

Recent Advances in Bridge-Less Power Factor Correction Converter

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Abstract. Power Factor Corrector (PFC) is a device used in electrical systems to improve power efficiency by reducing reactive power and harmonics, resulting in a higher power factor and reduced energy consumption. It enhances the utilization of electrical networks and minimizes wastage of power resources. This paper reviews the current research on the new bridge-less PFC converter, firstly comparing and analyzing seven configurations and control strategies of traditional Boost, bridge-less Boost, bi-directional switched bridge-less Boost, Pseudo totem bridge-less Boost, dual diode bridge-less Boost, and five-level flying across capacitor bridge-less, and then discussing the characteristics of the bridge-less PFC based on the practical application of the GaN power device. Through the study of bridge-less PFC converter, this paper discusses its advantages and applications in depth, and provides technical support for the realization of high-efficiency, stable and sustainable energy conversion, so as to better promote the development of the energy field.

Keywords: Multilevel; totem pole; power factor correction; converter; bridge-less.

1. Introduction

With the development of modern technology, energy sustainability and conservation has become a topic of great concern. In the process of power conversion, AC-DC conversion plays a crucial role. Any fluctuation of AC voltage may lead to the instability of output DC voltage, which may affect the normal operation of the equipment. So, rectification equipment comes into being. However, the rectification process may introduce voltage ripples, and such ripples may interfere with devices that require a stable DC power supply. Therefore, in many applications, high limits on voltage ripple are required.

DC power supplies are often required to supply current to a variety of devices and circuits. These devices may have different current loading characteristics, and the AC to DC rectification process must be able to maintain stable output voltages and currents under different loads. The rectification process involves converting the energy of an AC current into a DC current, and the electronic components introduce a certain amount of energy loss, so efficiency becomes very important. An efficient rectification process reduces energy waste and heat generation. AC currents may contain harmonic components of various frequencies, especially in the case of non-pure sinusoidal AC sources. These harmonic components may be amplified or reflected in the DC output, resulting in degradation of the power supply quality. However, conventional rectification processes are generally inefficient, and although conventional diode passive rectification circuits are less costly, they can lead to serious harmonic pollution problems.

Power factor corrector (PFC) reduces harmonic currents by adding power electronics, which reduces transmission losses and thus harmonics, thereby improving power factor. In this context, power factor correction converters have become a research hotspot, which can improve power utilization, save energy, reduce harmonic pollution and improve grid stability. In order to improve the efficiency of rectifier, PFC came into existence, PFC, is used to improve the power factor of the AC circuit, thus increasing the efficiency of electrical energy utilization. Power factor is a measure of the ratio between the useful power and the total apparent power in a circuit. It is a value between 0 and 1. The closer it is to 1, the more useful power there is in the circuit and the more efficiently the

electrical energy is utilized. When the power factor is low, there is more reactive power in the circuit, resulting in wasted energy. Useful power is the power in a circuit that is actually used to perform work. Whereas apparent power is the total current actually flowing in the circuit multiplied by the complex value of the voltage, which includes both useful and reactive power. The goal of PFC is to reduce the loss of ineffective power by keeping the power factor as close as possible to 1. PFC achieves this by controlling the input current waveform of the circuit. The specific workflow is divided into the following stages: Rectifier stage: AC power input is converted to DC voltage through a rectifier. The waveform of the current may be discontinuous, resulting in a low power factor. PFC control stage: In order to improve the power factor, it is necessary to synchronize the current waveform with the voltage waveform, thus reducing the loss of ineffective power. This is achieved by controlling the switching elements of the rectifier to keep the input current synchronized with the input voltage. This control can be achieved using both continuous conduction mode (CCM) and discontinuous conduction mode (DCM) [1]. Control strategy: The PFC controller will adjust the on-time of the rectifier switching elements in real time according to the current and voltage waveform information. In this way, the current waveform will be synchronized with the voltage waveform, thus improving the power factor.

