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Comprehensive Review on Harmonic Suppression by Filters in PWM Inverter Circuits

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Abstract:
As a core component of modern power electronics technology, PWM inverter circuit plays an important role in the fields of motor drive, renewable energy grid connection and power transmission. However, due to its high-frequency switching characteristics, the circuit introduces significant harmonic components in the output voltage and current, which affects power quality and may cause equipment loss, electromagnetic interference and grid stability problems. In order to effectively suppress harmonics, the filter has been widely used in PWM inverter circuit. Based on the impedance characteristics of passive components, the passive filter weakens the harmonics of a specific frequency through the LC or LCL network. Its structure is simple and its loss is low, but it has poor adaptability to dynamic harmonics. Relying on real-time harmonic detection and power conversion technology, the active filter can dynamically compensate for different load conditions, improve the harmonic suppression effect, and enhance the adaptability of the system to load fluctuations. The hybrid filter combines the advantages of passive and active filters, and improves the harmonic suppression ability while reducing the power loss. It is especially suitable for high-power inverter systems and complex load environments.

Keywords: PWM inverter circuit, harmonic suppression, filter, passive filter

1. Introduction

PWM (Pulse Width Modulation) inverter circuit plays an important role in the field of modern power electronics. It is widely used in AC motor drive, photovoltaic grid-connected system, UPS (Uninterruptible Power Supply) and other scenarios. PWM technology converts DC power supply into high-quality AC voltage or current through high-frequency switching control [1]. However, due to the limited switching speed of the switching device and the non-ideality of the PWM modulation method, the circuit inevitably

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generates harmonic components during operation, which affects the quality of the output waveform and causes a series of power quality problems [2]. The existence of harmonics not only reduces the power utilization rate of the system, but also may cause equipment heating, mechanical vibration, electromagnetic interference (EMI) and other problems, and even affect the stability of the power supply system. With the continuous development of power electronics technology, higher requirements are put forward for the harmonic suppression ability of PWM inverters. As the main harmonic suppression method, the filter can effectively reduce the harmonic content, improve the system performance and improve the power quality through reasonable circuit design and parameter optimization [3].

2. Harmonic characteristics of PWM inverter circuit

2.1 Mechanism of harmonic generation

The harmonic components of the PWM inverter circuit are derived from the switching modulation process and the non-ideal switching characteristics of the power devices. The basic principle of PWM technology is to generate a pulse sequence with a fixed switching frequency by comparing the high frequency carrier and the reference signal, so as to synthesize the AC voltage close to the sine wave. Since the PWM signal is essentially a periodic rectangular wave, its Fourier series expansion shows that the waveform contains a large number of high-order harmonics in addition to the fundamental component [4]. The harmonics of PWM inverter circuit are mainly determined by switching frequency, modulation index, carrier ratio and other parameters, and different modulation methods will affect the amplitude and distribution characteristics of harmonics.

The switching frequency and its frequency doubling components constitute the main part of the harmonic spectrum. Under the SPWM (Sinusoidal PWM) modulation mode, the harmonics in the output voltage are mainly concentrated near the carrier frequency and its frequency doubling component, while the low-order harmonics are relatively few. When the modulation ratio changes, the harmonic amplitude and distribution characteristics will also change. For asymmetric modulation methods, such as unipolar PWM, its harmonic components are more complex than bipolar PWM, and may introduce larger harmonics in the low frequency band, affecting the power quality of the system [5].

The switching characteristics of power semiconductor devices are also an important factor in harmonic generation. Ideally, the turn-on and turn-off of power devices should be instantaneous. However, in practical applications, due to the parasitic capacitance, parasitic inductance and switching loss of the device, overshoot, oscillation and delay will occur in the switching process, thus introducing additional harmonic components into the output voltage and current [6]. Especially in high-frequency PWM inverters, the influence of parasitic parameters is more significant, and the amplitude of higher harmonics may be further increased. In addition, in order to prevent the bridge arm through, the dead time (Dead-Time) is usually introduced into the control strategy of the PWM inverter, which will cause the output waveform distortion and lead to the increase of low-order harmonics [7].

