduced in the laboratory simulation.

5 Challenges and Prospects

The double closed-loop suppression algorithm in 2.1 can not only suppress the voltage harmonics caused by the outer loop of the voltage without changing the bandwidth of the collected voltage but also effectively restrain the content of current harmonics generated by the secondary ripple voltage caused by the outer loop of the voltage. However, it is difficult to implement, and it is necessary to insert a notch filter with which parameters to achieve the best overall filtering effect. In addition, there are few studies on this method, and there is a lack of available data. However, the theoretical compensation method and the moving average algorithm in 2.2 only suppress the voltage harmonics under the working condition of the outer loop of the voltage, because the secondary ripple voltage cannot disappear, so the harmonics of the inner loop of the current are not considered to be affected by the harmonics of the outer loop of the improved voltage. Future research is able to focus on single-phase PWM rectifiers and study more suitable low-pass filter capacitors based on the double closed-loop suppression algorithm. In addition, based on the theoretical compensation method and the moving average algorithm, it is possible to reduce the content of harmonic current by inserting a filter into the inner loop of the current in the double closed-loop suppression algorithm, to further strengthen the suppression of the low harmonic content. For a harmonic suppression algorithm based on feedback linearization, whether its advantages and performance in practical application can be fully utilized still has a long road to studied. The analysis and improvement of the suppression algorithm of the low-order harmonics of the PWM will help to promote the implementation of railway power automation in China and improve the quality of the power grid.

6 Conclusion

Based on the circuit topology of the PWM, this paper first systematically sorts out the causes of its low-order harmonics and then analyzes several common methods for suppressing low-order harmonics in academic circles: the double-closed-loop suppression algorithm of PWM, the theoretical compensation method of PWM and the suppression algorithm of sliding average harmonics, and the harmonic suppression algorithm in view of feedback linearization of PWM. Among them, the double closed-loop suppression algorithm of PWM proposed by Zhang is as follows: the traditional PI control is changed to PR control in the inner loop of the current, to track the AC signal without static error, and in the voltage outer loop control, the filter is introduced to try to diminish the content of the low harmonics of the system, to implement zero steady-state error, and efficiently restrain the content of the lower harmonics while expanding the frequency band, to make up for the problem of too narrow frequency band caused by PR control. The theoretical compensation method and the suppression algorithm of the sliding average harmonic of PWM proposed by Yi are as follows: based on the function expression of the compensation ripple, the ripple voltage is reduced by the averaging method, and the sliding window is used to compensate for the slow sampling rate caused by the averaging. PWM proposed by Deng is a harmonic suppression algorithm based on feedback linearization, which is based on the application of the new algorithm LFB control, and the notch filter is added to the PI control of the voltage outer loop and the sliding mode controller is added to the current inner loop, to effectively reduce the size of THD. These three strategies are shown to be beneficial to the suppression of the content of lower harmonics in the final simulation experiments, and also greatly reduce the size of THD. A relatively good suppression strategy is given for the low harmonic suppression of PWM, and it is hoped that the low harmonic content that has an impact on system performance can be continuously reduced based on the suppression strategy given by the above-mentioned academic community in the future.

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