Filtering stage: After the PFC control stage, a filter circuit may be used to further smooth the current waveform to ensure that the current and voltage output from the circuit is stable. The development of power factor correction converters has gone through a process from traditional bridge to bridge-less to fly across capacitor bridge-less, with refinements and improvements in each type of converter. The traditional passive power factor correction converter has a simple structure, but with the upgrading of equipment, it is no longer sufficient to meet the requirements in terms of harmonic reduction and power factor improvement and is gradually being replaced by more advanced active power factor correction converters. Bridge-less has higher efficiency, less component count, smaller size, higher reliability, and has higher electromagnetic interference (EMI) performance [2].

This paper focuses on different PFC converters and analyzes the bridge-less PFC circuits from the point of view of standards related to harmonics and advantages and disadvantages at the time of application.

2. Harmonics Related Standards

Especially with the increase of power equipment, harmonic pollution is becoming more and more serious, resulting in power system losses, equipment failure, power quality degradation, interference with communication equipment, and harm to human health hazards. In order to cope with this problem, international committees and many countries have set strict standards.

The IEEE 519 standard specifies the maximum allowable voltage fluctuation, the maximum allowable current fluctuation, and the maximum allowable power factor for harmonics in power systems. According to the IEEE 519 standard, the maximum permissible harmonic current in a power system is 5%, the maximum permissible harmonic voltage is 2%, and the maximum permissible power factor is 0.95. The IEEE 519 standard also specifies the various types of harmonics in a power system, including sinusoidal, triangular, and square waves, etc., as well as the negative effects of each type of harmonic on the power system IEC 61000-3-12 standard to limit harmonic pollution. The Table 1 shows IEC 61000-3-12 Harmonic current limits. The Table 2 shows IEC 61000-3-12 equipment current emission limits [3]. Notably, for the equipment current emission limits, the relative value of the 12th and lower even harmonic currents should not exceed $16/n\%$, the same as the odd harmonic currents are handled in the same way as the even harmonics higher than the 12th are considered total harmonic distortion (THD) and partial weighted harmonic distortion (PWhD).

Table 1 IEC 61000-3-12 Harmonic current limits

Harmonic number n	Maximum permissible harmonic current A	harmonic number n	Maximum permissible harmonic current A
odd harmonic		even harmonic wave	
3	2.30	2	1.08
5	1.14	4	0.43
7	0.77	6	0.30
9	0.40	$8 \leq n \leq 40$	$0.23 \times 8/n$
11	0.33		
13	0.21		
$15 \leq n \leq 39$	$0.15 \times 15/n$		

Table 2 IEC 61000-3-12 Equipment current emission limits

Rsce	Single harmonic current tolerance value (I_n/I_1) %						Harmonic current distortion factor tolerance value %	
	I3	I5	I7	I9	I11	I13	THD	PWHD
—								
33	21.6	10.7	7.2	3.8	3.1	2	23	23
66	24	13	8	5	4	3	26	26
120	27	15	10	6	5	4	30	30
250	35	20	13	9	8	6	40	40
≥ 350	41	24	15	12	10	8	47	47

3. Comparative Analysis of Different PFC Converters

This chapter describes the principles of operation and compares the advantages and disadvantages of each of these PFC converters [4], laying the foundation for the development of the next PFC converter. Figure 1 introduces the classification of two main kinds of PFC.

