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Research on Switch-Linear Hybrid Power Supply Based on Energy Feedback Scheme

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Abstract

As an essential component of a superconducting magnet system, the superconducting magnet power supply is responsible for the excitation and de-excitation of the superconducting magnet coil. This type of power supply needs to meet the requirements of high precision and high stability in output current. In response to these requirements, this paper proposes a switched linear composite power supply that achieves energy feedback, ensuring high precision and bidirectionality of the output current. The losses are quantitatively analyzed. To verify the feasibility of the proposed composite structure power supply, a simulation model with a peak power of 2 kW and a maximum current of 100 A was constructed. The output current stability reached 10 ppm, achieving high stability of the constant current source system for inductive loads.

1 INTRODUCTION

The superconducting magnet power supply, classified by its main circuit topology, can be divided into three types: phase-controlled rectifier power supplies, linear power supplies, and switching power supplies.

Phase-controlled rectifier power supply topologies use thyristors, which are inexpensive and have high power ratings. The circuit control is simple, and the reliability is high, making them mainly suitable for high-power applications in steady-state strong magnetic field devices, tokamak devices, and other hundreds of kilowatts to megawatts levels. For instance, the 4×10 MW excitation power supply of the National High Magnetic Field Laboratory in the United States[1] and the EAST vertical field power supply of the Institute of Plasma Physics[2], Chinese Academy of Sciences, use phase-controlled rectifier power supplies. However, phase-controlled rectifier power supplies also have obvious drawbacks, such as slow response speed, difficulty in miniaturization, and complex harmonic components in the output current[3,4].

Switching power supplies operate at high switching speeds, resulting in low losses. Researchers at the High Magnetic Field Laboratory of the Chinese Academy of Sciences have proposed a 2kW superconducting magnet power supply with energy feedback[5], allowing the superconducting magnet's energy to be fed back to the grid via intermediate bus capacitors. Additionally, Tianli Dai and colleagues at the University of Science and Technology of China have proposed a high-power density energy feedback-type superconducting magnet power supply[6]. This power supply uses bidirectional converters at all stages, including a three-level PWM rectifier at the input stage, a dual-active bridge converter at the intermediate stage, and a polarity-reversing H-bridge at the output stage. Due to the ability of this topology to allow bidirectional energy flow, during de-excitation, the energy stored in the superconducting magnet flows back to the power grid. However, the switch-mode power supply has poor versatility for magnet loads with different inductance values. Changes in the magnet's inductance cause changes in the system's transfer function, and a filtering stage is required on the output side. Typically, an LC filter is used, making the system a third-order system, which increases the difficulty in designing the controller.

On the other hand, linear power supplies offer advantages such as low output current ripple, high current stability, and rapid system response[7,8]. In linear power supplies, transistors operate in a linear amplification state, resulting in significant losses and low system efficiency. Furthermore, during demagnetization, the high energy stored in superconducting magnets, up to several megajoules, is dissipated as heat through linear transistors or discharge resistors, imposing substantial thermal management challenges.

With the maturation of power electronics technology, switching-linear power supplies have become a new option for medium and small power superconducting magnet power supplies. The switching-linear composite power supply, distinct from both switching and linear power supplies, combines the high efficiency and power density of switching power supplies with the high precision and rapid response of linear power supplies[9,10].

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In conclusion, high-precision switching-linear composite power supplies with energy feedback capabilities represent a current development direction for superconducting magnet power supplies, offering advantages such as high efficiency, miniaturization, and high precision. The remainder of this paper is organized as follows: Chapter 2 analyzes the evolution and operating modes of relevant topologies and verifies them through simulations. Chapter 3 examines the impact of adding linear elements on overall losses from a loss perspective. Chapter 4 provides a summary of this paper.

