Comprehensive Analysis on Power Factor Correction Circuit

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Abstract. With the development of industrial power electronics, the current era can be called the "world energy era". Energy has never been more important, especially with the growing demand for today's "green" energy sources. power factor correction circuits have become an integral part of most current AC voltage input power applications, whether it is automotive battery power, portable energy storage (such as power banks), traditional server power, or lighting systems. However, the basic principles of power factor correction converters are rarely described in detail. This paper will summarize and illustrate the basic principle of the power factor correction circuit, and first introduce the research background of power factor correction technology; At the same time, three operating modes of power factor correction circuit are analyzed: continuous on-mode (CCM), critical on-mode (CRM) and discontinuous on-mode (DCM), and their advantages and disadvantages are to be further discussed. In addition, the PFC converters with optimized topology and excellent performance will be introduced, and the application prospect and prospect of three-phase PFC converters will be presented.

Keywords: Power Factor Correction; Topology; Boost; Totem Pole; Passive PFC; Active PFC.

1. Introduction

Environmental protection has become one of the key concerns of societies, governments and people from all walks of life due to the effects of greenhouse gas emissions, the scarcity of fossil fuels and their high and low prices. There is a growing concern to produce energy in a sustainable, efficient and beneficial way to minimize damage to the environment. Therefore, renewable electricity has become an alternative solution to meet society's requirements for the volume and security of fossil fuel supply.

Efficient and non-polluting use of electric energy is now a universal concern in all countries of the world. According to statistics, the actual application of more than 70% of the power is converted through the power electronic device to be used, but in the power electronic current converter device, the rectifier accounted for about 90%, and most of the use of uncontrolled or phase-controlled rectifier, power factor is low, injected into the grid a large number of high harmonics, a great waste of power [1]. Residents in daily life only need to pay for the actual power (wattage) consumed and will not pay for the amount of reactive power flowing back into the grid, while commercial factories will be the best part of the cost of the useless power, because of its consumption of power base is too large. Although residential users do not need to pay for the cost of electricity or useless power, according to the "European Union EN61000-3-2 standard": all power with more than 75W switching power supply needs to be installed at least a passive PFC (power factor correction) module. In addition, in the 80Plus power supply certification, it is required that the power factor needs to exceed 0.9, or even more.

Therefore, since the mid to late 1980s, the solution to power loss has gradually become a research hotspot in the field of power electronics technology. Academic and engineering research on harmonic suppression, there are two main ways to solve harmonic pollution: one is the implementation of harmonic compensation of the power grid, and the other is to improve the power electronic equipment itself. The former includes passive filtering and active filtering (APF) of the power system, and the latter includes passive and active power factor correction (PFC) of power electronic devices [2, 3].

Power factor is one of the measures for the safe and efficient use of electrical energy. From initially because of a large number of inductive loads into the grid brought about by the reactive power loss,

to later because of a variety of non-linear rectifiers into the grid brought about by harmonic pollution, and then to the current power electronic devices, especially switching power supplies are widely used and brought about by a large number of harmonics on the grid, the power factor correction technology has gone through the reactive power compensation to the passive, active filtering, and then to active power factor correction and the unit of power factor conversion technology development process. Power factor conversion technology development process. The development of power factor correction technology has become an increasingly important part of the development of power electronics technology and has become an important support for the further development of power electronics technology.

At present, with the enforcement of worldwide harmonic standards, the production and manufacture of power electronic devices with low harmonic pollution will become an inevitable trend. In recent years with the continuous research of PFC technology, single-phase power factor correction technology is more researched, and it is quite mature in terms of circuit topology and control.

In this context, the aim of this study is to analyze and compare the above-mentioned existing techniques in the development of power correction circuits for AC-DC boost converters with high input power factors and regulated voltage. This paper presents a review of PFC circuit topologies in order to identify the characteristics, advantages and disadvantages of using such topologies with respect to complexity, cost and applications. The main contribution of this paper is to introduce and analyze in detail several topologies commonly used for PFC circuits so far. Important aspects of converter performance are analyzed in terms of input and output current and voltage, switching tube characteristics etc.