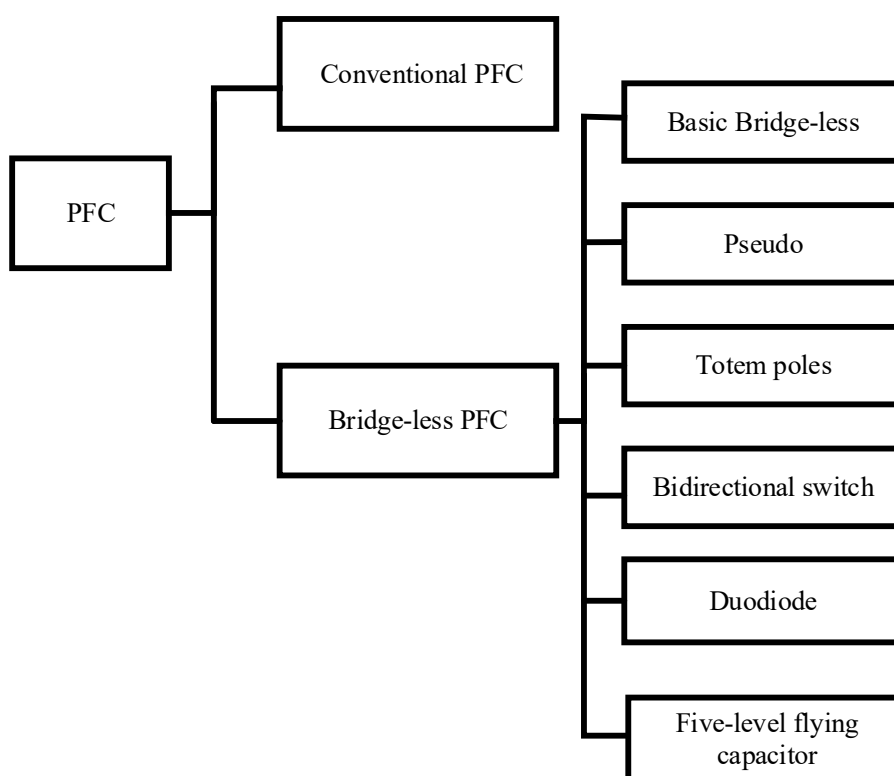


Fig. 1 PFC Classification introduction chart [4].

3.1. Traditional Boost Converter

The traditional Boost converter is a DC-DC converter, as shown in Figure 2, mainly used to boost the input voltage to a higher output voltage. Its basic topology includes a switch element, an inductor, and a series of parallel input and output capacitors.

During operation, when the switch element is turned on, the current in the inductor increases, and the voltage on the input capacitor decreases. When the switch element is turned off, the current in the inductor decreases, and the voltage on the output capacitor increases. By controlling the timing of the switch element's on and off states, stable voltage boost can be achieved.

In traditional Boost converters, a bridge rectifier is used to convert the AC input voltage to DC voltage before it is fed into the Boost converter for boosting. This topology enables the isolation between the input power source and the output power source, ensuring the stability of the output voltage. Figure 2 is a traditional boost PFC converter.

The traditional Boost PFC circuit has advantages such as improving power factor, reducing harmonic distortion, increasing system efficiency, and achieving high voltage output. These advantages make the Boost PFC circuit widely used in industrial and commercial applications.

However, the rectifier bridge introduces a secondary-side ground connection, resulting in no isolation between the output and input power sources, and they are in a common ground state. This can cause severe electromagnetic interference problems and increase circuit complexity. Also, due to the existence of the rectifier bridge, the switching devices in the traditional Boost PFC circuit need to withstand higher voltage and current stresses, which limits the improvement of switching frequency and efficiency. In addition, the on-state losses of the switching devices are high, resulting in significant energy losses and large common-mode interference, which can be introduced to the output and affect the system's stability and electromagnetic compatibility.

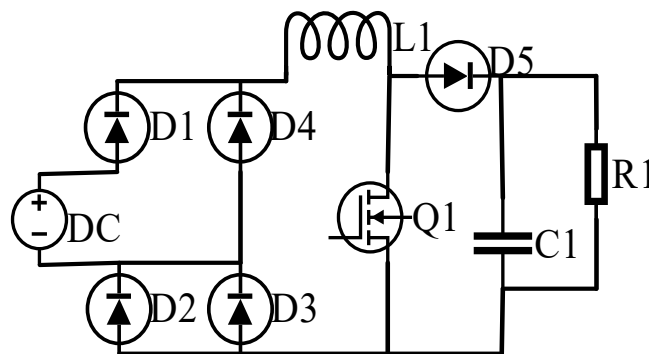


Fig. 2 Traditional Boost PFC converter [4]

3.2. Bridge-less Boost PFC converter

As shown in Fig. 3, the input voltage is filtered through the input LCL filter to obtain the DC input voltage [5], V_{in} . The input voltage is controlled by the power switch and is applied to the inductor L1 with the load. When the power switch is turned on, the current in the inductor L1 starts to increase, storing a certain amount of energy. When the power switch is turned off, the stored energy in L1 is transferred to the capacitor C1. Through periodic switching operations, the bridge-less Boost PFC circuit converts the input voltage into the output voltage, achieving power factor correction.