2 Topologies Analysis

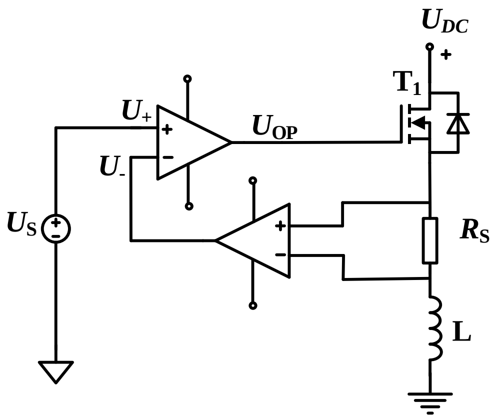

Fig. 1. Switch-linear Power Supply Basic Topology

Figure 1 shows a typical linear constant current source topology, where U_S is connected to the positive input of the operational amplifier. The high end of R_S voltage is connected to the inverting input of the operational amplifier, serving as the negative feedback voltage signal. The output of the operational amplifier is connected to the gate of T_1. The following relationships exist in the circuit.

$$I_o = U_s / R_s \qquad (1)$$

When I_o increases, the voltage drop across R_S increases accordingly, causing the voltage at the inverting input of the operational amplifier to rise. Since U_S remains constant, the voltage at U_+ stays unchanged. As a result, the output voltage of the operational amplifier will decrease, leading to a lower gate potential for T_1, which reduces the output current until equilibrium is achieved. Conversely, when I_o decreases, the process reverses. This analysis indicates that the output current IS of the constant current source is determined by the ratio of the reference voltage to the sampling resistor and is unaffected by the power supply voltage and load resistance. In practical design, by keeping the sampling resistor R_S constant and adjusting the reference voltage U_S, the output reference current value can be modified[11].

In practical applications, a current sensor is directly used instead of a sampling resistor to avoid design issues related to different high-end and low-end sampling drives. In the application scenario of a basic constant current source circuit for superconducting magnets, a de-excitation circuit needs to be added to release the energy stored in the magnet at a certain rate. Anhui Jinyi Power proposes a topology, as shown in Figure 2[12]. Through two linear adjustment tubes, T_1 and T_2, the excitation and de-excitation circuit currents are controlled separately. During excitation, T_1 operates, and since diode is off, the current does not flow through the de-excitation circuit. During de-excitation, the current in the load inductance decreases, diode conducts, and the linear adjustment tube T_2 starts working. During the de-excitation process, all the energy stored in the load inductance is dissipated in the de-excitation circuit, causing energy wastage and posing a challenge to the system's heat dissipation.

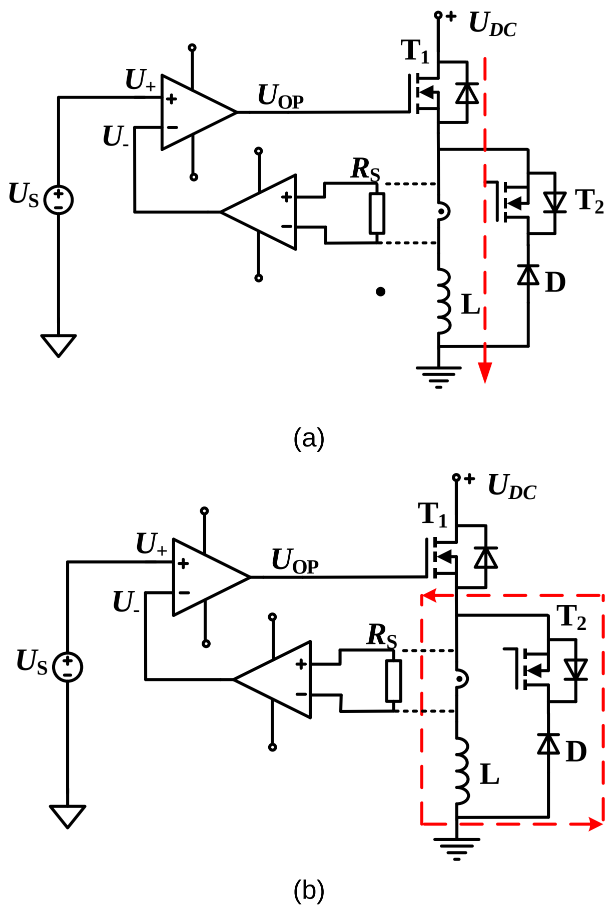

Fig. 2. Constant Current Source Structure.

To achieve the purpose of energy feedback and solve the issues present in the de-excitation circuit of Figure 3, A hybrid power supply structure using an H-bridge is proposed. The H-bridge hybrid power supply, through the switching of Q_1 and Q_2 and the linear adjustment of T_1 and T_2, accomplishes two main objectives: first, it enables energy feedback from the load end; second, it operates in two quadrants, allowing bidirectional current flow, which supports both forward and reverse excitation. The preceding stage provides DC voltage，the following mainly analyzes the working modes of the H-bridge.