2. Power Factor Correction

The power factor is the ratio of active power to apparent power (total power consumption). If the phase difference between AC voltage and current is φ, then power factor (PF) = cosφ. If you want to improve the efficiency of the circuit, then you must find a way to improve the PF. through the study of power electronics, we know that the switching power supply is a capacitive input type circuit, the phase difference between the current and voltage will cause the loss of exchange power, pure resistance is a power-consuming device, the AC power under different loads of the Voltage and current phase are different, pure resistance load on the current and voltage in phase, in pure capacitive load on the current ahead of the voltage 90°; in pure inductive load on the voltage ahead of the current 90°. PFC is mainly to control the waveform of the input current, so that it is synchronized with the waveform of the input voltage, to improve the power factor, to reduce the harmonic content, so that the power supply output current is more stable, to prevent the input power supply "crash test". "PFC circuits are mainly used in new energy batteries, personal computers, server systems and other electronic products that require a large amount of power supply. Inductive load PFC, as shown in Fig. 1.

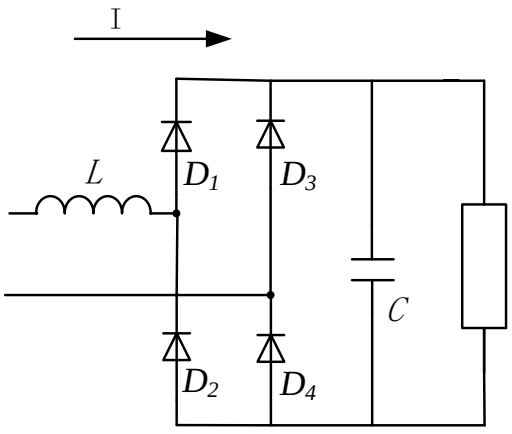


Fig. 1 Inductive load PFC [3]

3. Basic classification and topology of PFC circuits

With the development of power electronics technology, the current PFC has two kinds of a passive PFC circuit and an active PFC circuit two.

3.1. Passive PFC

"Passive" refers to the use of transistors and other active components of the correction circuit, generally composed of diodes, resistors, capacitors and inductors and other passive components [4]. In practice, passive PFC was once widely used because of its relatively low cost [5].

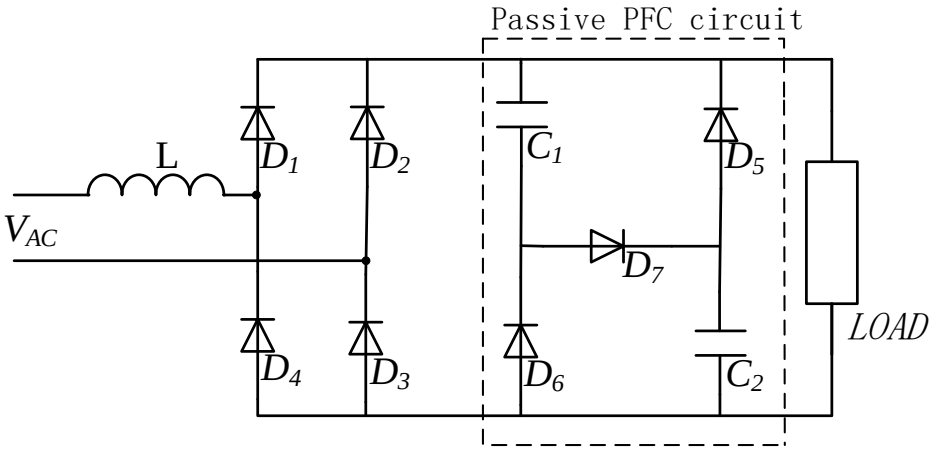


Fig. 2 Valley-filled passive PFC [4]

The Fig. 2 shows a valley-filling passive PFC circuit diagram to analyze the operating principle of this passive PFC circuit work. Let the peak value of the AC input voltage be Um, and the pulsating DC voltage of the bridge rectifier output beU_{BR} , in the positive half cycle of the AC supply($0 \leq \omega t \leq \pi$).

(1) at $0 \leq \omega t \leq \pi / 2$, the AC voltage changes from 0 to the peak Um according to the sinusoidal law, the diodes D1 and D3 in the bridge rectifier circuit conduct, the power supply current flows to the load on the one hand, on the other hand, along the series circuit of C1,D7, C2 to the capacitor C1,C2 charging.C1,C2's capacity is equal, so at any moment, the voltage at the ends of the series connection of C1.C2 is equal to the voltage output from bridge rectifierU_{BR}.C1,C2 series voltage is equal to the output voltage of the bridge rectifier at any time, when the AC input voltage reaches the peak value of Um, C1,C2 series voltage is also equal to UP, C1,C2 series voltage are Um / 2.