The bridge-less Boost PFC circuit solves the above-mentioned problems by eliminating the rectifier bridge. However, this also means that the PFC inductor is directly connected to the AC power source. Since the inductor is equivalent to an open circuit for high-frequency signals, the PFC output in the bridge-less Boost PFC circuit is isolated from and floating with the input power source, which can cause severe electromagnetic interference problems. As a result, the topology of the bridge-less Boost PFC circuit was initially limited by factors such as complex sampling and control circuits,

semiconductor devices, and electromagnetic interference, and it could not be widely used in the industry.

Further analysis of the circuit structure reveals that, in each positive and negative half-cycle of the input voltage, only two semiconductor devices are in the working state, leading to low on-state losses in the bridge-less Boost PFC circuit. In addition, the circuit is connected through diodes and capacitors, making the PFC output at the output terminal no longer floating, greatly reducing the degree of common-mode interference. Furthermore, the bridge-less Boost PFC circuit also has the advantages of a simple main circuit structure and high device utilization. The figure 3 is Bridge-less boost PFC converter.

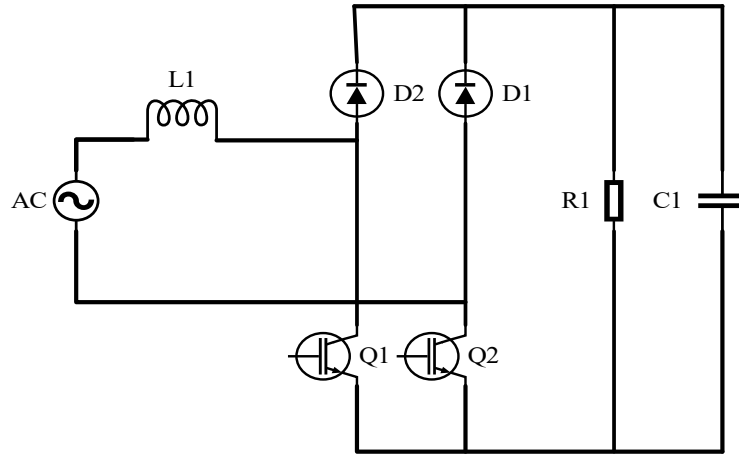


Fig. 3 Traditional Boost PFC converter [5]

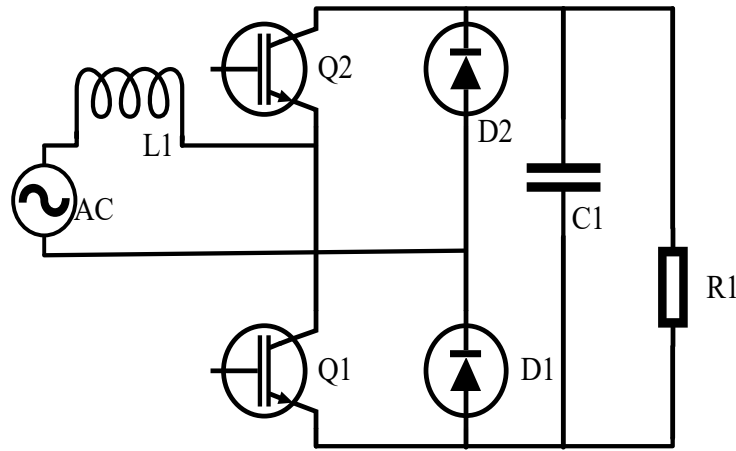


Fig. 4 Totem-Pole Bridge-less Boost PFC Circuit [6]