2.2 The influence of harmonics on power system

The harmonic problem of PWM inverter circuit has many effects on the stability of power system and the reliability of equipment operation. Due to the existence of harmonic current, the copper loss and iron loss of transmission lines and transformers increase, which reduces the operating efficiency of the system. Harmonic current will cause additional hysteresis loss and eddy current loss in the transformer core, which will cause the temperature rise of the transformer. Harmonics may also lead to increased skin effect of power cables, increase the effective impedance of the line, and affect the power transmission capacity [8]. Electromagnetic interference is an important problem caused by harmonics. High-frequency harmonic components may interfere with the surrounding electronic equipment through conduction or radiation, affecting the normal operation of communication systems, measuring instruments and other sensitive equipment. In industrial automation and aerospace applications, electromagnetic compatibility (EMC) requirements are extremely strict, so effective filtering and shielding measures are needed to suppress the effects of harmonics. [10]

Harmonics will also have adverse effects on the relay protection and control system of the power system. The relay protection device in the power grid usually depends on the waveform signal of voltage and current to judge the fault state, and the existence of high-frequency harmonics may cause the relay protection to malfunction or refuse to operate. For example, in differential protection and distance protection systems, high-order harmonic components may interfere with the action criteria of protection devices and affect the reliable operation of the power grid. [11].

3 .The type and principle of filter in PWM inverter circuit

3.1 Passive filter (LC, LCL filter)

The passive filter mainly relies on passive components

(inductance, capacitance and resistance) to form a harmonic suppression network. By selecting the appropriate resonant frequency, the high-frequency harmonics can be attenuated or short-circuited to the ground, thereby improving the output waveform of the inverter. LC filter is the most basic low-pass filter structure, which is composed of series inductance and parallel capacitance. It provides a low impedance channel at the fundamental frequency, and forms a high impedance for high-frequency harmonics, so that it can be effectively attenuated. The filter is simple in structure, easy to design, and has low power loss. It has been widely used in motor drive systems and grid-connected inverters [12].

Compared with the LC filter, the LCL filter has an additional series inductance, which is better in harmonic suppression performance. The topology exhibits a steep attenuation characteristic near the switching frequency, which can more effectively reduce the high-frequency harmonic content and make the output voltage or current waveform closer to the sine waveform. [13]. At the same time, since the LCL filter may produce resonance at a specific frequency point, in order to suppress this problem, it is usually necessary to add a resistor to the shunt capacitor branch or adopt an active damping strategy to ensure the stable operation of the system.

3.2 Active filter (shunt and series active filter)

Active power filter relies on power electronic devices and digital control technology to realize dynamic compensation of harmonics by detecting harmonic components in real time and actively injecting compensation current or voltage with opposite phase. This type of filter can adapt to load changes and has strong harmonic suppression ability, which is especially suitable for dynamic load environments and occasions with complex harmonic components [14].

Shunt active power filter (SAPF) is a common topology. Its working principle is to detect the harmonic component in the system current in real time, and generate a compensation current with the same amplitude and opposite phase of the harmonic current through the power converter, so that the load side current is close to the sinusoidal waveform. The filter can effectively suppress a specific number of harmonics, and can be used for reactive power compensation to improve the power factor of the system. The series active power filter (SAPF) compensates the voltage source in series in the system voltage path to offset the harmonic voltage distortion and make the output voltage of the inverter approach the ideal sinusoidal waveform. This structure can effectively suppress voltage harmonics and improve voltage transient characteristics to combat grid imbalance. In some application scenarios with high voltage quality requirements, such as precision electronic equipment power supply systems, the filtering scheme can significantly improve the quality of power supply [15].