(2) In $\pi / 2 \leq \omega t \leq \pi$, the bridge rectifier output voltage U_{BR} began to decrease from Um, the series voltage of C1, C2 is higher than U_{BR} D7 cut-off, the charging of C1, C2 stops, but D1, D3 is still on, the power supply still provides current to the load. When the value of U_{BR} is reduced to Um / 2, D1, D3 cut-off, capacitor C1, C2 parallel to the load power supply. In the negative half cycle of AC power supply, the four diodes D1, D2, D3 and D4 of the bridge rectifier circuit are turned on, and D1 and D3 are cut off. The valley filling circuit is still positive and negative pulsating DC, capacitor C1, C2 charging and discharging process, diode D5, D6, D7 conduction is the same as the positive half cycle.

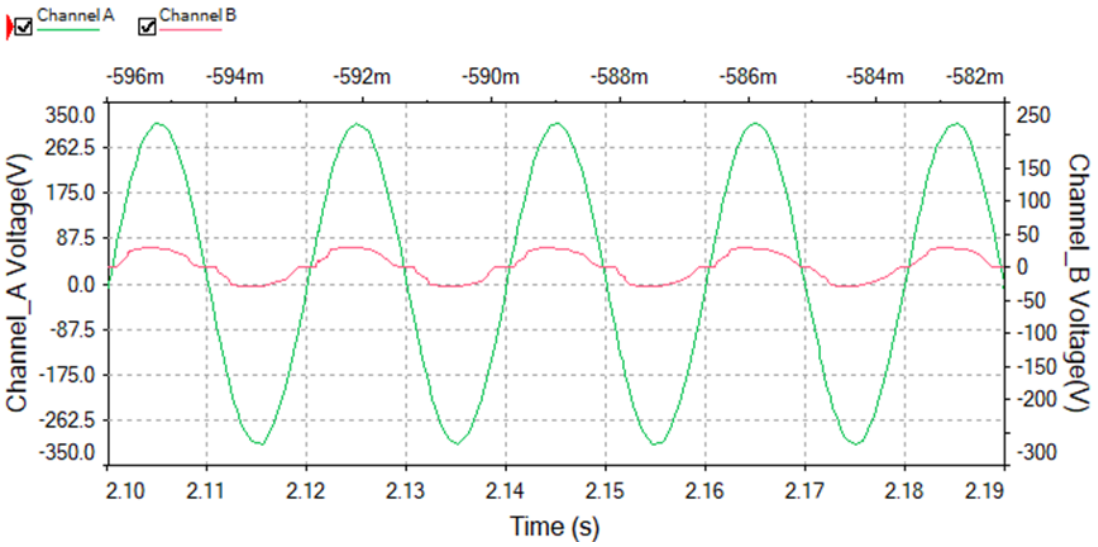


Fig. 3 Input voltage and current waveform of valley-filled passive PFC (Photo/Picture credit: Original)

Input voltage and current waveform of valley-filled passive PFC, as shown in Fig.3.A brief analysis of the passive PFC circuit operation we can see that with the selection of C1=C2=22μF/200V, the line power factor is up to 0.918, the third current harmonic is only about 15%, the fifth harmonic is about 7.7% and the total harmonic distortion THD is about 33.98%. Although this PFC circuit has the advantage of low cost, the output voltage ripple is large and has low values. The current harmonic components of this PFC cannot fully meet the requirements of low distortion [6], so this type of PFC circuit design method has now been gradually replaced by active.

3.2. Partially Switched PFC

Compared to passive PFC, partially switched PFC adds a switching device to improve the power factor by extending the power supply current output time. Partially Switched PFC, as shown in Fig. 4. When the switching device is on, the power from the supply is stored in the inductor.