3.3. Totem-Pole Bridge-less Boost PFC Circuit

As shown in Fig. 4, the input voltage enters the bridge-less Boost PFC circuit after rectification and filtering. There are two switches in the circuit, namely the main switch and the auxiliary switch [6]. The main switch and the auxiliary switch are controlled to work alternately, ensuring that one switch is always conducting at any time to reduce power switch voltage drop losses. The input voltage passes through the Boost inductor first, and then enters the output capacitor through the diode between the main switch and the auxiliary switch. The Boost inductor plays the role of current accumulation and energy conversion. When the main switch is conducting, the current in the Boost inductor increases, while the auxiliary switch is open, and the output capacitor is charging. When the main switch is off, the current in the Boost inductor decreases, while the auxiliary switch is conducting, and the output capacitor releases energy to the load. This cycle allows for energy conversion and output.

The totem-pole bridge-less PFC converter using the bridge-less Boost topology can form almost sinusoidal current on the input voltage waveform, thereby achieving a high-power factor. This helps reduce grid pollution and comply with energy efficiency standards. The voltage and current waveforms of the totem-pole bridge-less PFC converter is adjusted to maximize the product of voltage and current. This high efficiency energy conversion can save energy and reduce circuit losses.

However, the circuit structure of the totem-pole bridge-less PFC converter is relatively complex, requiring precise control of the main switch and auxiliary switch operations to achieve high power factor and high efficiency energy conversion. This may require more circuit components and control systems. Due to the complexity, the totem-pole bridge-less PFC converter may require more components and materials, resulting in higher manufacturing costs. This may be a disadvantage for certain applications. Figure 4 is Totem-Pole Bridge-less boost PFC circuit.

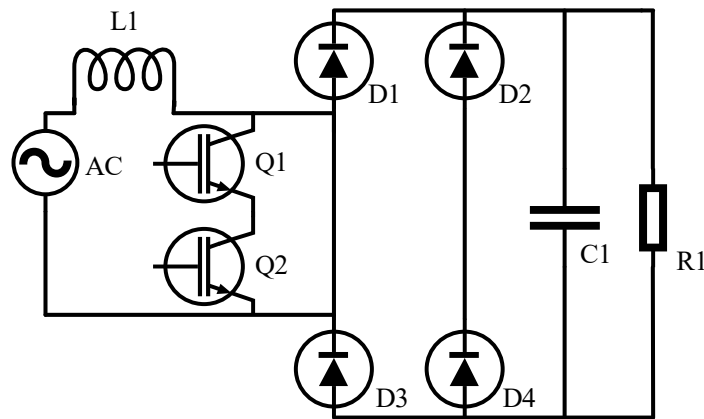


Fig. 5 Bidirectional Switch Type Bridge-less Boost PFC Circuit [7]

3.4. Bidirectional Switch Type Bridge-less Boost PFC Circuit

As shown in Fig. 5, the bidirectional switch type bridge-less Boost PFC circuit is a commonly used PFC circuit topology. It consists of four switch devices and one energy storage element [7].

During the positive half-cycle period, switches S1 and S2 are conducting while switches S3 and S4 are off. At this time, the power supply voltage is applied to inductor L1, and energy is stored in the inductor. When switch S2 is conducting, the current of the inductor increases, causing the voltage of capacitor C1 to decrease, and energy is stored in the capacitor. At the end of the switching period, the energy stored on capacitor C1 is transferred to the load RL in the form of current on inductor L1.

During the negative half-cycle period, switches S3 and S4 are conducting while switches S1 and S2 are off. Similarly, the power supply voltage is applied to inductor L1, and energy is stored in the inductor. When switch S3 is conducting, the current of the inductor increases, causing the voltage of capacitor C2 to decrease, and energy is stored in the capacitor. At the end of the switching period, the energy stored on capacitor C2 is transferred to the load RL in the form of current on inductor L1.

