**Academic Journal of Science and Technology**
ISSN: 2771-3032 | Vol. 20, No. 1, 2026

# ANPC-5L Inverter Floating Capacitor Pre-Charge Solution Design

**Haohui Yuan *, Qiwei He, Yu Wang**

School of Mechanical Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

*** Corresponding author:** Haohui Yuan

**Abstract:** This paper proposes novel solutions addressing the pre-charge issue of floating capacitors in two ANPC five-level topologies. Floating capacitors play a crucial role in ANPC five-level topologies, where their pre-charge process directly impacts voltage stability during system startup. Traditional pre-charge methods often suffer from low safety, inefficient charging, and poor stability. Therefore, for the three-capacitor ANPC topology, this paper employs a pre-charge scheme utilizing the topology's inherent redundant state. For the single-capacitor ANPC topology, this paper designs a scheme that extracts energy from the control circuit and elevates the floating capacitor voltage to the required level via a push-pull boost circuit. Leveraging the high-efficiency energy conversion characteristics of the push-pull circuit, this approach achieves stable capacitor charging within a short timeframe while maintaining low circuit complexity. Experimental results demonstrate that both proposed approaches can reliably charge the floating capacitor to the target voltage. Compared to conventional methods, the three-capacitor pre-charge scheme reduces inverter size and simplifies control. The single-capacitor pre-charge approach significantly enhances charging safety while lowering system energy consumption. The proposed solutions show promising application prospects and can be widely adopted in power electronic systems demanding high efficiency and reliability.

**Keywords:** Photovoltaic Inverter; ANPC; Floating Capacitor; Push-Pull Circuit; Power Electronics; Pre-charge.

## 1. Introduction

In recent years, the photovoltaic industry has undergone remarkable development, with advancements in technology, market scale, and policy support indicating that photovoltaic energy is gradually transitioning from a supplementary to a mainstream energy source [1]. The growth of the photovoltaic industry is inseparable from inverter technology, and multilevel inverters have emerged as a significant research focus in power electronics development in recent years. Compared to traditional two-level inverters, multilevel inverters offer advantages in numerous aspects. With the rise of applications such as renewable energy, smart grids, and electric vehicles, the demand for high-power, high-efficiency power conversion continues to grow. Traditional two-level inverters face voltage stress and harmonic issues in high-power applications. By utilizing multiple voltage levels, multilevel inverters can better approximate sinusoidal waveforms, reduce harmonic content in the output current, thereby minimizing interference with loads and the grid, and improving the system's power quality [2]. Additionally, multilevel inverters can utilize power devices with lower rated voltages at the same power level. This approach reduces device costs and thermal management requirements to some extent while minimizing system size.

The application of floating capacitors in multilevel inverters can be observed across various topologies, such as three-level, five-level, or higher-level inverter designs. Each design features specific floating capacitor configurations tailored to distinct performance requirements and application scenarios. These capacitors play a crucial role within inverters, serving as essential components for enhancing performance, ensuring system stability, and achieving efficient energy conversion [3]. By connecting between different levels of the inverter, floating capacitors enable switching between multiple voltage levels, thereby increasing the number of available output voltage points. They also balance the voltage distribution across these levels during operation. Simultaneously, during inversion, these capacitors function as energy storage devices, capable of storing and releasing energy throughout the inverter's switching cycles to maintain stable output waveforms [4].

However, the floating capacitor must be precharged before the inverter starts to ensure its proper operation thereafter. Numerous methods exist for capacitor charging. During high-voltage inversion, the conventional approach involves drawing power from the bus via resistors. However, this method operates at extremely high voltage levels, posing a significant risk of overcharging the capacitor. Furthermore, the high voltage complicates control [5]. This paper proposes a push-pull circuit-based pre-charge module for floating capacitors. This design enables safe and convenient capacitor charging using low-voltage control circuits, demonstrating practical utility.