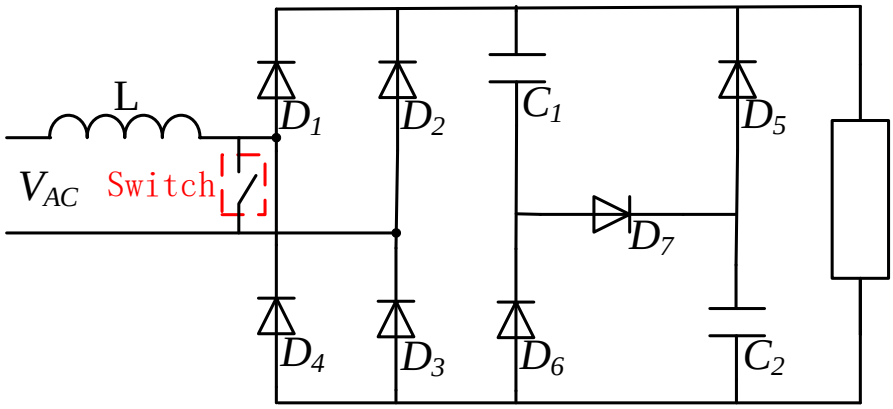


Fig. 4 Partially Switched PFC [4]

3.3. Active PFC

Active PFC circuit has a very good effect, basically can completely eliminate the distortion of the current waveform, and the phase of the voltage and current can be controlled to maintain the same, it is basically a complete solution to the power factor, electromagnetic compatibility, electromagnetic interference, but the circuit is very complex.

The topology of the basic active PFC (utilizing a buck circuit) is shown below [7]. The red arrow represents the current path when the MOSFET is on, and the green arrow shows the current path when the MOSFET is off.

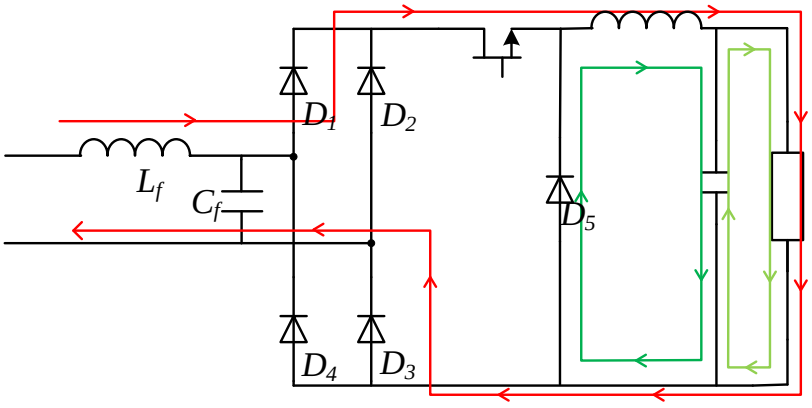


Fig.5 Active buck PFC [7]

When the switch is closed, the power supply charges the inductor and the output, the charging time is t1, at which time the inductor current increases linearly; after the switch is closed, the inductor discharges to the load, the duration of this phase is t2, at which time the inductor current decreases linearly; after the inductor current decreases to zero, the output capacitor delivers the current to the load.

According to the current conduction mode, active PFC can be divided into 3 modes: discontinuous on-mode (DCM) modes, the continuous on-mode (CCM) modes, and critical on-mode (CRM), and the comparison are summarized in Table 1.

Table 1. Comparison between different modulation

paradigm	Control methods	Output Capacity and applications	Advantage	Drawbacks
CCM	PWM	＞300W Industrial Power Supplies	Low current ripple Low peak current, low turn-off loss	Long conduction losses and long reverse diode recovery time
CRM	PFM	75-300W TV, PC, Commercial Power	Small current ripple Small conduction loss	High peak current and high turn-off loss
DCM	PWM	25-100W LED Lighting, Small Capacity Power Supplies	Small conduction loss	High ripple current High peak current and high turn-off loss

3.3.1 Continuous conduction mode CCM

In continuous conduction mode, CCM operating mode current waveform, as shown in Fig. 6. There will always be current flowing through the inductor, so the MOSFET needs to turn on before the inductor current becomes zero. Typically, CCM operates at a fixed frequency to control the input current as a sinusoidal waveform. The advantage of CCM over other modes is that it reduces the ripple of the inductor current. The disadvantage is that when the MOSFET is turned on, the voltage from the filter capacitor is applied to the diode in reverse, and since the minority carriers in forward conduction are still clustered on both sides of the PN junction, the diode develops a large reverse current because of the drift motion of the minority carriers under the action of this reverse voltage.

This reverse current, together with the inductive current will flow through the MOSFET, so the MOSFET will produce a large turn-on loss. In order to reduce the turn-on loss, it is recommended to use SiC Schottky diodes to take advantage of the short reverse recovery time of Schottky diodes.

