

Topology Selection and Control Research on External Power Box of Export EMU

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Abstract

To meet the requirement that an export Electric Multiple Units (EMUs) be compatible with both AC 1500 V/50 Hz and AC 1000 V/16.7 Hz external power supplies, the external power supply system was designed and optimized. Firstly, several main circuit topologies for the external power supply system are proposed, and the technical characteristics, advantages, and disadvantages of each are analyzed. Subsequently, an improved combined external power supply scheme with significant advantages in size and cost was investigated. Key parameter selection was carried out, and the inductance design under extreme conditions, such as supply voltage fluctuations, was analyzed. In addition, the corresponding control and protection strategies were proposed. Finally, Simulation results verified the feasibility and correctness of the proposed scheme. The research ideas and methods can guide the design of the external power supply system for export EMUs.

Keywords

External Power Supply, Main Circuit, Parameter Selection, Voltage Fluctuation, Control and Protection

1. Introduction

To meet the emergency power supply capacity for daily servicing and maintenance of EMUs, and the emergency power supply capacity for lighting, heating, air conditioning, etc., of EMUs in the event of failure, the functional requirements for ground external power supply are usually considered in the design [1]-[3]. Currently, the external ground power supply mode for CRH1 and CRH5 EMUs in China is 3AC 400 V/50 Hz, and 3AC 380 V/50 Hz is used for CRH3 and Fuxing standard EMUs. Since the power supply mode of the ground external power supply is consistent with that of the train auxiliary system, its system composition is

relatively simple. It is only necessary to connect the ground power supply to the on-board external power box via the cable and configure the circuit breaker, flexible cable, connector, and other components in the box to provide direct power to the EMU's auxiliary system [4]-[6]. In Europe, there are various power supply modes for external power supply, such as Denmark using single-phase AC 1500 V/50 Hz and Sweden using single-phase AC 1000 V/16.7 Hz. A certain type of EMU exported to Europe needs to meet the operational requirements of Sweden, Denmark, and other countries simultaneously, so it must be compatible with AC 1500 V/50 Hz and AC 1000 V/16.7 Hz when powered by an external power supply. To address this demand, this paper will analyze the selection of the main circuit topology for the external power supply system, the selection of key parameters, and the external power supply's adaptability to fluctuations, and propose corresponding control and protection strategies. Finally, the correctness of the external power supply scheme is verified by MATLAB simulation.

2. Analysis of Main Circuit Topology

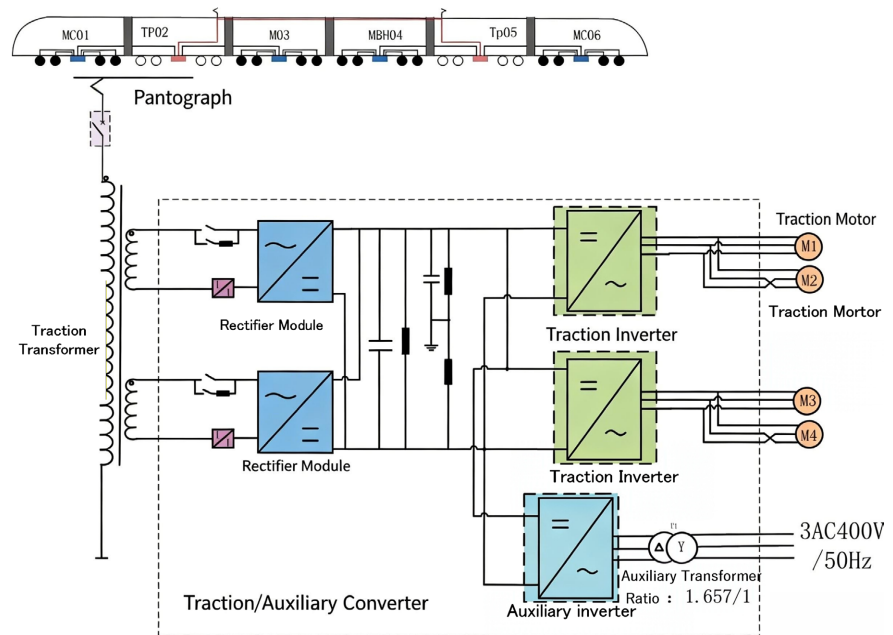


Figure 1. Schematic diagram of the main traction circuit of a certain EMU model exported to Europe.

The traction converter of an EMU exported to Europe adopts the integrated design of the main and auxiliary. The auxiliary inverter takes power from the intermediate DC circuit (the working voltage of the intermediate circuit is 1800 V), and outputs a 3AC 400 V/50 Hz power supply through the auxiliary inverter and auxiliary transformer to supply power for the auxiliary load. The capacity of a single auxiliary converter is about 180 kVA when the contact network is normally supplied. The main circuit principle of the traction system is shown in **Figure 1**. The main function of the external power supply system is to provide 3AC 400

V/50 Hz power for the auxiliary load after converting the two external AC 1000 V/16.7 Hz (Sweden) and AC 1500 V/50 Hz (Denmark) ground power supplies. When the external power supply is used, the auxiliary load is mainly the train air conditioner, fan, heating, and battery charger, with a capacity of about 60 kVA.

2.1. Independent External Power Supply Scheme

The independent external power box designed in this study can convert the two modes of ground power, AC 1000 V/16.7 Hz and AC 1500 V/50 Hz, to 3AC 400 V/50 Hz, and directly connect to the three-phase bus of the train auxiliary system to realize the power supply function for the auxiliary system. The main circuit topology is shown in **Figure 2(a)**, and the circuit principle of the external power box is shown in **Figure 2(b)**. This scheme is decoupled from the traction components, has strong flexibility of on-board layout, and is not affected by the status of other traction equipment during operation. However, due to the high voltage level and the need for a rectifier/inverter, the scheme has no advantages in terms of volume and cost.