## 2. ANPC-5L Topology Analysis

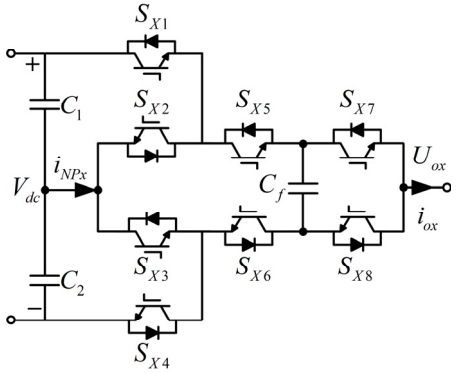



**Figure 1.** Single-Capacitor ANPC-5L topology

Generally speaking, photovoltaic inverter systems can be categorized into various forms based on their composition and deployment methods. However, among these different forms, the main circuit topology options for inverter systems are limited. For main circuit topologies employing the ANPC five-level (ANPC-5L) scheme, there are primarily two circuit configurations as shown in Figures 1 and 2.

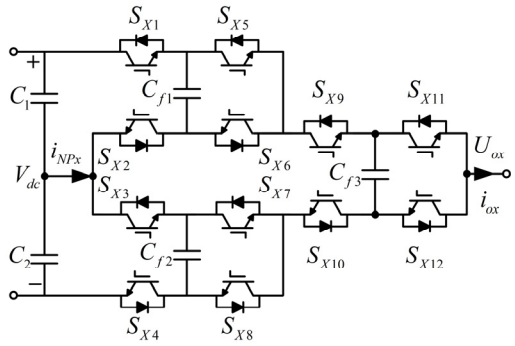



**Figure 2.** Three-Capacitor ANPC-5L topology

Whether single-capacitor or three-capacitor ANPC inverters, their fundamental operating principle involves implementing individual control over each switching element to ensure the load receives a voltage output closer to a sine wave [6]. During operation, the inverter periodically switches between different modes, with current flowing through distinct paths within the topology. The voltage across the floating capacitor should ideally be maintained at $V_{\mathrm{dc}}/4$.

For the three-capacitor ANPC-5L, current flows through the capacitors via different paths in each mode, and the capacitor voltage directly influences the inverter's output voltage [7]. Figure 3 below shows its P1 mode.

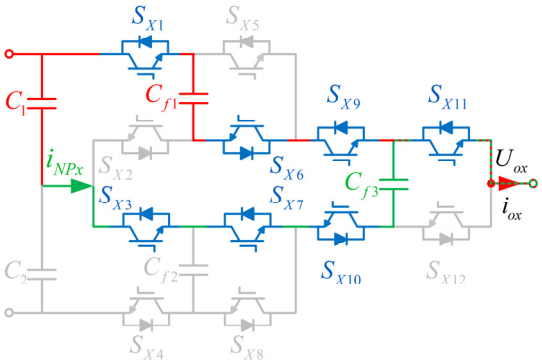



**Figure 3.** Three-Capacitor ANPC-5L P1 modal current path

For the single-capacitor ANPC-5L topology, this process becomes more complex and requires analysis under two modes where the inverter outputs a voltage of $V_{\mathrm{dc}}/4$. Nevertheless, the voltage across the floating capacitor directly influences the inverter's output voltage. Figure 4 below illustrates its P1P2 mode.

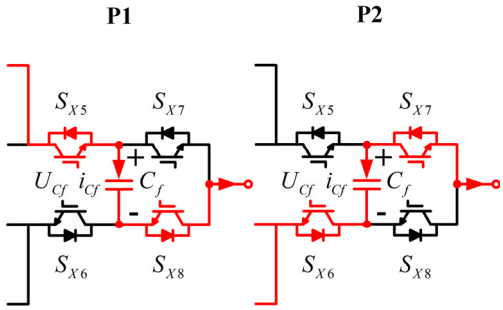



**Figure 4.** Single-Capacitor ANPC-5L P1P2 modes current path

The current flow direction $i_{ox}$ is defined as positive. When the inverter operates in P1 mode with positive current flow, the current flows through the floating capacitor $C_f$ in the forward direction, charging the capacitor and increasing its voltage. When the current flows in the negative direction, it discharges the capacitor through $C_f$ in the reverse direction, causing the voltage to decrease.

When the inverter operates in P2 mode with positive current direction, the current flows negatively through the floating capacitor $C_f$, discharging the capacitor and decreasing its voltage. When the current direction is negative, the current flows positively through the floating capacitor $C_f$, charging the capacitor and increasing its voltage [8].