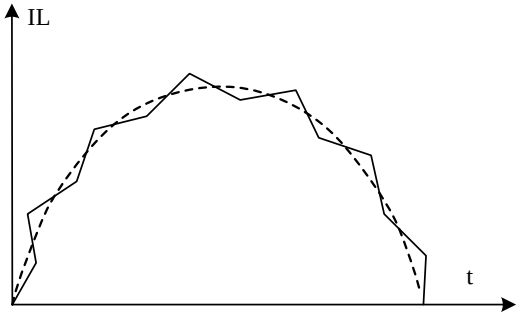


Fig. 6 CCM operating mode current waveform [4]

3.3.2 Critical conduction mode CRM

In critical conduction mode, CRM operating mode current waveform, as shown in Fig. 7. the MOSFET will turn on when the inductor current drops to 0, so the turn-on loss of the MOSFET is small. The CRM needs to monitor the circuit output voltage and then adjust the MOSFET pulse width according to the voltage. When the output voltage is too high, it will decrease the MOSFET pulse width; when the output voltage is too low, it will increase the MOSFET pulse width. So, the resonant frequency will also not be fixed as it needs to be adjusted according to the output voltage.

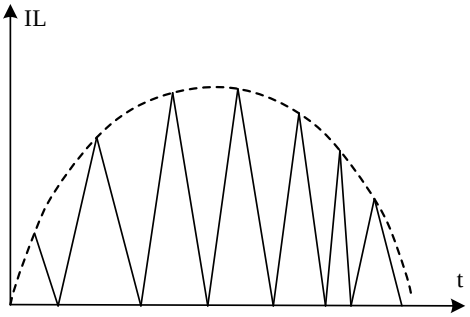


Fig. 7 CRM operating mode current waveform [4]

3.3.3 Discontinuous conduction mode DCM

In discontinuous conduction mode, DCM operating mode current waveform, as shown in Fig.8. there are periods of zero current in each cycle. Compared to the other two modes, DCM has higher peak currents, higher MOSFET turn-off losses, and lower overall efficiency of the circuit. However, DCM is not affected by the diode reverse recovery time and the MOSFET turn-on losses are small.

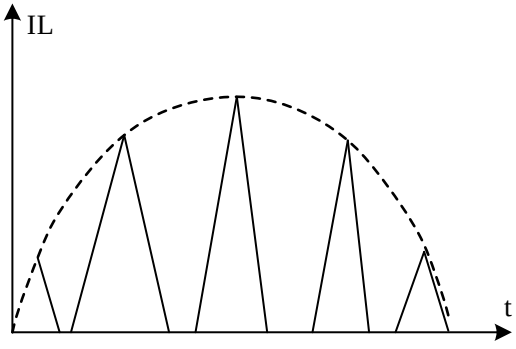


Fig. 8 DCM operating mode current waveform [4]

4. PFC circuit optimization topology

Traditional PFC circuits often use silicon devices as power conversion devices [8], silicon device performance development has almost reached the limit, but in modern high-frequency occasions gradually cannot meet the efficiency requirements. In recent years based on gallium nitride (GaN), silicon carbide (SiC) based on the third generation of wide-bandwidth semiconductor devices began to receive attention, based on the GaN material switching tube has a fast-switching speed, low switching losses and no reverse recovery problems, for power factor correction circuit technology to further innovate to provide the conditions.

4.1. Bridgeless boost PFC circuit

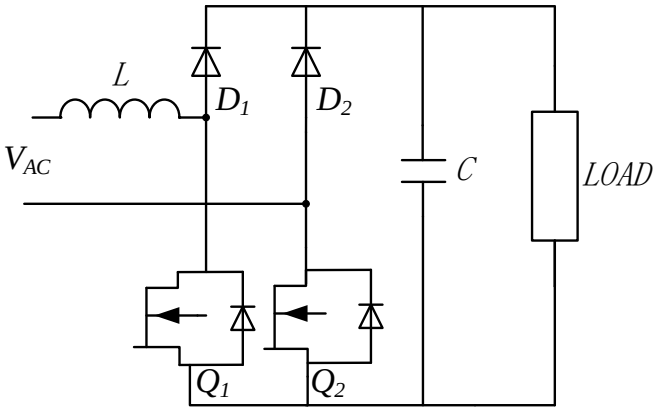


Fig. 9 Bridgeless boost PFC circuit [8]

Bridgeless boost PFC circuit, as shown in Fig.9.A Bridgeless PFC converter scheme is proposed by foreign countries, in 1983, by Rockwell's D. M. Mitchell. first proposed the basic bridgeless Boost PFC converter scheme, as shown in the figure, compared with the traditional Boost PFC scheme which reduces the number of switching devices in the conduction path, thus improving the efficiency by reducing the conduction loss.

