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Design of Supercapacitor-Based Inverter-Type High-Voltage Power Supply Module for Neutral Beam in HL-3 Device

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Abstract

High-voltage power supply constitutes a critical component of the neutral beam injection heating system, determining both the beam energy and the quality of the extracted beam current. As voltage levels progressively increase, PSM high-voltage power supplies have become inadequate for experimental requirements. To enable rapid switching of neutral beam modulated injection power, this paper proposes an inverter-type high-voltage power supply based on supercapacitor energy storage. The supercapacitor energy storage approach reduces the required grid capacity and mitigates impact on the power grid. A DC-DC resonant converter topology employing soft-switching technology enhances the power supply response speed while reducing switching losses in the switching devices. The circuit topology of the power supply module is designed, and system modeling calculations are performed based on the power supply performance specifications. PSIM simulation models of the charging circuit and main circuit are established to verify the power supply performance specifications through simulation. A prototype inverter power supply module is constructed to conduct relevant performance specification tests. Simulation and experimental validation demonstrate that the power supply module can achieve a stable output of 1600V/50A, satisfying the design requirements of 6MW/120kV.

Full Text

Design of Inverter-Type High Voltage Power Supply Module for HL-3 Device Neutral Beam Injection Based on Supercapacitor Energy Storage

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Abstract

[**Background**] The high voltage power supply is a critical component of the neutral beam injection heating system, determining both beam energy and extraction beam quality. As voltage levels progressively increase, PSM (Pulse Step Modulation) high voltage power supplies can no longer meet experimental requirements. [**Purpose**] To achieve rapid switching of injected power for neutral beam modulation, this paper proposes an inverter-type high voltage power supply based on supercapacitor energy storage. [**Methods**] Supercapacitor energy storage is employed to reduce required grid capacity and minimize grid impact. A DC-DC resonant converter structure with soft-switching technology is utilized to improve power supply response speed and reduce switching losses. The power module circuit topology is designed, and system modeling calculations are completed based on performance specifications. PSIM simulation models of the charging circuit and main loop are established to verify power supply performance through simulation. A prototype inverter power supply module is built and tested for relevant performance indicators. [**Results and Conclusions**] Simulation and experimental verification demonstrate that the power module achieves stable output of 1600V/50A, meeting the design requirements of 6MW/120kV.

Keywords: HL-3 device, supercapacitor, neutral beam injection, inverter high-voltage power supply, DC-DC resonant converter

Neutral beam injection (NBI) heating is one of the most effective methods for tokamak devices, with major medium and large tokamak facilities worldwide employing NBI heating systems equipped with complete neutral beam injection heating infrastructure [1,2]. Currently, high voltage power supply topologies for auxiliary heating systems in tokamak devices primarily consist of two types: Pulse Step Modulation (PSM) high voltage power supplies and inverter-type high voltage power supplies. PSM power supplies are mainly used for high voltage outputs below 100kV [3], while inverter-type high voltage power supplies can meet power demands of several hundred kilovolts and above [4]. Large tokamak devices both domestically and internationally, including JT-60U, ITER, DEMO, and CRAFT, have adopted inverter-type high voltage power supply technology for their neutral beam high voltage power supplies [5-7].

The HL-3 (China' s HL-3) device has constructed a 5MW neutral beam heating beam line, with its high voltage power supply system employing PSM high voltage power supply technology and rated output parameters of 80kV voltage, 50A current, and 5s pulse width [8]. While PSM high voltage power supplies offer advantages such as simple circuit structure and flexible control methods, the gradual increase in neutral beam energy demands higher voltage levels that PSM high voltage power supplies cannot satisfy. To study plasma momentum transport mechanisms, the high voltage power supply must provide modulated output to match load plasma parameters for optimal perveance, enabling NBI modulated injection [9]. Modulated output requires the power supply to have significant capability for rapid high-voltage switching during modulation injection. To reduce grid capacity requirements and minimize grid impact while improving high voltage power supply stability and response performance, this paper designs a high-frequency inverter-type high voltage power supply system based on supercapacitors.