This bidirectional switch type bridge-less Boost PFC circuit can control the flow of electrical energy in both positive and negative half-cycles, thereby correcting the input current and improving the power factor. Compared to traditional Boost PFC circuits, the bidirectional switch type bridge-less Boost PFC circuit has the following advantages: Provides higher power factor correction performance to better meet the quality requirements of the power system. Improves the waveform of the input current and reduces input harmonics. Better adaptation to different input voltage ranges.

However, it should be noted that the design and control of the bidirectional switch type bridge-less Boost PFC circuit are more complex, requiring precise control algorithms and higher switching frequencies. Additionally, the selection and parameter design of capacitors and inductors need to be carefully considered.

3.5. Pseudo Totem-Pole Bridge-less Boost PFC Circuit

As shown in Fig. 6, the Pseudo Totem-Pole Bridge-less Boost PFC circuit is a commonly used PFC circuit. Its working principle is to rectify and filter the input voltage to obtain a DC voltage, and then use this DC voltage to control the resonant converter to achieve power factor correction[8].

This circuit can effectively improve the power factor of the power supply system, reduce harmonic pollution, and improve the efficiency of the power supply. Compared to traditional Boost PFC circuits, the Pseudo Totem-Pole Bridge-less Boost PFC circuit has a smaller volume and is suitable for applications with limited space. **Better Reliability:** The bridge-less circuit structure is simpler compared to the bridge structure, reducing the number of components and improving overall reliability. However, due to the limitation of the specifications of power switch devices in the circuit, the bridge-less structure experiences higher current stress. **Input inductor Oscillation:** In some cases, the input inductor may experience unstable oscillation, requiring appropriate compensation and control.

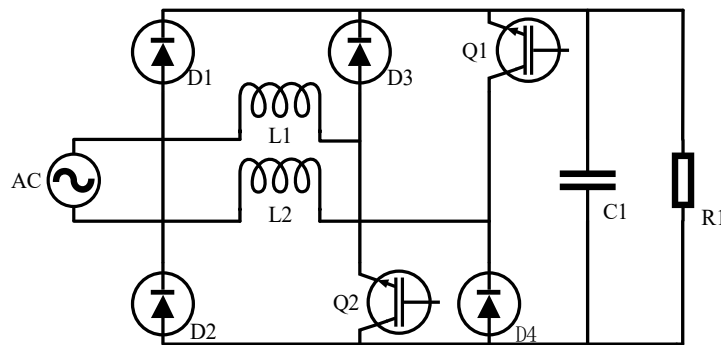


Fig. 6 Pseudo Totem-Pole Bridgeless Boost PFC Circuit [8]

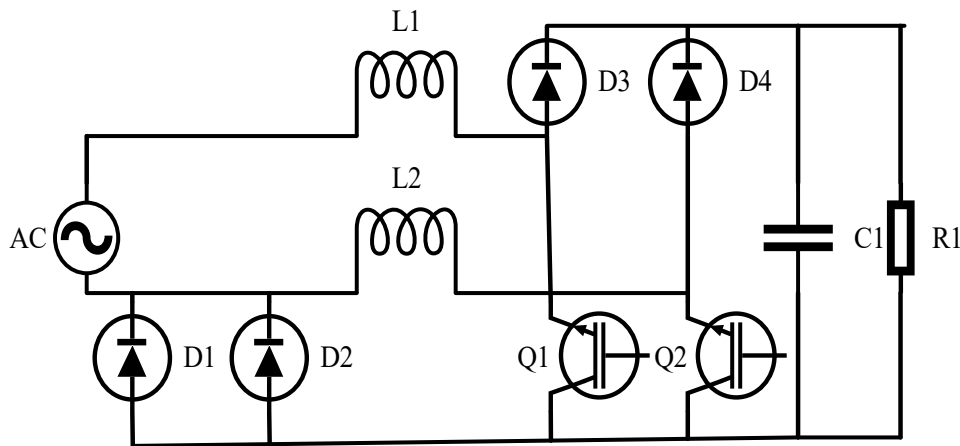


Fig. 7 Dual diode-based Bridge-less Boost PFC circuit [9]

3.6. Dual Diode Bridge-less Boost PFC Circuit

Fig. 7 showed the dual diode bridge-less Boost PFC circuit, also known as the five-level flying capacitor bridge-less PFC circuit [9]. The AC input voltage is converted to DC voltage through a bridge rectifier circuit. The DC voltage passes through a dual diode full-wave bridge rectifier circuit to provide a stable voltage supply to the DC-DC converter. Energy is stored in capacitors to convert DC voltage into pulsed voltage. The pulse voltage is regulated in amplitude and frequency by switching devices, producing stable output voltage and controlling the relationship between output voltage and input voltage.