3.3 Hybrid filter

Hybrid filter combines the advantages of passive filter and active filter, which can not only reduce the power loss of passive filter in low frequency band, but also make up for the limitation of active filter in high frequency harmonic compensation ability. The filter usually uses an LC or LCL passive filter as the basic structure, supplemented by an active compensation circuit to achieve harmonic suppression in a wide frequency range [16]. In the hybrid filtering scheme, the active part is mainly used for high frequency harmonic compensation, while the low frequency harmonic is attenuated by the passive filter. This combination can significantly reduce the power capacity requirements of the active filter, improve the filtering efficiency of the overall system, and effectively avoid the resonance problem of the pure passive filter. Hybrid filters are widely used in grid-connected inverter systems, motor drive systems, and high-power industrial load environments to improve power quality and ensure stable operation of equipment. [17]

4.Analysis of harmonic suppression effect of filter

4.1 Filter performance evaluation index

The key indexes to measure the harmonic suppression ability of the filter include total harmonic distortion (THD), power factor (PF), spectrum analysis index and system loss. THD reflects the proportion of the harmonic component in the output current or voltage relative to the fundamental wave, which is the core index to measure the filtering effect. The lower THD indicates that the harmonic suppression effect is good, and the output waveform is close to the sinusoidal shape. Power factor is an important parameter to measure the efficiency of power conversion. The introduction of filters should not reduce the power factor of the system, otherwise it may affect the effectiveness of energy transmission. In the process of harmonic compensation, the filter should avoid additional reactive power exchange to reduce reactive power loss and improve the operating efficiency of the overall system [18]. The spectrum analysis method is used to evaluate the filter ‘s ability to suppress different harmonics. By comparing the amplitude of the harmonic components before and after filtering, the harmonic attenuation ability of the filter in a specific frequency band can be clarified. The loss characteristics of the system are also important evaluation parameters. The introduction of the filter may lead to additional power loss. Therefore, it is necessary to optimize the design to reduce energy loss and improve system economy [19].

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4.2 Comparison and application scenarios of different filters

Because of its simple structure and low cost, the passive filter is suitable for scenarios with high requirements for fixed-frequency harmonic suppression, such as industrial drive, grid parallel compensation, etc. However, it has poor adaptability to dynamic harmonic changes and may cause resonance problems due to improper parameter selection. Therefore, it needs to be accurately tuned in complex load environments.

Because of its good dynamic compensation ability, the active filter is suitable for applications with complex harmonic components and wide frequency range, such as nonlinear load power supply system, frequency converter power supply system and so on. Shunt active power filter has excellent performance in high-order harmonic compensation, which is suitable for reducing harmonic current, while series active power filter is more suitable for voltage quality control, such as power supply protection of precision equipment. The hybrid filter combines the advantages of passive and active filters and is widely used in high-power inverter systems, photovoltaic grid-connected systems, and smart grids. Its advantage is that it reduces the capacity requirements of active filters and improves the comprehensiveness of harmonic suppression. It is an ideal choice for high-power application scenarios. [20]

5. Conclusion

The wide application of PWM inverter circuits in modern power electronics technology has promoted the development of efficient energy conversion, but the harmonic problem has always been a key factor affecting system performance. Due to the switching characteristics and modulation mode of the PWM inverter, the output voltage and current inevitably contain high-order harmonics. These harmonics not only reduce the power quality, but also may cause equipment loss, electromagnetic interference and power system instability. In order to solve this problem, various filters are widely used in PWM inverter circuits to effectively suppress harmonic components, improve the quality of output waveforms, and improve the operating efficiency and reliability of the system.

The passive filter uses passive components such as inductors and capacitors to construct a low-pass filter network, and attenuates harmonics of a specific frequency through impedance matching and resonance characteristics. The LC filter has a simple structure and is suitable for the suppression of specific harmonic frequencies, while the LCL filter has stronger harmonic attenuation ability and performs well in high-frequency harmonic suppression. However, the passive filter has limitations in dynamic response, and may produce resonance problems that affect system stability. The active power filter can effectively suppress harmonics in a wide frequency range by detecting and compensating harmonics in real time through the power converter, and can adapt to load changes to achieve dynamic compensation. Shunt active power filter is suitable for harmonic current compensation, while series active power filter is mainly used to improve voltage quality. In practical applications, due to the large power capacity demand and high-power loss of active filters, hybrid filtering schemes are often used in high-power systems to combine passive filters with active filters to optimize filtering effects and reduce operating costs.

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