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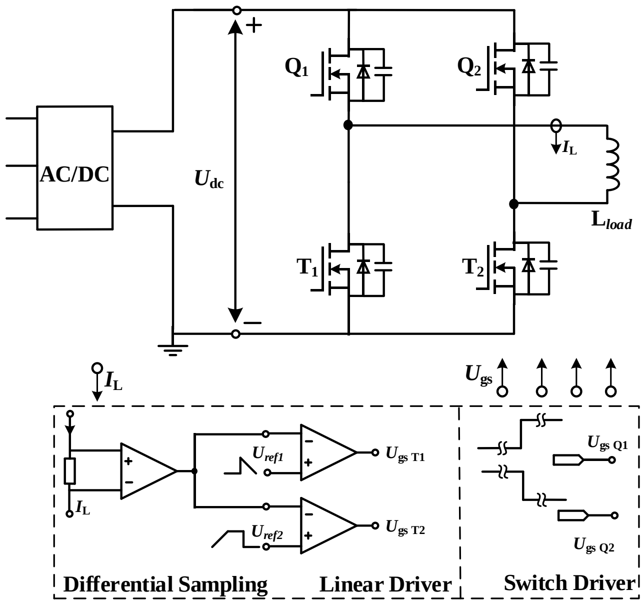

Fig. 3. H-bridge hybrid power supply

According to the direction in the figure, assume that when the current flows downward, the superconducting magnet is in a forward excitation state.

0-t_1 period: At this time, Q_1 remains open, and T_2 is in a linear adjustment state, operating in the constant current region of the MOSFET. By continuously adjusting the gate drive voltage of T_2, the current is controlled to achieve high stability.

t_1-t_2 period: During this period, the system remains in a constant current state, and the current remains stable.

When the magnet is de-excited, Q_1 and T_2 are turned off, and the current continues to flow through the body diodes of Q_2 and T_1. Then, Q_2 and T_1 are turned on, and the current flows through the channels of the switching tubes, reducing the loss through the body diodes. At this time, the magnet charges the preceding stage DC-DC, achieving energy feedback. Similarly, when the current flows upward, the magnet is in a reverse excitation state. T_1 is in a linear adjustment state. When the magnet is de-excited, the body diodes of Q_1 and T_2 continue the current flow. Then Q_1 and T_2 are turned on, achieving energy feedback.