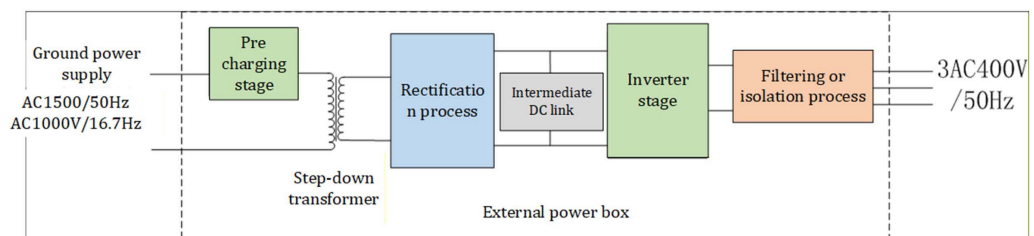
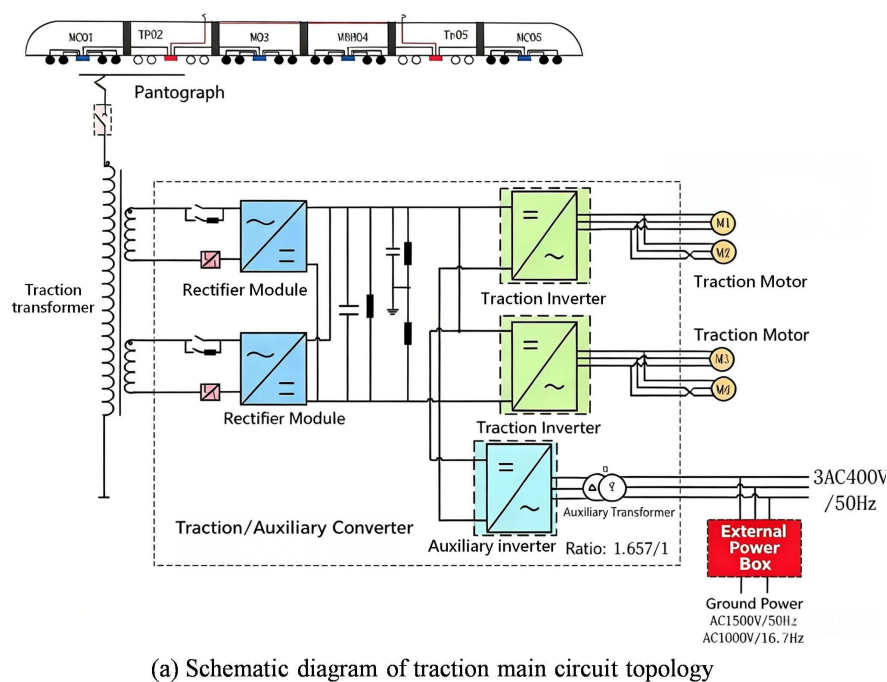


Figure 2. Schematic diagram of the independent external power supply box scheme.

2.2. Combination Scheme of External Power Box and Traction Converter

The external power supply box is designed to connect the ground power supply to the traction converter, charge the intermediate DC circuit through the four-quadrant module rectification of the traction converter, and then use the auxiliary inverter link to output a 3AC 400 V/50 Hz power supply for the auxiliary system. By reusing the existing traction converter resources, this scheme can significantly reduce the system volume and cost [7], and its main circuit topology is shown in **Figure 3**. The scheme of the external power box is as follows.

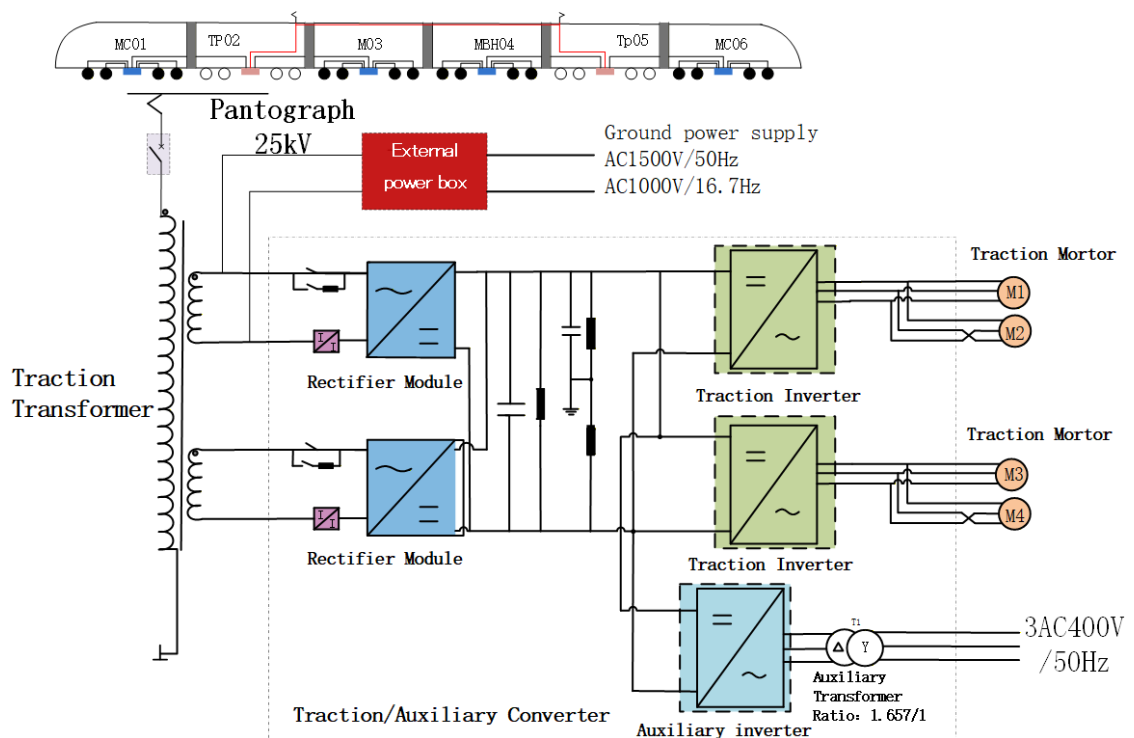


Figure 3. Topology diagram of the external power supply cabinet + traction converter integrated.

(1) Option 1: Only the circuit breaker is set in the external power supply box. After the ground power supply is connected to the traction converter, the intermediate DC circuit is charged through the four-quadrant module diode uncontrolled rectification. When the ground power supply is AC 1500 v/50 Hz mode, the rectified intermediate DC voltage $U_D = 1.414 \times U_N = 2121 \text{ V}$, U_N is the ground power supply voltage. since the intermediate DC link components of traction converter (such as direct support capacitor, secondary resonant capacitor, resistance, etc.) are selected according to the rated working voltage of 2000 V, according to IEC 61881-2010 standard requirements for power electronic capacitors of rail transit rolling stock equipment: 1) the working time per day under 1.1 times of rated working voltage shall not exceed 8 h; 2) the working time per day under 1.15 times of rated working voltage shall not exceed 0.5 h; 3) the working time per day under 1.2 times of rated working voltage shall not exceed 5 min.