By efficiently controlling the switching transistors for power regulation, energy transfer becomes more efficient, allowing for high energy utilization. The presence of flying capacitors ensures smoother output voltage fluctuations with low harmonic content. **Power factor correction:** By

controlling the switching time and frequency of the transistors, the input current approximates a sine wave, achieving power factor correction.

This circuit requires precise control algorithms and parameter settings to ensure stable output and power factor correction. Due to the complexity of the circuit and controller required, the design and manufacturing costs of this circuit are relatively high. Figure 7 is a Dual diode-based Bridge-less Boost PFC circuit.

3.7. Five-level flying capacitor Bridge-less PFC circuit

The five-level flying capacitor Bridge-less PFC circuit is a high-performance PFC circuit, as shown in Fig. 8 [10]. The AC input voltage is converted into a pulse voltage through rectification bridge and filtered by an inductor. The term "bridge-less" indicates that the circuit does not have switching devices connected to ground. It can be seen as a pair of complementary high-frequency switch converters, consisting of two pairs of switching devices. Each pair of switching devices consists of a high-side switch transistor and a low-side switch transistor. The two pairs of switching devices alternate switching, enabling the circuit to achieve multi-level output. In the bridge-less circuit, by adding flying capacitors, the ripple of the output voltage can be effectively reduced, improving the stability and output voltage quality of the circuit.

The main advantages of the five-level flying capacitor Bridge-less PFC include: The five-level flying capacitor Bridge-less PFC can provide a higher power factor, reducing reactive power losses in the system and improving energy utilization efficiency. Additionally, the output voltage of the five-level flying capacitor Bridge-less PFC has better waveform quality, reducing interference to the power grid and other devices, improving system reliability and stability. It can also adapt to large input voltage fluctuations, with a wide input voltage range, suitable for environments with poor power quality. Moreover, it can automatically switch between different control modes according to the needs of the power grid to achieve better power factor correction.

The main disadvantages of the five-level flying capacitor Bridge-less PFC include: The control algorithm for the five-level flying capacitor Bridge-less PFC is relatively complex, requiring advanced control techniques and computational resources. Compared to traditional bridge-less PFC, the five-level flying capacitor Bridge-less PFC requires more capacitors to achieve multi-level output, increasing system cost and volume, as well as causing some efficiency losses, which may lead to some energy waste. The system cost of the five-level flying capacitor Bridge-less PFC is relatively high due to the requirement of complex control algorithms and additional capacitors. Figure 8 is a five-level flying capacitor Bridge-less PFC circuit.

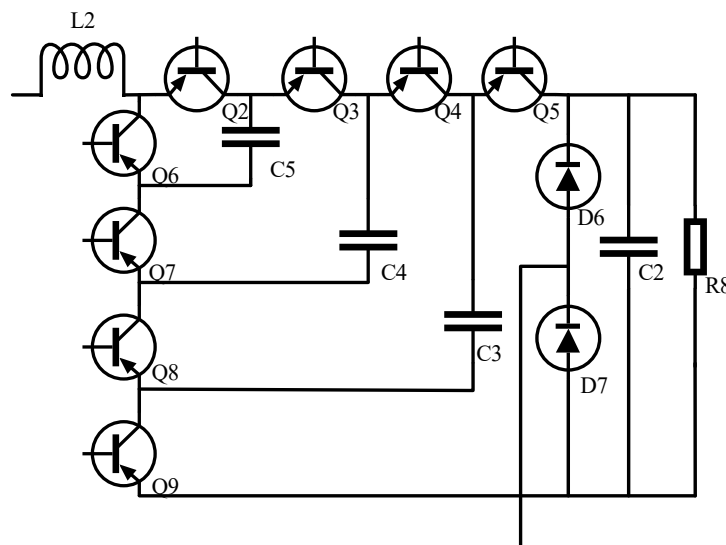


Fig. 8 Five-level flying capacitor Bridge-less PFC circuit [9]

The comparison between different PFCs is summarized in Table 3.