The same phenomenon occurs in the N1 and N2 modes, which output a voltage of $-V_{\mathrm{dc}}/4$. Therefore, to ensure the normal operation of the inverter, it is necessary to guarantee that the floating capacitor reaches the required voltage before the inverter starts. How to achieve this is the subject of this paper.

## 3. Pre-charge Design

(1) Analysis of traditional pre-charge methods

Pre-charge of floating capacitors refers to the process of pre-charging these capacitors to an appropriate voltage level via an external circuit during system startup or power-up. The conventional approach involves sourcing electrical energy from the main DC bus or power supply and charging the floating capacitors by controlling the current flow [9].

As shown in Figure 5, during system startup, the capacitor is gradually charged by connecting a resistor in series with the high-voltage bus. The current flowing through the resistor is limited, ensuring the capacitor charging current does not become excessive. Once the floating capacitor reaches its predetermined charging voltage, the resistor connection to the power source can be disconnected, allowing the inverter to enter its normal operating state.

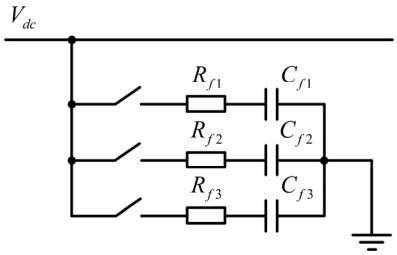



**Figure 5.** DC Bus power extraction

This charging circuit design is extremely simple and low-cost, but it is essential to ensure the reliability of the current-limiting resistor. Failure to do so may cause abnormal capacitor charging, affecting system startup. Furthermore, the charging process involves high voltage. Should the current-limiting resistor fail or experience an abnormal short-circuit fault, the high voltage on the busbar would directly connect to the floating capacitor. This would generate a massive current, causing inverter failure and potentially damaging the low-voltage control section [10].

(2) Three-Capacitor pre-charge solution design

For the three-capacitor ANPC-5L solution, since it incorporates four redundant modes with zero output, this characteristic can be leveraged to pre-charge its three floating capacitors. A current-limiting resistor $R_X$ is connected in series across the floating capacitor $C_{f3}$, enabling the inverter to operate under no-load conditions while running in the four

redundant modes with zero output voltage, as illustrated in Figure 6 below.

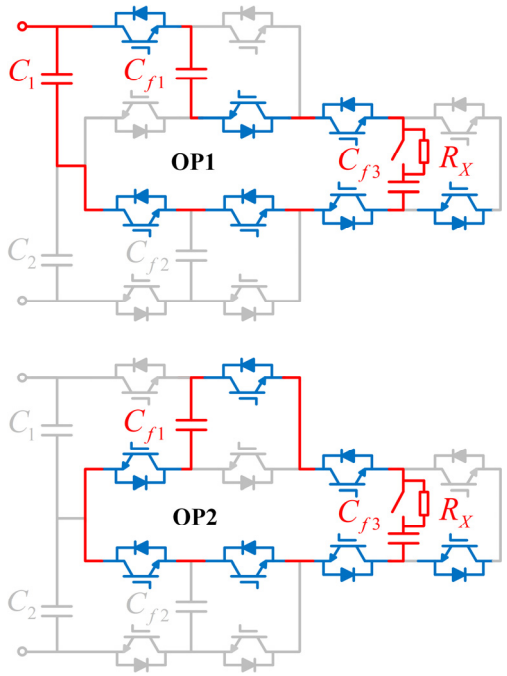



**Figure 6.** Three-Capacitor ANPC-5L OP1 and OP2 modes

After stabilization, the following relationships exist between capacitors in OP1 and OP2 modes:

$$\begin{cases} V_{C1} = V_{Cf1} + V_{Cf3} \\ V_{Cf1} = V_{Cf3} \end{cases} \tag{1}$$

Similarly, in ON1 and ON2 modes, we obtain:

$$\begin{cases} V_{C2} = V_{Cf2} + V_{Cf3} \\ V_{Cf2} = V_{Cf3} \end{cases} \tag{2}$$

Given conditions:

$$V_{C1} + V_{C2} = V_{dc} \tag{3}$$

Obtain:

$$V_{C1} = V_{C2} = V_{C3} = V_{dc} / 4 \tag{4}$$

The conclusions derived above demonstrate the theoretical feasibility of the pre-charge scheme for the floating capacitor in the three-capacitor ANPC-5L topology mentioned earlier. By altering the inverter's operating mode, the floating capacitor can be charged to the required voltage.