Considering the uncontrollability of the service time and the power fluctuation range of the external power supply, if it exceeds the allowable voltage range for a long time, the service life and reliability of the capacitor will be reduced, and the capacitor will be damaged in serious cases, with potential safety hazards. If it is necessary to meet the requirements of this working condition, it is necessary to redesign the capacitor with a higher withstand voltage level, which will inevitably lead to an increase in capacitor size and cost. However, because the power supply function of the external power supply is only used under specific circumstances, its actual work proportion is relatively low, so the overall economy of the scheme is poor.

(2) Option 2: The ground power supply is connected to the traction converter after passing through the step-down transformer in the external power supply box, and then the boost is realized through the PWM rectification of the four-quadrant module to supply power for the intermediate DC circuit. At the same time, protection and monitoring elements such as circuit breakers, voltage, and current detection units are also set inside the system. The circuit principle is shown in **Figure 4**.

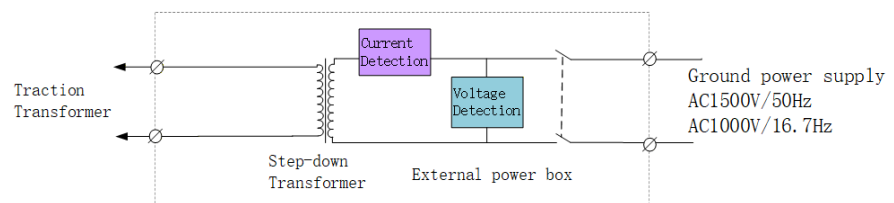


Figure 4. Schematic diagram of the step-down transformer configuration.

The scheme shown in **Figure 4** can avoid the risk that the intermediate voltage exceeds the rated working voltage due to uncontrolled rectification in scheme 1. According to Faraday's law of electromagnetic induction:

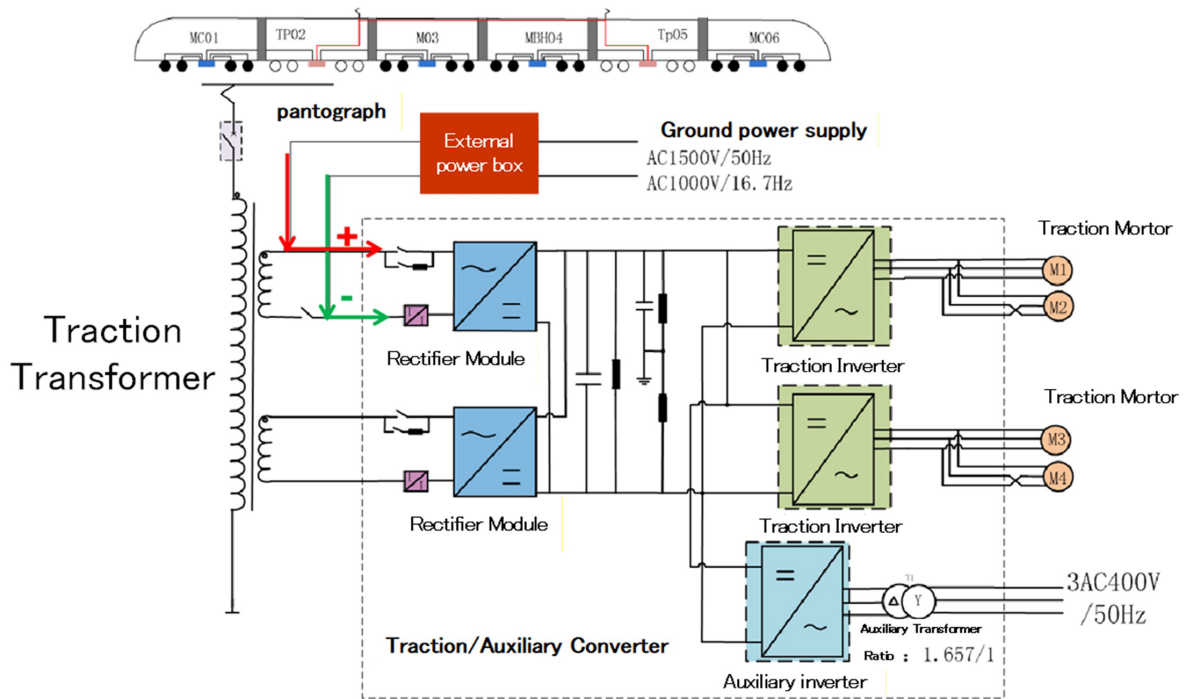
$$E = 4.44 \cdot f \cdot N \cdot B \cdot S \quad (1)$$

where E is the effective value of induced potential, f is the frequency, N is the number of turns, B is the magnetic flux density of the iron core, S is the cross-sectional area of the iron core.

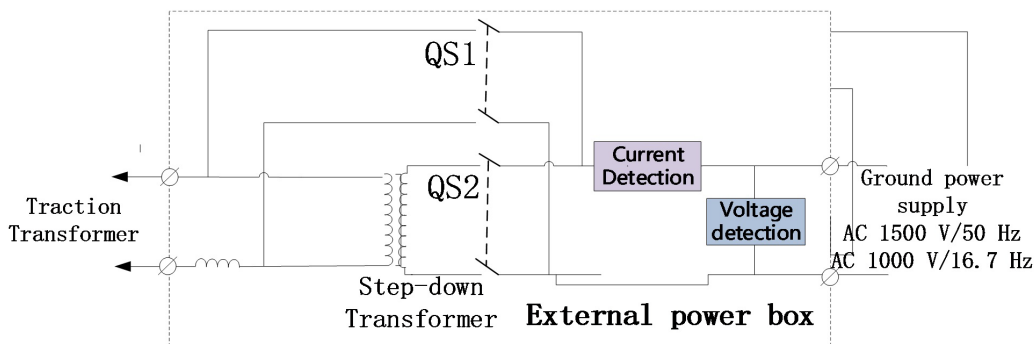
From Equation (1), it can be concluded that under the same induced potential, a lower frequency increases the number of turns and main flux density, resulting in a larger iron core. This is a key factor impacting the transformer's volume and quality. Since the step-down transformer must accommodate the AC 1000 V/16.7 Hz power supply mode, its volume and mass are markedly greater. As a result, in engineering applications, the increased size and mass diminish the practical advantages of this scheme.