The traditional bridgeless Boost PFC circuit topology often uses MOSFET as the main switching tube, however, there is a body diode reverse recovery problem with MOSFET, and if it works in the CCM mode, the body diode reverses recovery results in large losses, which affects the efficiency of the circuit.

Bridgeless PFC in the positive and negative half-cycle, two tubes a renewal of a high-frequency switch, the advantages of this topology are the use of power components is relatively small, the two tubes can be driven together, simplifying the design of the drive circuit, while allowing the direct use of traditional APFC control chip has become possible. However, it also has several problems, the current flow direction is complex and not common ground, current sampling difficulties, and there is a large common mode interference so the input filter should be carefully designed. But the bridgeless PFC is subject to EMI problems and the constraints of the semiconductor manufacturing technology and digital control technology at that time and cannot really get the application.

4.2. Totem Pole Bridgeless PFC Circuit

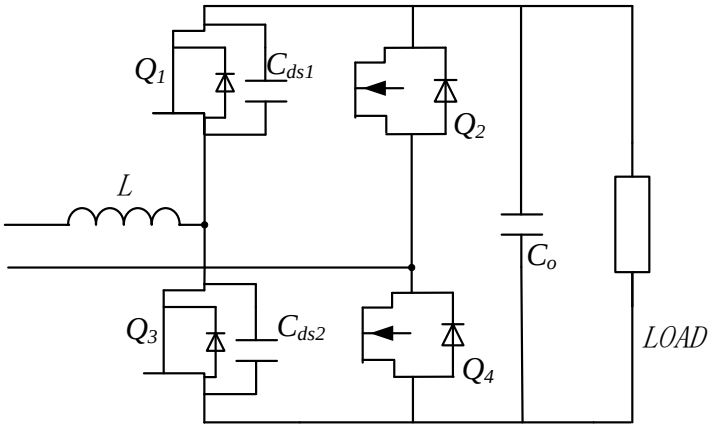


Fig. 10 Totem pole bridgeless PFC circuit [8]

Totem pole bridgeless PFC circuit, as shown in Fig. 10. Totem pole type bridgeless PFC circuit topology as shown in Figure, the topology of the main circuit structure is simple, consisting of a high-frequency bridge arm and low-frequency bridge arm, in which the low-frequency bridge arm switching tubes Q2, Q4 switching state corresponds to the positive and negative cycles of the input signal, so that the positive and negative polarity of the voltage at the ends of the capacitor Co is always unchanged; high-frequency bridge arm switching tubes Q1, Q3 alternately on to form a Boost PFC structure, to realize the power factor correction. Totem pole bridgeless PFC circuit topology is essentially a Boost PFC circuit topology, and thus can work in the CCM, DCM and CRM state, but because the totem pole bridgeless PFC topology using MOSFET body diode current continuation, the traditional Si material MOSFETs have a large reverse recovery current, recovery time is long, and with the increase in the switching frequency of the reverse recovery time increases in the whole switching cycle, which will lead to the problem of the power factor correction. As the switching frequency increases, the proportion of reverse recovery time in the whole switching cycle increases, which will lead to a reduction in the converter efficiency and is prone to the problem of large current spikes. Therefore, the totem pole bridgeless PFC converter using Si devices often only works in the DCM and CRM states, which limits the output power of the converter. To solve this problem, high-frequency bridge-arm switching devices are replaced with cascade-type GaN devices. The good reverse recovery performance of GaN devices is used to improve the overall efficiency and stability of the circuit [9].