1 Supercapacitors

Electric double-layer capacitors (EDLCs) are a type of supercapacitor whose operating principle is primarily based on the electrochemical double layer formed by physical adsorption at the electrode-electrolyte interface [10]. During electrode charging, ions accumulate on the electrode surface, forming a thin layer with charge opposite to the electrode surface without involving actual electron transfer or chemical reactions. This physical process can be rapidly reversed, enabling fast charge and discharge cycles. EDLCs offer advantages including high power density, long cycle life, wide operating temperature range, fast charge/discharge capability, and low equivalent series resistance (ESR) [11]. Neutral beam injection high voltage power supply systems have substantial power requirements, with a single neutral beam injection line typically reaching several to tens of megawatts and requiring long-pulse operation, necessitating energy storage units with high power and energy density. While pulse capacitors offer high power density, their energy density is too low; energy batteries provide high energy density but insufficient power density; lithium-ion capacitors combine lithium-ion battery anodes with EDLC cathodes to achieve higher energy density than supercapacitors but have larger equivalent series resistance. Therefore, EDLC supercapacitors are selected as the energy storage device for the neutral beam high voltage power supply system.

2 6MW Inverter-Type High Voltage Power Supply Topology

2.1 Inverter Power System Structure Topology

The 6MW inverter-type high voltage power supply system has rated output parameters of 120kV voltage and 50A current. The system consists of a high-power transformer, charging module circuits, supercapacitors, and inverter module circuits, with the overall structure topology shown in Figure 1 [Figure 1: see original paper]. The power supply system comprises 126 inverter power modules, including three supercapacitor modules, with each capacitor module powering 42 power modules. The 126 inverter power modules connected through phase-shifted series connection effectively reduce output voltage ripple and achieve the rated output of 120kV/50A [12,13]. The inverter power supply system supports multiple operation modes: it can use AC 10kV or AC 6kV grid power transformed to AC 650V via a high-power transformer to achieve rated output with 5s pulse width. For convenience in neutral beam test platform conditioning experiments, supercapacitor energy storage can be employed, with AC 380V grid power charging the supercapacitors through a charging circuit, then boosting to achieve rated output of 1600V/50A with 1s pulse width. Using supercapacitor energy storage reduces required grid capacity and minimizes grid impact.

2.2 Inverter Power Module Main Circuit Topology

The inverter power module main circuit topology is shown in Figure 2 [Figure 2: see original paper]. Each power module consists of a supercapacitor charging circuit, six-pulse rectifier input circuit, inverter boost circuit, output rectifier circuit, and filter circuit [14]. The module can operate directly from AC 380V for power supply functional testing with rated output parameters of 1000V voltage, 50A current, and 20ms pulse width. When AC 10kV or AC 6kV grid power is available, it is transformed to AC 650V via a high-power transformer, providing rated output of 1600V voltage, 50A current, and 5s pulse width. Alternatively, supercapacitor energy storage can be used, with AC 380V charging the supercapacitors through a charging circuit, then boosting to achieve rated output of 1600V voltage, 50A current, and 1s pulse width. The inverter stage employs a phase-shifted full-bridge inverter circuit operating at 6kHz frequency. Phase-shifted control with zero-voltage soft-switching technology reduces switching losses and resonant losses while improving system dynamic response speed [15]. The output rectifier circuit uses diode full-wave rectification followed by T-type LC filtering. Modules employ phase-shifted series connection to achieve the 120kV/50A rated output, significantly reducing output ripple.