(3) Option 3: Based on the shortcomings of scheme 2, this paper proposes an improved scheme, as shown in **Figure 5**. In this scheme, the step-down transformer only needs to meet the AC 1500 V/50 Hz power supply mode, which significantly reduces the volume and mass. At the same time, under the condition of

AC 1000 V/16.7 Hz power supply, the ground power supply is connected to the traction converter through the series additional inductance and the secondary winding of the traction transformer, and then the boost is realized through the four quadrant module PWM rectifier to supply power for the intermediate DC circuit; Under the condition of AC 1500 V/50 Hz power supply, the ground power supply is first reduced by the step-down transformer, then connected to the traction converter in series with the additional inductance and the secondary winding of the traction transformer, and then boosted by four quadrant module rectification to supply power for the intermediate DC circuit.



(a) Traction main circuit topology



(b) External Power Supply Box Circuit Principle

Figure 5. Schematic diagram of the improved external power supply cabinet configuration.

Compared with Option 1, Option 3 avoids excessive DC-link voltage stress and the consequent risk to capacitor reliability or costly redesign. Compared with Op-

tion 2, Option 3 eliminates the need for a bulky and heavy 16.7 Hz step-down transformer by reusing the traction transformer's secondary winding and adding only a small inductor and a 50 Hz step-down transformer. This results in significantly lower mass and cost while maintaining full functional compatibility with both power supply modes. Therefore, Option 3 is selected as the preferred scheme for further study.

3. Selection and Design of Key Parameters

The improved external power box scheme can be compatible with AC 1500 V/50 Hz and AC 1000 V/16.7 Hz ground power supply modes, in which the step-down transformer only needs to adapt to the AC 1500 V/50 Hz mode, so as to significantly reduce the volume and mass of equipment, which is the preferred scheme to realize the miniaturization and lightweight of EMUs. Based on this, this paper will focus on the feasibility of the scheme and the selection of key parameters.

3.1. Calculation of Power Supply Capacity of External Ground Power Supply

It can be seen from the above description that when the external power supply is used, the auxiliary load capacity $P_{\text{Load}} = 60$ kVA, the auxiliary system power factor $\lambda_{Au} = 0.85$, and the efficiency $\eta_{Au} = 0.9$ are usually set, so the output power of the intermediate circuit of the traction converter is

$$P_M = \frac{P_{\text{Load}} \times \lambda_{Au}}{\eta_{Au}} = \frac{60 \times 0.85}{0.9} = 56.7 \text{ kW} \quad (2)$$

When the four-quadrant PWM rectifier is used, the efficiency of the traction converter is $\eta_{\text{conv}} \approx 0.92$, and the power factor at the grid side is taken as $\eta_{UN} \approx 0.95$, then:

1) When the AC 1000 V/16.7 Hz power supply mode is adopted, the total capacity of the power supply is

$$P_{N1} = \frac{P_M \times \lambda_{Au}}{\eta_{UN} \times \eta_{\text{conv}}} = \frac{56.7}{0.95 \times 0.92} = 65 \text{ kVA} \quad (3)$$

Under this mode, the rated output current of the power supply is

$$i_{N1} = \frac{P_{N1}}{U_1} = \frac{65000}{1000} = 65 \text{ A} \quad (4)$$

2) When the AC 1500 v/50 Hz power supply is adopted, the efficiency of the step-down transformer is $\eta_{Au} \approx 0.94$, and the total capacity of the power supply is

$$P_{N2} = \frac{P_M}{\eta_{UN} \times \eta_{TR} \times \eta_{\text{conv}}} = \frac{56.7}{0.95 \times 0.94 \times 0.92} = 70 \text{ kVA} \quad (5)$$

Under this mode, the rated output current of the power supply is

$$i_{N2} = \frac{P_{N2}}{U_2} = \frac{70000}{1500} = 47 \text{ A} \quad (6)$$

3.2. Parameter Design of Step-Down Transformer

In order to be consistent with the output voltage of the AC 1000 V/16.7 Hz power supply mode, the transformation ratio of the step-down transformer is designed as 1500 V: 1000 V. When the two power supply modes work, they can be regarded as the circuit structure of the single-phase four-quadrant converter, and the AC side transient equivalent circuit is shown in Figure 6.

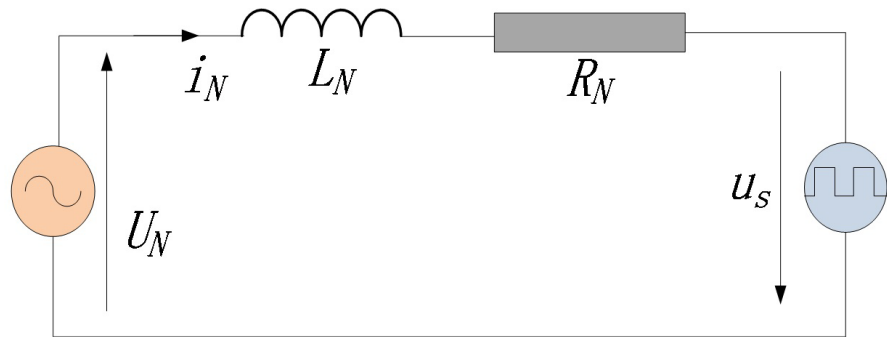


Figure 6. Equivalent circuit of the four-quadrant converter.