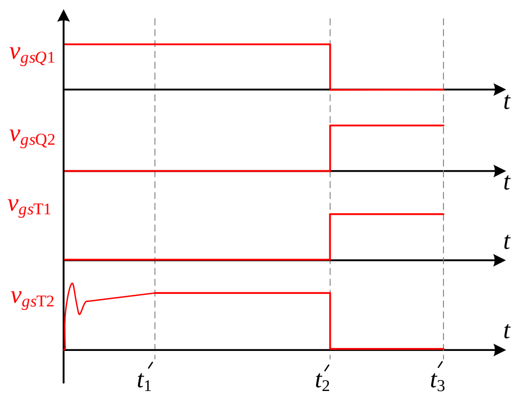

Fig. 4. Control Logic of the Hybrid Power Supply

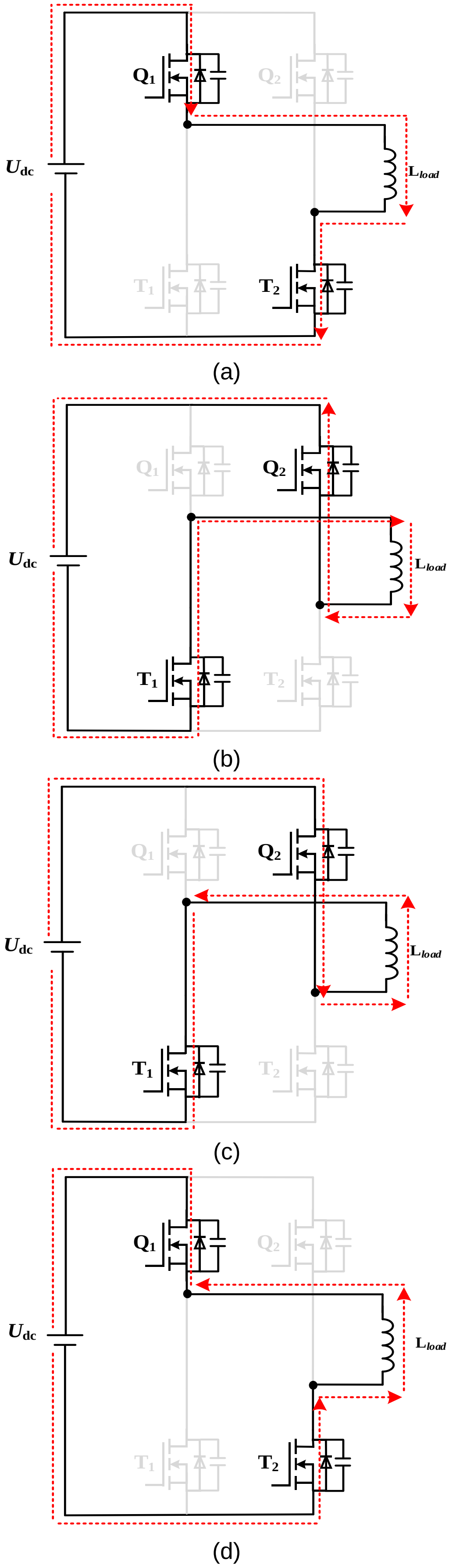

Fig. 5. Working Mode Analysis.

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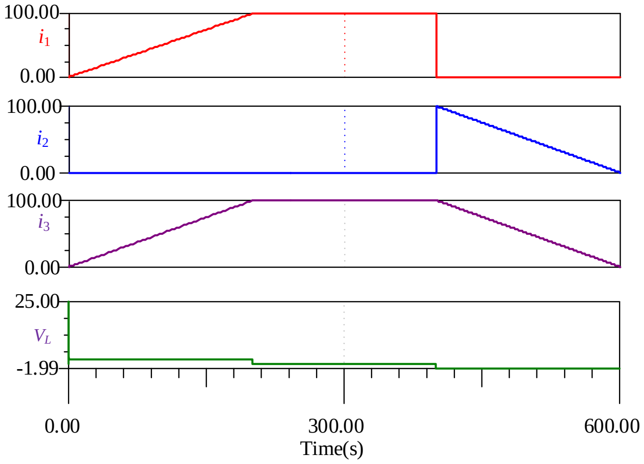

Fig. 6. Voltage and current at 4H inductance load

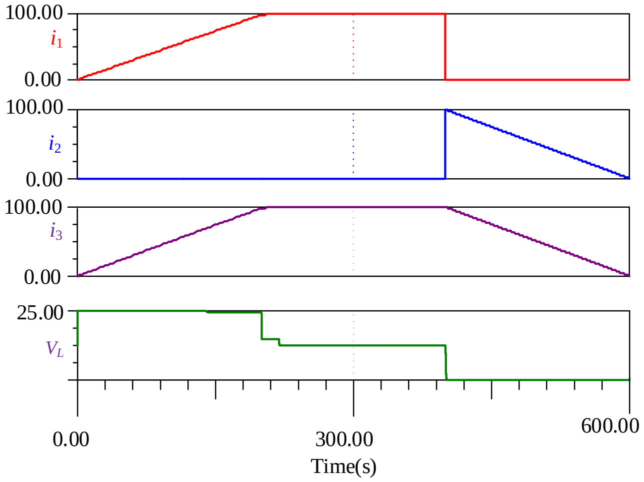

Fig. 7. Voltage and current at 50H inductance load

In Figure 6 and 7, i_1 is the excitation circuit current, i_2 is the de-excitation circuit current, i_3 is the load inductance current, and V_L is the load inductance voltage. When the current rise or fall slope is constant, the voltage across the load inductance is a constant value. Simulation results show that the composite power supply can achieve the corresponding functions for magnets with different inductance values. The switch-mode power supply output with LC filtering connected to the superconducting load forms a third-order system, while the composite power supply forms a first-order system, making it easier to control when the inductance value changes.