2.3 Supercapacitor Charging Circuit Topology

The supercapacitor charging circuit consists of a soft-start stage, EMI filter stage, PFC converter stage, and DC-DC converter stage, with the topology shown in Figure 3 [Figure 3: see original paper]. The front-stage PFC converter adopts a Vienna topology, which further improves power factor and suppresses harmonics by adding reactive current control. This achieves excellent power factor with lower space requirements, enhancing overall power supply system stability and reliability. The rear-stage DC-DC converter employs an interleaved phase-shifted three-phase LLC topology, effectively reducing inductor saturation current, with total inductance decreasing as the number of interleaved phases increases [16]. The three-phase LLC converter comprises four parts: inverter switches, resonant tank, transformer, and diode rectifier. Power MOSFETs first convert the input DC voltage into a high-frequency square wave, which then enters the resonant tank to eliminate harmonics and output a fundamental frequency sine wave. This is transmitted through a high-frequency transformer to the converter secondary side for voltage step-up or step-down as required by the application, and finally converted to stable DC output through uncontrolled diode rectification. A single-stage charging circuit achieves a rated charging voltage of 500V, with two stages in series providing a rated charging voltage of 1000V.

3 Parameter Design

3.1 Supercapacitor Parameter Design

Based on inverter power module parameters in supercapacitor power supply mode—rated voltage 1600V, rated current 50A, and pulse width 1s—the rated output power of the inverter power module is calculated as 80kW. The supercapacitor rated voltage during charging is 1000V, with minimum discharge voltage not lower than 800V. According to the rated output power and minimum discharge voltage, the maximum output current per module is determined to be 100A. Each supercapacitor module in the inverter-type high voltage power supply system powers 42 modules, resulting in a module current of 4200A. The minimum supercapacitor capacity is:

$$(4200 \times 1) / (1000 - 800) \text{ F} = 21\text{F}$$

Therefore, supercapacitor modules with 6F capacity, 160V rated voltage, and 220A maximum discharge current are selected, using 34 modules in parallel first, then 7 groups in series to form a supercapacitor cabinet.

3.2 Charging Circuit Parameter Design

The supercapacitor charging circuit primarily consists of a front-stage PFC rectifier circuit and rear-stage DC-DC converter circuit, with the front-stage PFC using a Vienna topology and the rear-stage DC-DC using a three-phase LLC topology. Based on supercapacitor parameters, the single-stage charging circuit parameters are designed as shown in Table 1 .

Table 1 Parameters of single-stage charging circuit for supercapacitor

Technical Parameters	Parameter indicators
Input voltage	380V-420V
Output voltage	500V
Rating	10kW
Resonant frequency	50kHz
Maximum operating frequency	80kHz

An equivalent circuit diagram of the three-phase LLC converter is established, which can be considered as three single-phase LLC converters, as shown in Figure 4 [Figure 4: see original paper].

Figure 4 LLC equivalent circuit diagram

First, determine the equivalent load impedance on the transformer primary side: R_{ac} = 5.19Ω. Then, determine the static gain M_{min} = 0.8. n is the transformer turns ratio, take n = 10. Therefore, we can obtain M_{min} = 1/2.

With input voltage between 380-420V, the maximum static gain is therefore determined. Next, determine the maximum quality factor for ZVS operation region. V_o is 500V, according to the input and output voltage at the resonance point, the transformer primary-secondary turns ratio n, the minimum static gain M_{min} is 0.8. M_{max} = 0.95.

λ is the ratio of magnetizing inductance to resonant inductance, generally taken as $\lambda = 0.2$, therefore we get M_{max} = 0.74. Considering a certain margin, 90% of M_{max}: M_{max}' = 0.74.

The resonant network quality factor is: Q_{max} = 0.9 × Q_{max} = 0.67, which is the characteristic impedance, yielding: Z_o = 3.46Ω.

The series resonant circuit resonant frequency is f_r = 50kHz. Therefore, the resonant network parameters can be calculated as: L_r = 4.49 H, L_m = 22.45 H, C_r = 388nF.

4 Simulation and Testing

4.1 Circuit Simulation

PSIM software is used to establish simulation models of the supercapacitor charging circuit and phase-shifted full-bridge main circuit. To reduce simulation computational load, the front-stage Vienna circuit in the supercapacitor charging circuit is replaced with a DC source, establishing a PSIM simulation model of the three-phase LLC circuit as shown in Figure 5 [Figure 5: see original paper].