Table 3: Comparison of 7 different PFC converters

Type of PFC Converter	Advantages	Disadvantages
Traditional Boost PFC	High power factor low harmonic distortion	- Severe EMI - complex circuitry
Basic Bridgeless Boost PFC	- Low output voltage ripple - high efficiency - low switch losses - Complex structure	- Complex structure - high cost - requires control. - driver circuitry
Totem-Pole Bridgeless Boost PFC	- Stable voltage, simple structure - high efficiency - low switch losses	- High cost and volume - high design complexity
Bidirectional Switch Bridgeless Boost PFC	Improvement in input current waveform	- requires more precise control algorithms. - careful selection of capacitors and inductors
Pseudo Totem-Pole Bridgeless Boost PFC	- Smaller size - high performance	- high current stress - input inductor oscillation
Diode-Capacitor Bridgeless Boost PFC	- High efficiency - low harmonic distortion	- requires more precise power algorithms and parameter settings. - complex circuitry and controllers
Five-level Flying-Capacitor Bridgeless PFC	High power and multi-mode	- requires more capacitors. - high cost - significant efficiency loss

4. Future Outlook

4.1. A More Efficient PFC Topology

As power electronics continue to advance, more efficient and compact PFC topologies may emerge in the future to achieve lower power losses and higher power density. New topologies such as three-level PFC and multilevel PFC can provide better performance and lower harmonic distortion.

4.2. New Semiconductor Materials

Future semiconductor device technology will further promote the development of PFC technology. or the development of wide band gap semiconductor materials, power integrated circuits (ics), translation competence etc. [11], may provide higher efficiency and better performance for PFC systems.

4.3. Broadening Application Scenarios

Future PFC systems may integrate more intelligent and adaptive control strategies to adapt to different load situations and network conditions. This will make the PFC system more flexible and able to achieve optimal performance in different working environments. PFC technology may be combined with wireless power transmission technology to make energy transmission more efficient and convenient. This helps to build a more flexible power distribution network, especially in special environments such as industrial automation and unmanned equipment. The application of PFC technology in energy storage systems and microgrids will increase. By integrating PFCS with energy storage devices, better energy management and load balancing can be achieved, enhancing the reliability of the power system. As renewable energy sources such as solar and wind continue to increase, the importance of PFC technology in integrating these energy sources into the power network will also rise. PFCS can help stabilize power networks and reduce problems caused by fluctuations in renewable energy sources. PFC technology can also be used to improve power quality

and reduce harmonic and electromagnetic interference in power networks, thus ensuring the normal operation of sensitive equipment.

However, despite the remarkable research results, there are still some problems to be solved. Future research can focus on improving converter efficiency and stability, improving anti-interference ability and load changes, and further promoting the development of flying straddle-type capacitive multilevel totem pole bridge-free PFC converter by improving design, optimizing control algorithms and applying new materials, so as to make greater contributions to energy conversion and sustainable development.

5. Conclusion

In this paper, the flyspan capacitor multilevel totem pole bridgeless PFC converter is the main research object. Compared with other traditional topologies, the importance of the flyspan capacitor multilevel PFC converter is highlighted in the case of the rapid depletion of global energy resources, and the advantages of flyspan capacitor multilevel can reduce voltage pressure and improve equivalent frequency are summarized. Starting from 7 different topologies, this paper summarizes several common basic unit structures. The new materials and new modes of multilevel topology provide a new direction for the study of new topology and give a prospect for the future.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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