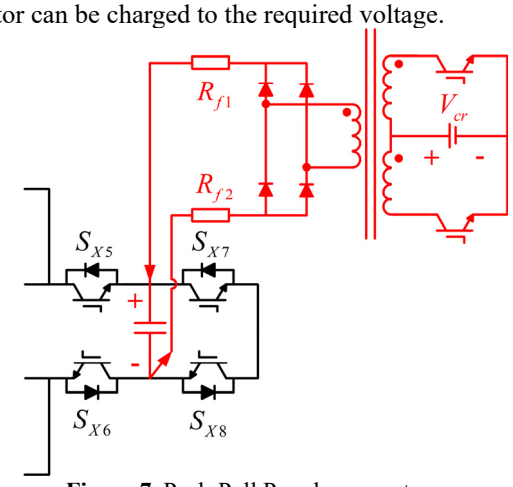



**Figure 7.** Push-Pull Pre-charge system

(3) Single-Capacitor Pre-charge solution design

The traditional method of drawing power from the busbar fails to achieve effective isolation between the high-voltage busbar and the low-voltage control circuit. This paper proposes a boost module utilizing a push-pull transformer to draw power from the low-voltage control circuit, thereby isolating high and low voltages to ensure charging safety. The system schematic is shown in Figure 7.

Using a separate pre-charge module not only prevents hazards from high-voltage side voltages but also allows flexible output of different voltage levels to meet various voltage requirements. Moreover, due to the characteristics of transformer output, when the floating capacitor voltage approaches the preset value, its rate of change becomes minimal, facilitating the disconnection of the charging circuit.

This circuit serves solely as a charging power source for the capacitor, thus placing minimal demands on its output waveform. The basic structure of the push-pull circuit is relatively simple, making it easy to design and implement, with straightforward control requirements. Only two control signals are needed to drive the two power devices, reducing the complexity of the driver circuit. The alternating operation of the two power devices reduces the thermal load on each individual device, thereby improving overall thermal performance.

(4) Simulation

This section establishes simulation models for the single-capacitor and three-capacitor ANPC-5L topologies within the MATLAB/Simulink environment to validate the feasibility of the two pre-charge schemes mentioned above. The specific simulation parameters are shown in Table 1.

**Table 1.** Simulation parameters

| Parameter | | Value |
|---|---|---|
| Sampling time | $T$ | 1e − 6s |
| Bus voltage | $V_{dc}$ | 2000V |
| Current-limiting resistor | $R_X$ | 800Ω |
| Current-limiting resistor | $R_f$ | 400Ω |
| Switching frequency | $f$ | 1kHz |
| Transformer Turns Ratio | $n$ | 1:1:45 |
| Low-voltage side voltage | $V_{cr}$ | 12V |
| Busbar Capacitor | $C_X$ | 470$\mu$F |
| Floating capacitor | $C_{fX}$ | 100$\mu$F |

The three-capacitor ANPC-5L pre-charge solution exhibits the following simulated voltage waveform for the floating capacitor charge, as shown in Figure 8.

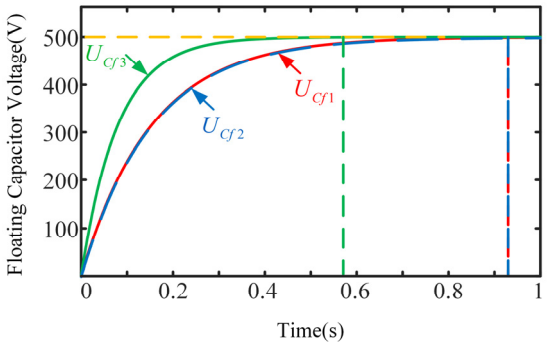



**Figure 8.** Three-Capacitor ANPC-5L floating capacitor charging

Observing the waveform diagram reveals that the voltage waveforms of floating capacitors $C_{f1}$ and $C_{f2}$ are nearly identical, both charging to 500V after approximately 0.9 seconds. Floating capacitor $C_{f3}$ charges to 500V after approximately 0.5 seconds. Throughout the entire charging process, the voltage changes across all three floating

capacitors are continuous.