L_N is the sum of leakage inductance and additional inductance of secondary winding of traction transformer when AC 1000 V/16.7 Hz power supply is applied; When AC 1500 V/50 Hz power supply is applied, L_N is the sum of the leakage inductance of the secondary winding of the traction transformer, the additional inductance and the leakage inductance of the step-down transformer; The design of L_N needs to ensure the tracking performance of grid side current and effectively suppress the harmonic of grid side current. Excessive inductance value will reduce the current dynamic response speed, and too small an inductance value will weaken the suppression of AC side current harmonics [8]. It is assumed that in a switching cycle, the intermediate DC voltage U_d and the power supply voltage U_N act on both ends of the inductance L_N at the same time. At this time, the L_N current change rate is the largest. To meet the working requirements, there are

$$\frac{1}{L_N} \int_0^{T_s} (\sqrt{2}U_N \sin(\omega t) + U_d) dt \geq \sqrt{2}i_N \sin(\omega T_s) \tag{7}$$

where U_N is the effective value of power supply voltage, i_N is the effective value of power supply current, and T_s is the switching cycle.

Since $a = b$ when the current is at zero crossing, it can be obtained by substituting into Equation (7):

$$L_N \leq \frac{U_N T_s}{2i_N} + \frac{\sqrt{2}U_d}{2\omega i_N} \tag{8}$$

When the voltage at both ends of the inductor is the maximum, the ripple value of the inductor current is the maximum. The maximum voltage appears on the inductor at the time when the network voltage is the maximum. The current tran-

sient waveform in a switching cycle is shown in **Figure 7**.

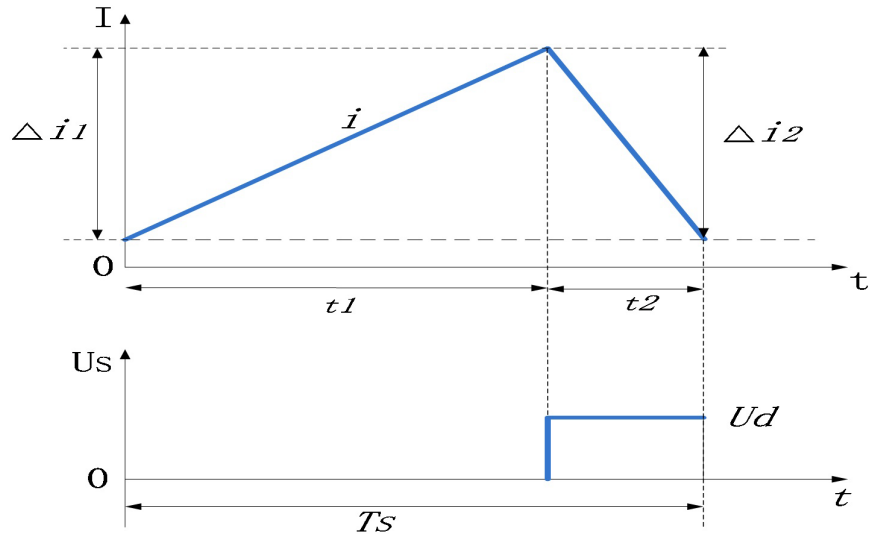


Figure 7. Current waveform at the maximum grid voltage.

Select $0 < t < t_1$ when the IGBT switch is closed, and

$$L_N \cdot (\Delta i_1 / t_1) = \sqrt{2} U_N \tag{9}$$

Select $t_1 < t < t_2$ when the IGBT switch is off, and

$$L_N \cdot (\Delta i_2 / t_2) = \sqrt{2} U_N \tag{10}$$

Because the current change rate near the peak value of the sine wave current is the smallest, which is approximately 0, there is

$$|\Delta i_1| = |\Delta i_2|, \tag{11}$$

$$t_1 + t_2 = T_s. \tag{12}$$

If the maximum allowable value of inductance current ripple is Δi_{\max} , then the electrical induction meets a certain value, so that $\Delta i_{\max} \geq \Delta i_2$, the simultaneous Equations (9) - (12) can obtain

$$L_N \geq \frac{\sqrt{2} U_N t_1}{\Delta i_{\max} U_d} = \frac{\sqrt{2} U_N (U_d - \sqrt{2} U_N) T_s}{\Delta i_{\max} U_d}. \tag{13}$$

3.3. Design of Inductance Parameters

The main parameters of an EMU traction system are shown in **Table 1**.

Table 1. Main parameters of the external power supply system of a certain EMU.

Parameter	Value
Internal resistance of traction transformer winding/ Ω	0.026
Leakage inductance of traction transformer winding/mH	2.73
Auxiliary load capacity in case of external power supply/kVA	60

Continued

Given intermediate voltage of traction converter U_d/V	1800
Intermediate support capacitance of traction converter/mF	32.4
Current ripple limit in case of external power supply/A	100
Four-quadrant module switching frequency/Hz	900
Switching frequency of auxiliary inverter module/Hz	750

(1) Inductance design at rated supply voltage. Due to the low power of the external power supply, the switching frequency of the four-quadrant module of the traction converter can be increased to 900 Hz after accounting. At the same time, the inductance of the external power supply system is designed as follows, with the current ripple value Δi_{\max} no more than 100 A when the rated network voltage is working as the boundary:

1) When AC 1000 V/16.7 Hz is used for power supply, $U_N = 1000\text{ V}$, $U_d = 1800\text{ V}$, $\Delta i_{\max} = 100\text{ A}$, $i_N = 65\text{ A}$, $T_s = 1/1800\text{ s}$, $\omega = 2 \times \pi \times 16.7$ are substituted into Equations (8) and (13), respectively, to obtain $1.68\text{ mH} \leq L_N \leq 191.0\text{ mH}$.

2) When AC 1500 V/50 Hz is used for power supply, $U_N = 1000\text{ V}$, $U_d = 1800\text{ V}$, $\Delta i_{\max} = 100\text{ A}$, $i_N = 65\text{ A}$, $T_s = 1/1800\text{ s}$, $\omega = 2 \times \pi \times 50$ are substituted into Equations (8) and (13), respectively, to obtain $1.68\text{ mH} \leq L_N \leq 66.5\text{ mH}$.

Therefore, in the external power supply system under rated network voltage, the inductance value should meet the requirements of $1.68\text{ mH} \leq L_N \leq 66.5\text{ mH}$.

(2) It meets the inductance design under power supply voltage fluctuation. According to the provisions of the European standard "EN CLC/TS 50535-2010 auxiliary power converter system carried on the vehicle", when the power supply is AC 1000 V/16.7 Hz, the range of power supply voltage is AC 700 V~AC 1200 V; when the power supply is AC 1500 V/50 Hz, the range of power supply voltage is AC 1050 V~AC 1740 V.