4.3. Bidirectional Switching Totem Pole PFC

Bidirectional switch totem pole PFC, as shown in Fig.11.The topology of the bidirectional switching totem pole PFC converter shown in Fig. L is the filtering inductance of the main circuit of the PFC converter, and a reasonable inductance is generally selected according to the design of the input current ripple of the converter, C0 is the output filtering capacitance of the main circuit of the converter, and S1H is composed of bidirectional switching tubes along with S1L and D1, and the two groups of bidirectional switching tubes above and below the same bridge arm have the same parameter selection. S1 is a 650 V high-voltage MOSFET, S1L is a 60 V low-voltage MOSFET, and D1 is a 650 V high-voltage SiC diode. In the connection mode, S1H and S1L are connected in series in the reverse direction, and the SiC diode D1 is connected in parallel with the series of bi-directional switches as the continuity channel of the dead time period. On the other side of the bridge arm switching tube group S2H, S2L and D2 are connected in the same way. The inverse series connection of high-voltage and low-voltage MOS tubes and the rational use of silicon carbide devices together form a bidirectional switching totem pole PFC converter bi-directional switching tube group structure, which makes it possible for the traditional totem pole PFC converter to work stably in the CCM mode [10]. In the bi-directional switching tube group, the two MOSs do not use high-voltage MOSFETs, but high-voltage and low-voltage MOSFETs are connected in series because the low-voltage

MOSFETs have very small on-state losses. The on-state impedance of the popular low-voltage high-current MOSFETs in the market is often less than 10 mΩ, and their on-state loss is often negligible. Compared with the traditional totem pole PFC converter structure, when it works in the steady state, it will not cause a large circuit on-state loss because of the additional switching tubes, losing the efficiency advantage of the bridgeless PFC converter.

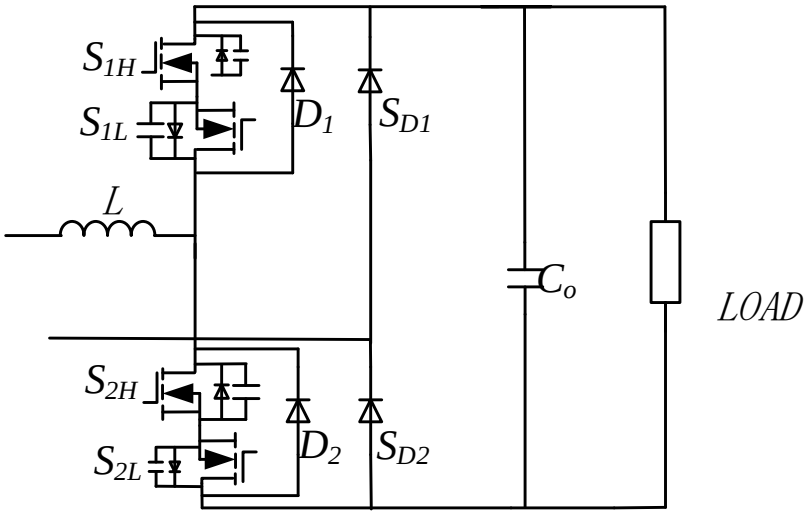


Fig. 11 Bidirectional switch totem pole PFC [8]

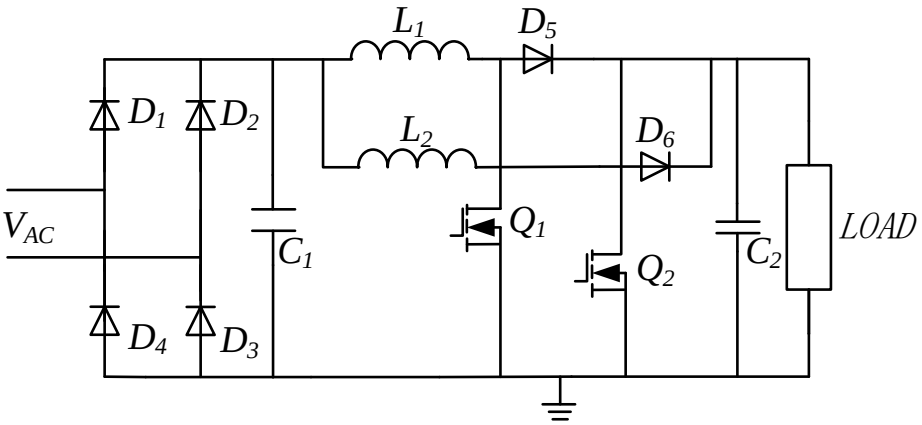


Fig. 12 Interleaved Boost PFC [8]

4.4. Interleaved Boost PFC

Interleaved Boost PFC, as shown in Fig.12.Interleaved boost PFC is the most common power factor correction topology. This topology incorporates a boost converter in addition to a rectifier diode bridge to convert the AC voltage to a DC voltage [11]. The boost converter raises the voltage to a higher value, which reduces the output voltage ripple and shapes the current into a sinusoidal waveform [12].