The voltage waveform of the floating capacitor in the single-capacitor ANPC-5L solution is shown in Figure 9 below.

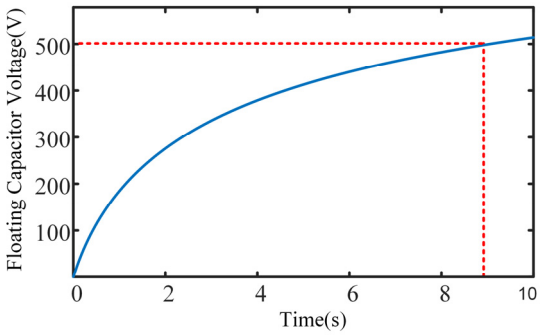



**Figure 9.** Single-Capacitor ANPC-5L floating capacitor charging

As shown in the waveform in Figure 9, the floating capacitor $C_f$ reaches 500V around 9 seconds, at which point the voltage change rate is relatively low, facilitating the disconnection of its power supply circuit by the circuit breaker.

The results of the modeling and simulation demonstrate that the proposed pre-charge scheme for the floating capacitor in both ANPC-5L topologies performs well in simulation, providing data support for subsequent physical implementation. It should be noted that due to the self-circulating current limitations inherent in the three-capacitor ANPC-5L topology, this scheme is not suitable for high-voltage applications.

# 4. Experimental Design and Validation

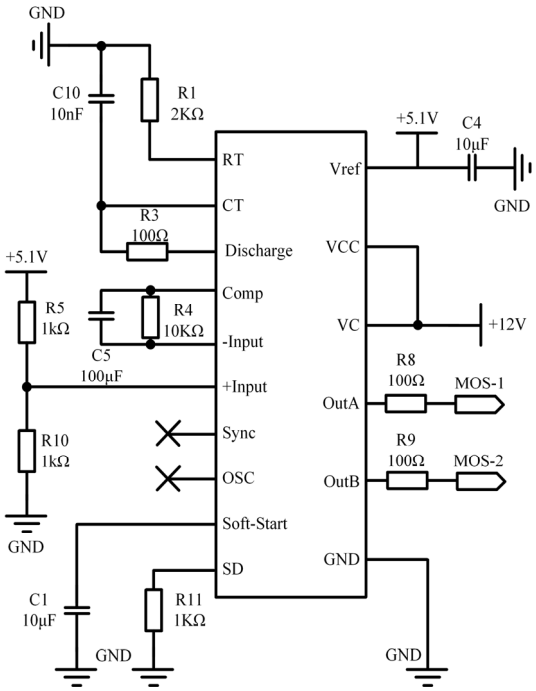



**Figure 10.** SG3525 configuration

(1) Experimental platform setup

Two ANPC-5L circuit topologies were physically constructed according to the parameters listed in Table 1. Since the three-capacitor scheme relies on a self-oscillating topology for pre-charge, this subsection will detail the pre-charge module design for the single-capacitor scheme. The pre-charge module primarily converts the 12V DC from the control circuit into 540V AC, which is then rectified using four fast recovery diodes and two current-limiting resistors.

Two complementary PWM waves generated by the SG3525 chip drive two IRF540 MOSFETs. The configuration of the SG3525 is shown in Figure 10.

The high-voltage side employs four FR307 fast recovery diodes with four current-limiting resistors for rectification. A push-pull transformer connects the low-voltage side to the high-voltage side.

Pin 9 is connected to pin 1, causing pin 9's voltage to track pin 2's voltage. The switching frequency is controlled by CT and RT, while the dead time is regulated by resistor R3. Two complementary PWM signals are output through pins 11 and 14 to drive the two MOSFETs, as shown in the circuit diagram below in Figure 11.