Assuming that the modulation ratio of the four-quadrant PWM rectifier is M , the relationship between the fundamental amplitude U_s of the AC side voltage and the intermediate DC voltage U_d is as follows:

$$M = \sqrt{2} U_s / U_d \quad (14)$$

Any semiconductor switching device has a certain turn-on and turn-off delay. In order to avoid the delay leading to the direct connection between the upper and lower bridge arms, it is usually necessary to set the dead time. Due to the influence of dead time, the maximum modulation ratio of the PWM rectifier needs to meet a certain upper limit [9], usually set as $M_{\max} \leq 0.95$. According to the equivalent circuit diagram of the four-quadrant rectifier, ignoring the equivalent resistance R_N in the diagram can get

$$U_s = \sqrt{U_N^2 + (\omega L_N i_N)^2}. \quad (15)$$

When the AC 1000 V/16.7 Hz power supply mode is adopted, the maximum network voltage $U_N = 1200 \text{ V}$, $i_N = 65 \text{ A}$, $\omega = 2 \times \pi \times 16.7$ can be substituted into Equations (7) and (8), and $L_N \leq 21.8 \text{ mH}$ can be obtained.

When the AC 1500V/50Hz power supply mode is adopted, the maximum network voltage $U_N = 1740 \text{ V}/\eta_C = 1740 \text{ V}/1.5 = 1160 \text{ V}$, $i_N = 65 \text{ A}$, $\omega = 2 \times \pi \times 50$ can be substituted into Equations (7) and (8), and $L_N \leq 16.7 \text{ mH}$ can be obtained.

Therefore, when the maximum network voltage is met, the inductance value in the external power supply system should meet the requirements of $L_N \leq 16.7 \text{ mH}$.

By analyzing the working principle and mathematical modeling of the four-quadrant converter [10]-[13], ignoring the equivalent resistance in the figure, the following mathematical relationship between the intermediate voltage and the power supply voltage can be obtained

$$U_d = \sqrt{2}U_N - L_N \frac{di_d}{dt} + \omega Li_q = \sqrt{2}U_N + L_N \frac{\Delta i}{T_s} + \omega Li_q \quad (16)$$

where i_d is the direct-axis current, i_q is the quadrature-axis current.

$$\Delta i \leq \Delta i_{\max} \quad (17)$$

Power factor

$$\lambda_{UN} = \sqrt{i_N^2 - i_q^2} / i_N \geq 0.95 \quad (18)$$

Simultaneous Equations (16) - (18) can obtain

$$U_d \leq \sqrt{2}U_N + L_N \Delta i_{\max} / T_s + \omega L \sqrt{0.05i_N^2} \quad (19)$$

When AC the 1000 V/16.7 Hz power supply mode is adopted, the minimum network voltage $U_N = 700 \text{ V}$, $U_d = 1800 \text{ V}$, $\Delta i_{\max} = 100 \text{ A}$, $i_N = 65 \text{ A}$, $T_s = 1/1800 \text{ s}$, $\omega = 2 \times \pi \times 16.7$ in normal operation, can be substituted into Equation (19) to obtain $L_N \geq 4.46 \text{ mH}$.

When the AC 1500 V/50 Hz power supply mode is adopted, the minimum network voltage, $U_N = 1050 \text{ V}/\eta_C = 1050 \text{ V}/1.5 = 700 \text{ V}$, $U_d = 1800 \text{ V}$, $\Delta i_{\max} = 100 \text{ A}$, $i_N = 65 \text{ A}$, $T_s = 1/1800 \text{ s}$, $\omega = 2 \times \pi \times 50$ in normal operation, can be substituted into Equation (19) to obtain $L_N \geq 4.39 \text{ mH}$.

4. Strategy of System Control and Protection

The power supply system of the EMU external power supply should not only meet the requirements of the power supply function for auxiliary loads, but also ensure its intelligent and safe operation. Therefore, the system control and protection strategy is designed as follows.

4.1. Adaptive Technology of Power Access Mode

The external power supply box is equipped with a voltage detection function at the input side of the ground power supply. The internal control unit monitors the amplitude and frequency of the ground power supply voltage in real time, auto-

matically identifies the power supply mode, and automatically configures the switch of the corresponding mode according to the current power supply mode.

1) Identification of AC 1000 V/16.7 Hz power supply mode. The enabling conditions in this mode are as follows: if the effective value of the power supply voltage $U > 0.6 \times 1000 \text{ V}$ and the power supply frequency f is [14.2, 19.2] Hz, and the duration exceeds 1 s, the 16.7 Hz power supply mode is set to be effective.

The setting conditions are as follows: if the effective value of the power supply voltage $U < 0.6 \times 1000 \text{ V}$ and the power supply frequency $f < 14.2 \text{ Hz}$ or $f > 19.2 \text{ Hz}$, lasting for more than 1s, the 16.7 Hz power supply mode is invalid.

2) Identification of AC 1500V/50Hz power supply mode. The enabling conditions in this mode are as follows: if the effective value of the power supply voltage $U > 0.6 \times 1500 \text{ v}$ and the power supply frequency f is [42.5, 57.5] Hz, and the duration exceeds 1s, the 50Hz power supply mode is set to be effective.

The setting conditions are as follows: if the effective value of the power supply voltage $U < 0.6 \times 1500 \text{ V}$ and the power supply frequency $f < 45.2 \text{ Hz}$ or $f > 57.5 \text{ Hz}$, lasting for more than 1 s, the 50 Hz power supply mode is invalid.

4.2. Protection Linkage and Locking Technology

First, the external power box adopts centralized key management. Before enabling the external power supply function, the safety protection measures for the grounding of the high-voltage main circuit must be completed before obtaining the opening key of the external power box.

Secondly, the external power box adopts an electrical interlocking design. When the external power plug is connected to the power supply, it is necessary to ensure that the main circuit of the traction power supply system is safely disconnected, such as triggering the pantograph lowering command, QS3 disconnection (as shown in **Figure 5(a)**), etc. At the same time, it is allowed to close the mode switches QS1 and QS2 in the external power box only after detecting that QS3 is in the off state (as shown in **Figure 5(b)**).