The two-phase interleaved parallel Boost PFC converter is basically the same as the single-phase boost converter, and each phase of the Boost PFC converter operates in basically the same way as the single-phase boost converter, which is controlled separately through two separate current amplifiers sharing a current reference principle while distributing an average current on both PWM outputs to maintain a stable and low-distortion sinusoidal input line current. When the two-phase currents are balanced, the two power stages operate in staggered phase shifts of -180°, which can speed up the transient response of the system. At the same time, in the inductor design of the staggered parallel circuit, the current flowing in a single inductor account for only half of the total input current, which largely controls the area of the inductor core, so the two single-phase Boost PFC converters are staggered in the circuit. Therefore, two single-phase Boost PFC converters are interleaved in parallel

in the circuit to meet the reduced capacity requirements of the power supply circuit for the input EMI filter and output filter capacitors, which can be replaced with smaller capacitors to improve the dynamic response of the system while saving capacitor costs. This topology necessitates the use of two inductors, with uncertainty in the direction of current flow, and the possibility that the low-frequency diode and the body diode of the MOS may conduct at the same time, increasing instability.

Table 2. Comparison between different Pfcs

Active PFC Topology	Applicable places	vantage	drawbacks
Bridgeless Boost PFC	·High Power Occasions	·Fewer power components used - simplifies control circuit design	·High losses in the rectifier section on the input side - low-efficiency limit ·Complex current flow - difficult sampling with large common mode interference
Totem Pole Bridgeless PFC	·High Power Density Applications ·high-end servers and telecommunication systems	·Low number of switching elements ·high power density ·Significant common mode rejection	·Requires additional active switching - complex control circuitry. ·Use of power diodes - high on-state voltage drop, high losses
Bidirectional switching totem PFC	·High Power Occasions ·Example: New energy tram power supply	·High power density ·High common mode rejection ·Diode material advantage - can operate in CCM mode	·Heavy losses in reverse recovery - Unreliable for long-term operation
Interleaved Boost PFC	·High Power Density Applications	·Extra Branch - Reduced Output Voltage Ripple, Small Layout Size, Low Cost, Low EMI ·Interleaved structure - increased efficiency and reduced input ripple	·Need more switches. ·High conduction loss

4.5. Topological comparison

Analysis of four modern commonly used PFC circuits, they are used in high-power occasions, from bridgeless boost PFC to totem pole bridgeless PFC to bidirectional switching totem PFC and finally to the interleaved boost PFC, step by step to optimize the topology, from the initial single-phase optimized topology to the two-phase topology, as well as in recent years the development of the three-phase PFC topology, whose basis, although they are all used in the single-pole PFC, but in the constant In the optimization process, while reducing the power components, improving the common mode rejection capability and reducing the ripple, the complexity of the control circuit caused by the increase of the three-phase and the difficulty of analyzing the current flow direction is also concurrently present, and the power of the three-phase PFC circuits is large, which is also big pollution to the power grid. Therefore, three-phase power factor correction technology has become a research hotspot in recent years. The comparison between different topologies are summarized in Table 2

5. Conclusion

In this paper, a comparative study of several PFC converters for applications with high-power situations has been carried out and it has been shown that each technique has its inherent advantages and disadvantages which are directly related to the complexity and performance of the overall circuit. All techniques apply an almost sinusoidal shape to the input current, since the power factor is close to 1 while regulating the DC output voltage. adding an inductor (with appropriately selected inductance) between the rectifier bridge stack and the filter capacitor uses the characteristic that the current on the inductor cannot be changed abruptly to smooth the fluctuation of the strong pulse of capacitor charging and to improve the aberration of the current waveform of the power supply line and the characteristic that the voltage on the inductor exceeds the current also compensates the filter capacitor current by the inductor. The characteristic of voltage ahead of current in the inductor also compensates for the characteristic of current ahead of voltage in the filter capacitor, so that the power factor, electromagnetic compatibility and electromagnetic interference can be improved. In short, low cost, simple structure, easy to implement, and has soft-switching performance, fast response speed, and low output ripple of the high-power factor converter is the ultimate goal of researchers. We consider the single-phase power factor correction circuit topology and control to be quite mature nowadays, three-phase power factor correction technology research is relatively less, three-phase PFC is increasingly attracting people's attention to the maturity of the single-phase PFC technology on three-phase PFC research has a great deal of reference significance, the three-phase PFC circuits have the complexity and strong coupling, the future of the future will be the focus of the field of industrial power electronics and the center of gravity.

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