Figure 5 LLC circuit PSIM simulation model

Substituting the calculated parameter values into the simulation model yields the output waveform shown in Figure 6 [Figure 6: see original paper]. The circuit can stably output 500V, with two-stage charging circuits in series achieving 1000V output, meeting supercapacitor charging requirements.

Figure 6 LLC circuit simulation output

The inverter power supply main circuit PSIM simulation model is established as shown in Figure 7 [Figure 7: see original paper]. The input source uses supercapacitors; according to design requirements, one set of supercapacitors has 29F capacity and powers 42 modules. Therefore, a capacitor capacity of 0.69F is selected with initial voltage 1000V, transformer ratio 63, and switching frequency 6kHz.

Figure 7 PSIM simulation modeling of inverter power supplies

Substituting the relevant design parameters into the simulation model yields the output waveform shown in Figure 8 [Figure 8: see original paper]. The circuit can stably output 1600V, though the output voltage ripple is relatively large due to the small filter capacitor selection. Since the neutral beam high voltage power supply system load is an ion source accelerator prone to inter-electrode arcing breakdown, the power supply short-circuit energy must be limited, preventing the use of excessively large filter capacitors. To address this issue, power modules employ phase-shifted series connection to effectively reduce output voltage ripple.

Figure 8 Inverter power supply simulation output

4.2 Experimental Testing

Based on theoretical calculations and simulation results, a prototype inverter power supply module was built and tested for step response performance, voltage ripple, and soft-switching performance. The dummy load uses a glass glaze non-inductive resistor of approximately 30Ω, operating at 1600V with 1s pulse width. The step response performance test of the power module is shown in Figure 9 [Figure 9: see original paper], with a rise time of approximately 2.3ms, enabling rapid power switching of the power module and meeting neutral beam modulated injection requirements.

Figure 9 Step response performance test

The voltage ripple test of the power module is shown in Figure 10 [Figure 10: see original paper]. The measured ripple voltage is 129V, yielding a ripple coefficient of $129/1600 \times 100\% = 8\%$. The power supply system uses phase-shifted series connection to achieve 120kV rated output, which can reduce output voltage ripple to below 1%, meeting system requirements.

Figure 10 Voltage ripple test

The soft-switching performance test of the power module is shown in Figure 11 [Figure 11: see original paper], where blue represents the MOSFET turn-on signal, yellow represents the MOSFET voltage, and green represents the transformer primary current. The figure shows that the MOSFET turn-on signal triggers after the MOSFET voltage drops to zero, achieving zero-voltage turn-on, and the turn-off signal triggers before the MOSFET voltage rises, achieving zero-voltage turn-off, effectively reducing switching losses.

Figure 11 Soft switch performance testing

As neutral beam injection systems demand progressively higher voltage levels from high voltage power supplies, PSM high voltage power supply solutions can no longer meet requirements. This paper investigates an inverter-type high voltage power supply technology based on supercapacitor energy storage, using supercapacitor energy storage to reduce required grid capacity and minimize grid impact. Through modeling and calculation of the circuit system, simu-

lation models of the supercapacitor charging circuit and power module main circuit were established. A prototype inverter module was built and tested for step response performance, voltage ripple, and soft-switching performance. Simulation and experimental verification demonstrate that high-frequency inverter technology effectively improves power supply performance, and rapid power switching of the high voltage power supply is crucial for achieving neutral beam modulated injection.

Author Contributions

ZHANG Jintao: Responsible for simulation design of the research scheme, prototype debugging, and drafting and revising the final manuscript. **TANG Xian:** Responsible for overall paper design, critical review and revision of the article. **WANG Yingqiao:** Provided theoretical guidance for the research scheme and critical review and revision of the article. **XIA Yuyang:** Participated in debugging scheme discussions for the experimental process and collection and analysis of experimental data. **LI Qing:** Provided guidance on experimental debugging methods and participated in debugging scheme discussions for the experimental process.

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