4.3. Four-Quadrant Rectifier Control

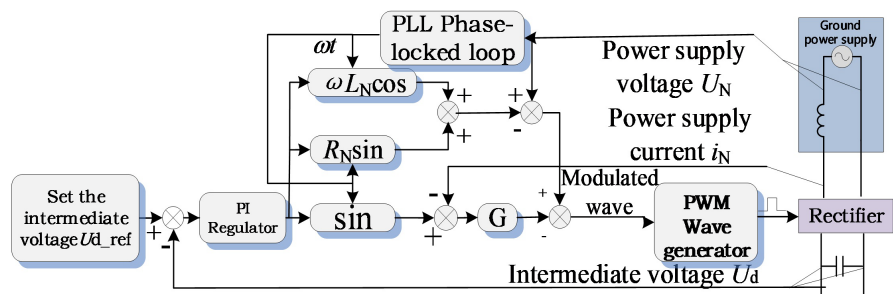


Figure 8. Block diagram of transient current control for the four-quadrant converter.

The main function of the four-quadrant rectifier is the characteristics of boost and AC/DC circuit conversion, which can convert the low single-phase voltage

boost at the input side into a stable intermediate voltage to meet the output demand of the auxiliary inverter. At the same time, it can improve the current harmonics at the power side to a certain extent and realize the unit's fundamental power factor at the power side approaching 1. Four-quadrant rectifier control based on transient current control is widely used because of its simple structure and obvious control effect. The implementation method control block diagram is shown in **Figure 8**.

4.4. Auxiliary Inverter Control Technology

The auxiliary inverter circuit topology generally adopts the voltage source type three-phase full bridge mode, and the output side supplies power to the load through the isolated step-down transformer or LC filter circuit. In order to improve the utilization rate of DC voltage and realize high steady-state accuracy and zero static error following of output AC voltage, space vector pulse width modulation (SVPWM) strategy is usually used in the control, and its control block diagram is shown in **Figure 9**.

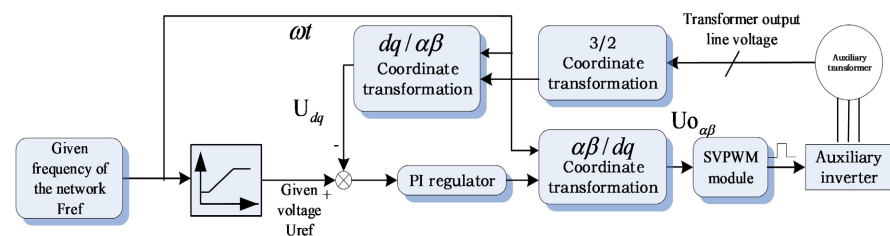


Figure 9. Block diagram of auxiliary inverter control.

4.5. System Timing Control Technology

The time sequence control method for designing the external power supply system is shown in **Figure 10**. The system principle is as follows:

1) Locking linkage protection. The external power plug is connected to the socket of the external power box of the train, and the pantograph lowering command of the train is triggered through the electrical interlock to disconnect the QS3 (as shown in **Figure 10**) contactor.

2) Adaptive detection of a power access mode. The control system identifies the ground input power supply voltage. When the AC 1000 V/16.7 Hz and AC 1500 V/50 Hz voltage requirements are met, it is determined to enter the ground power supply mode.

3) Precharge link. When the control system confirms that the pantograph is lowered and QS3 is disconnected, the system selects to close QS1 or QS2 according to the power supply mode. Then, the charging contactor and short-circuit contactor in the traction converter are put into operation time-sharing to gradually raise the intermediate DC voltage.

4) Four-quadrant rectifier voltage stabilization. After the short-circuit contactor is closed and the intermediate DC voltage rises to the threshold, the four-quadrant

rant rectifier starts to steadily raise the intermediate DC voltage to 1800 V.

5) The auxiliary inverter is started. After the intermediate voltage is stable, the auxiliary inverter is started immediately, and 3AC 400V is output to supply power for the auxiliary load. At this point, the external ground power supply is started.