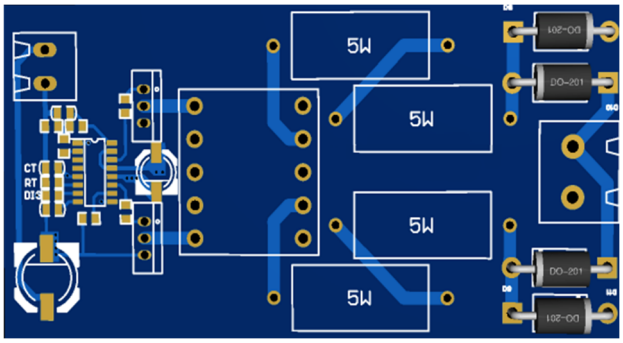



**Figure 11.** Pre-charge module design

(2) Testing and validation

Pre-charge experiments were conducted on the constructed three-capacitor ANPC-5L topology, with the results shown in Figure 12 below.

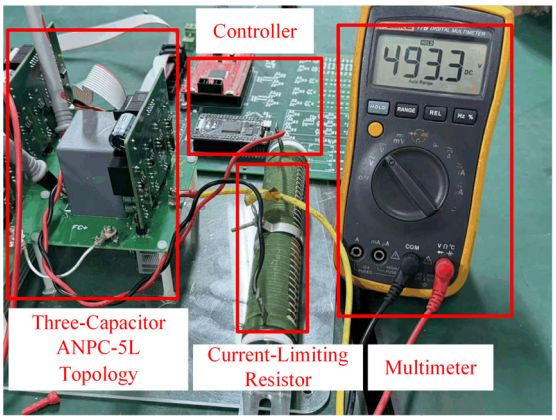



**Figure 12.** Three-Capacitor ANPC-5L pre-charge test

Measurements of the floating capacitor $C_{f3}$ voltage revealed that approximately 2 seconds after the inverter's pre-charge startup, the floating capacitor voltage reached 493.3V, meeting the voltage requirement for inverter startup.

The relevant pre-charge module was connected to the single-capacitor ANPC-5L test platform, as shown in Figure 13 below.

After approximately 10 seconds following the activation of the pre-charge module, the floating capacitor voltage reaches 510.5V, as shown in Figure 14 below, achieving the required voltage for inverter startup.

Through the above experiments, it was found that both pre-charge schemes can charge the floating capacitor to the required voltage before the inverter starts. This demonstrates that the two pre-charge schemes used in this paper are indeed feasible in practical engineering applications.

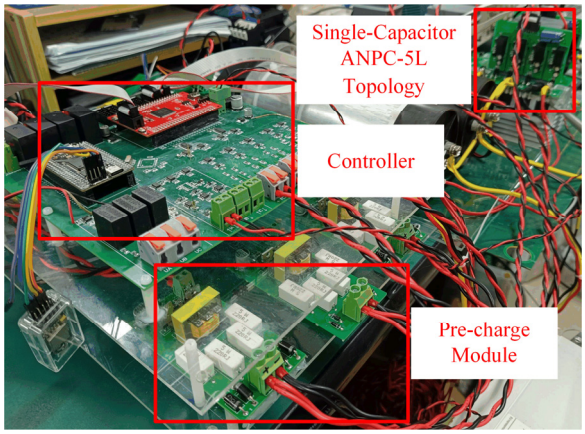



**Figure 13.** Pre-charge module with ANPC-5L test platform

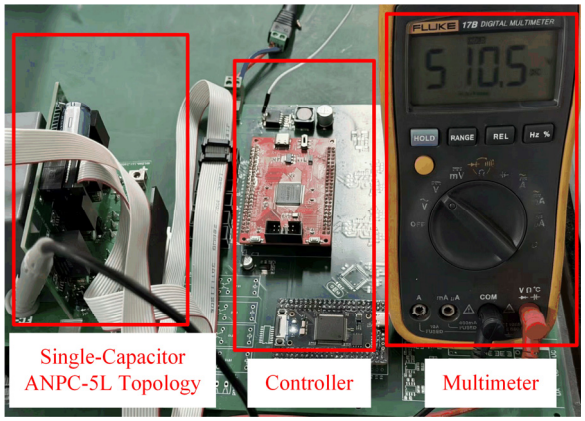



**Figure 14.** Single Capacitor ANPC-5L pre-charge test

## 5. Conclusion

The pre-charge issue of the floating capacitor in the ANPC-5L inverter studied in this paper is a critical aspect during system startup. Traditional pre-charge solutions have room for improvement in terms of safety and stability. This paper proposes tailored solutions for the pre-charge problems encountered in the floating capacitors of two commonly used ANPC-5L topologies. Each proposed solution undergoes theoretical derivation, modeling simulation, and experimental verification within the paper. The main conclusions are as follows:

(1) In inverters employing the ANPC-5L topology, conventional pre-charge schemes for floating capacitors primarily utilize a DC bus with series current-limiting resistors. While simple, this approach leaves room for optimization in terms of safety and stability.