3 Loss Analysis

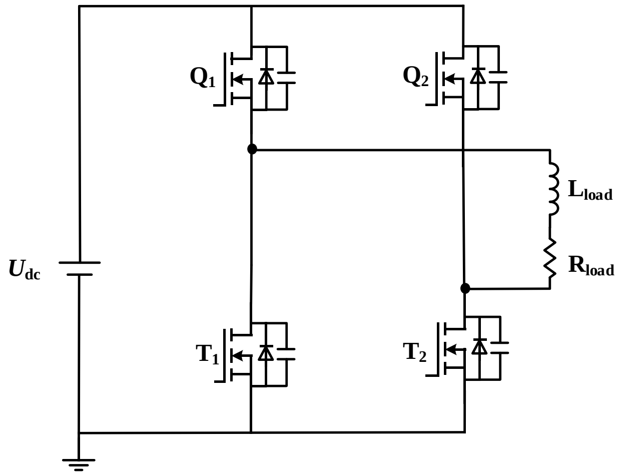

Fig. 8. Circuit topology with load resistance

The proposed composite power supply includes two linear adjustment transistors, which, when compared to switching modes, have higher losses when MOSFETs operate in the constant current region. During operation, the power primarily consists of the magnetic field generated by the superconductors and the associated losses. Using Texas Instruments' CSD18542KTT as an example, the losses in the composite power supply are analyzed as follows:

Linear Losses: These are the losses incurred by the linear adjustment transistors T_1 and T_2.

On-State Losses: These are the losses associated with the switching transistors Q_1 and Q_2 during their on-state.

Load Losses: These are losses due to the resistance in the superconducting device's wiring, which is inevitable.

The loss calculation formula is as follows:

$$P_1 = V_D \cdot I_D \tag{2}$$

$$P_2 = I_D^2 \cdot R_{ds(on)} \tag{3}$$

$$P_3 = I_D^2 \cdot R_o \tag{4}$$

Table.1. Loss Calculation Parameters

Parameters	Values
U_{DC}	12.5V
I_D	100A
Rds(on)	2.4m
R_O	2m

Among them, P_1 represents the linear losses, P_2 represents the on-state losses, and P_3 represents the load losses. The specific parameters are shown in the table below. During the excitation phase, the current rises linearly at 0.5 A/s to 100 A, and during the demagnetization phase, it decreases linearly at 0.5 A/s to 0 A.

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The calculated power losses are shown in the table below.

Table.2. Loss Calculation Results

Power	Excitation	Constant
P1	35W	70W
P2	8W	24W
P3	6.7W	20W

For the excitation phases, a graded control scheme for the transistor voltage drop can be implemented[13]. This involves controlling the voltage drop on the right side of the pre-cutoff trajectory and minimizing it to reduce losses while maintaining current.

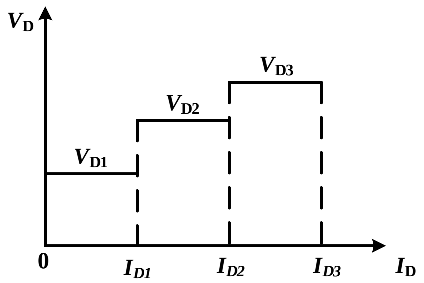

Fig. 8. Graded Control Strategy for Transistor Voltage Drop

The graded control of the transistor voltage drop is as follows: when the current is 0-40A, the voltage drop is controlled at 0.4V; at 40-60A, it is controlled at 0.5V; and at 60-100A, it is controlled at 0.7V. The linear loss power is then recalculated:

$$P_1 = V_{D1} \cdot I_{D1} + V_{D2} \cdot I_{D2} + V_{D3} \cdot I_{D3} \quad (5)$$

After calculation $P_1 = 27W$, the losses during the excitation and demagnetization phases are reduced by 23%.

4 Conclusion

This article investigates a high-precision switched-linear hybrid power supply for superconducting magnets, particularly focusing on innovative designs for energy feedback and bidirectional current output. As an essential part of the superconducting magnet system, the power supply is responsible for the excitation and demagnetization of the superconducting magnet coils. This type of power supply must meet the requirements of high precision and high stability in output current. The article proposes a hybrid power supply and structure, then quantitatively analyzes its losses. This structure uniquely combines switching power supplies and linear power supplies, achieving efficient energy conversion while ensuring high precision and bidirectionality of the output current.

The main contributions of this article are as follows:

(1) The article proposes a novel design for a switch-mode linear composite power supply. The H-bridge composite structure, composed of two linear adjustment tubes and two state-switching tubes, achieves the backflow of de-excitation energy.

(2) The H-bridge serves as the optimized design unit. Its topology is completely symmetrical, which ensures that different switching tubes on the same bridge arm are in different working states. The control logic is the same for both forward and reverse current flow, enabling bidirectional excitation of the superconducting magnet and providing freedom in the direction of the magnetic field for the magnet.

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