(2) This paper proposes a pre-charge solution for the three-capacitor ANPC-5L topology that requires no external components, relying solely on its own redundant mode. Final experimental results demonstrate that this approach can charge the floating capacitor to the required voltage within an extremely short time.

(3) For the single-capacitor ANPC-5L topology, this paper designs a pre-charge module that eliminates the need to connect to the high-voltage bus for charging. Instead, it performs boost charging directly from the control side, isolating the high-voltage side's influence on the inverter and enhancing the safety and stability of the pre-charge process.

The above results demonstrate that the pre-charge solutions proposed for both ANPC-5L topologies are practically feasible in engineering applications. These solutions not only meet the voltage requirements for the floating capacitor during inverter startup but also reduce system size, providing new insights and practical foundations for designing high-efficiency power electronic systems.

The trend of mass data in power system provides a basis for load characteristic analysis and prediction model establishment, but the classical load forecasting method can not afford such a huge time and computing resource consumption. The problem of over fitting in large sample set will affect the prediction accuracy. In this paper, a power load forecasting model is built by using the BP neural network model, making full use of the powerful data processing function of Clementine and preventing the over fitting function. The experimental results show that the BP neural network model has good predictability and robustness, and has a certain practical application value.

## References

[1] Wei Fangyi, Li Yan, Tian Ye, et al. Research on High-Efficiency Dual-Path Converter Applied to Photovoltaic Power Generation Systems [J]. Acta Energiae Solaris Sinica, 2024, 45(04): 468-474.

[2] Wang Jie, Lin Yujie, Wu Chengjian, et al. The Current Situation and Development of the Solar Photovoltaic Industry in the Context of Carbon Neutrality [J]. Energy Storage Science and Technology, 2022, 11(02): 731-732.

[3] Guo Yinyuan, Cheng Zhuo, Li Chunyang, et al. 1500 V megawatt-class high-efficiency three-level photovoltaic inverter [J]. Power Electronics, 2022, 56(12): 76-78.

[4] Yang Hanlu, Ma Haixiao, Jiang Tianjian, et al. A single phase PV inverter with flying capacitor [J]. Chinese Journal of Power Sources, 2024, 48(01): 156-160.

[5] Sun Xiaofeng, Liu Xinlei, Teng Jiaxun, et al. Power Balance Strategy of Cascaded H-bridge Photovoltaic Inverter Based on Hybrid Configuration of Photovoltaic and Energy Storage [J]. Proceedings of the CSEE, 2024, 44(05): 1948-1962.

[6] Qiu Changqing, Wang Dingquan, Hua Bin, et al. Research on the Analysis and Compensation Method of SVPWM Dead Zone Effect in Five-Level Active Clamping Converter [J]. Electric Machines and Control, 2023, 27(05): 117-137.

[7] Zhao Qingqing, Diao Naizhe, Sun Xianrui, et al. SVPWM for Five-Level Active Neutral-Point-Clamped Converter Based on Multispace Voltage Vector Mapping and Midpoint-Voltage Self-Balancing Strategy [J]. IEEE Transactions on Power Electronics, 2022, 37(11): 13456-13467.

[8] Song Lin, Nie Ziling, Ye Weiwei, et al. Research on Model Predictive Control of ANPC-5L Permanent Magnet Synchronous Motor Based on Feedforward Decoupling [J]. Transactions of China Electrotechnical Society, 2023, 38(07): 1910-1920.

[9] Wang Fusheng, Fu Hang, Zhang Xing, et al. Research on Five-Level Modulation Based on Carrier Superposition and Fly-Over Capacitor Control [J]. China Sciencepaper, 2017, 12(23): 2715-2720.

[10] Liu Wufeng, Lu Jianwei. Improved zero sequence voltage injection method to control neutral point potential balance of NPC inverter [J]. Modern Electronic Technique, 2022, 45(16): 18-24.