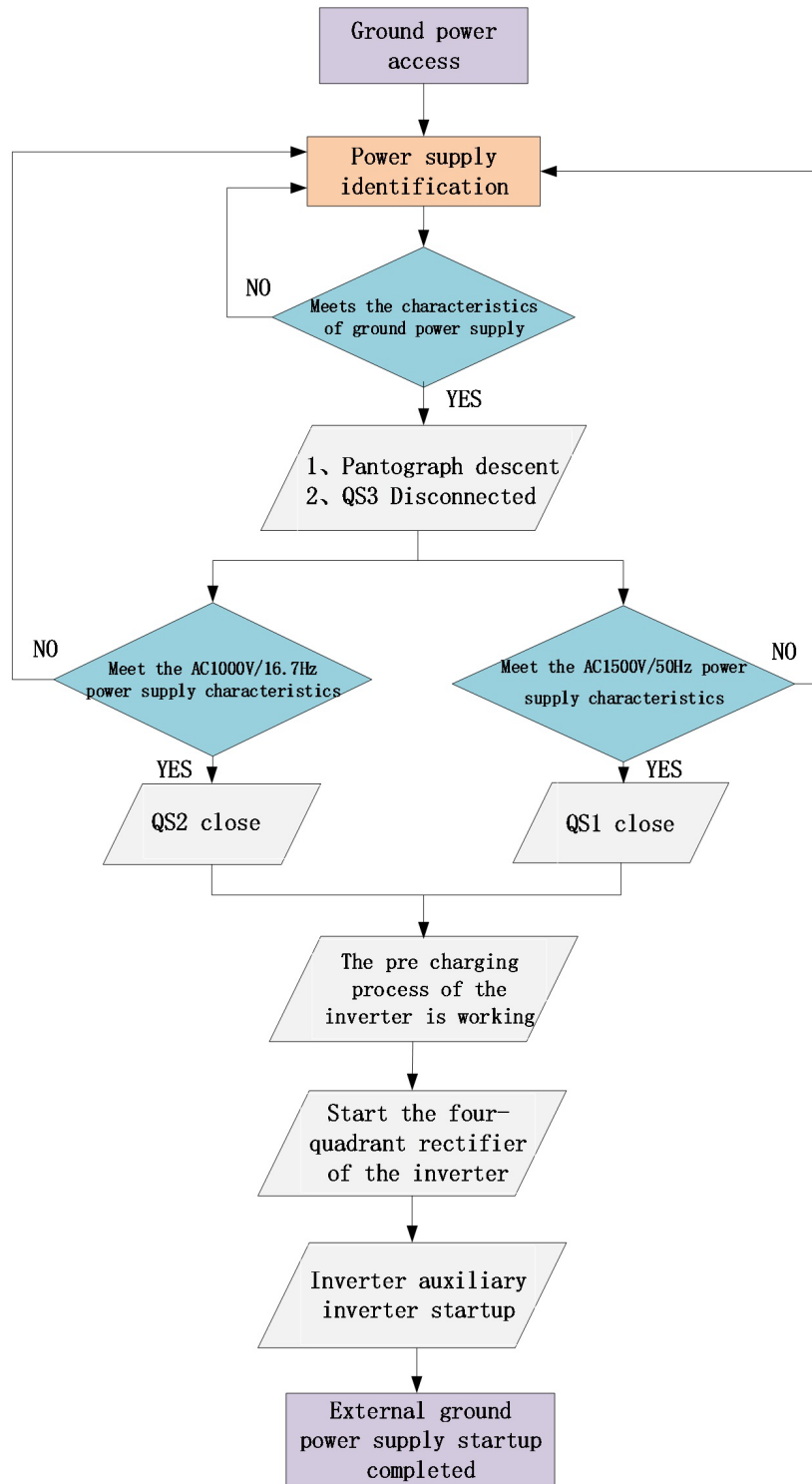


Figure 10. Timing diagram of the external power supply system.

5. Simulation Verification

In order to verify the feasibility of the improved external power supply scheme proposed in this paper, the MATLAB/Simulink model was built and simulated [14] [15]. The main parameters of the simulation are shown in **Table 1**, in which the PI parameters of the current loop are $K_p = 1.0$ 、 $K_i = 100$; The PI parameters of the voltage loop are $K_p = 0.3$ 、 $K_i = 10$, and the system inductance is set to 5 mH. Through the simulation calculation under two different ground power supply modes, the corresponding variation waveforms of voltage and current in each link of the external ground power supply system are obtained, as shown in **Figure 11**. **Figure 11(a)** shows the voltage and current waveforms during normal power supply under the AC 1000 V/16.7 Hz mode, and **Figure 11(b)** shows the voltage and current waveforms during normal power supply under the AC 1500 V/50 Hz mode. The results show that the proposed scheme can stabilize the intermediate voltage of the converter to 1800 V under both power supply modes, and achieve the output of 3AC 400 V/50 Hz from the auxiliary inverter, meeting the power supply requirements of the auxiliary system.

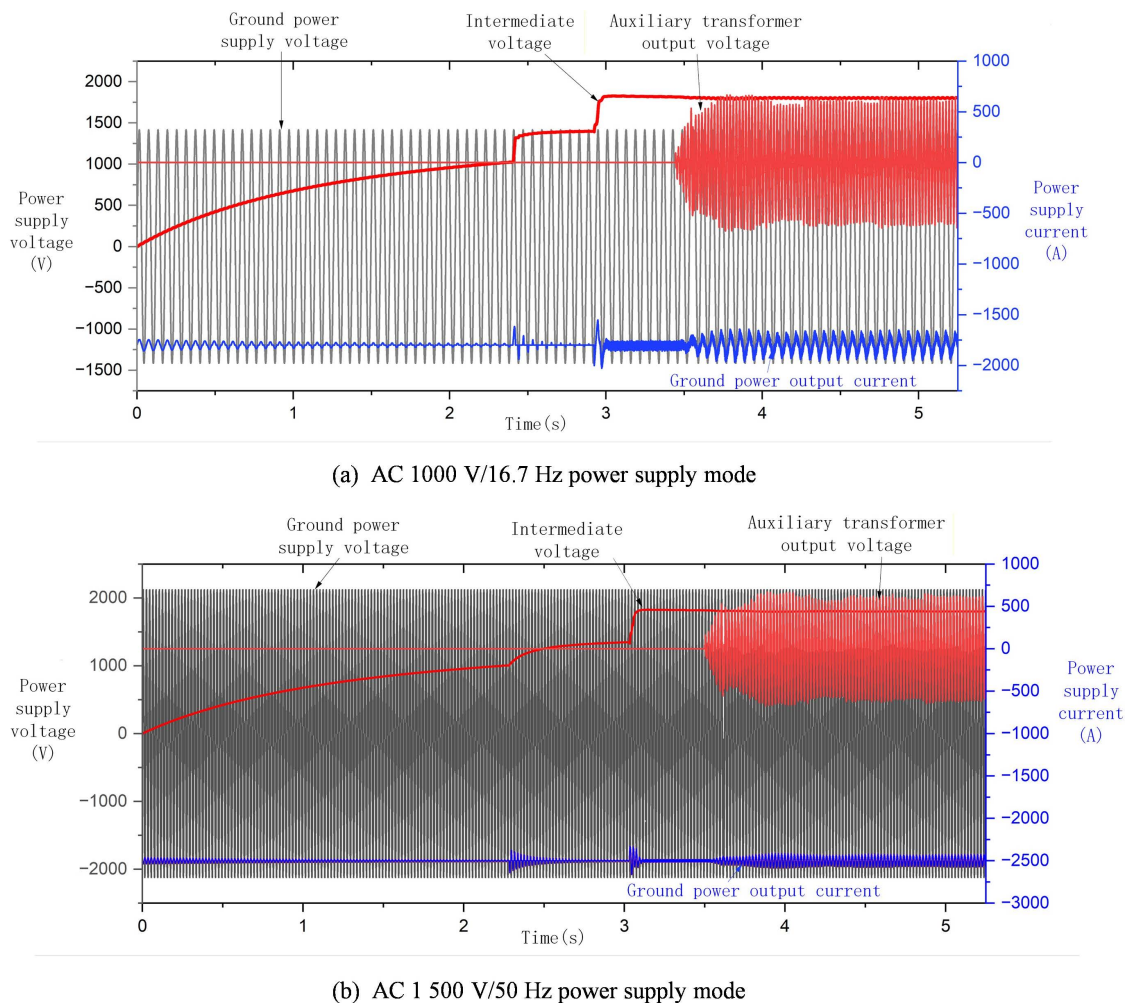
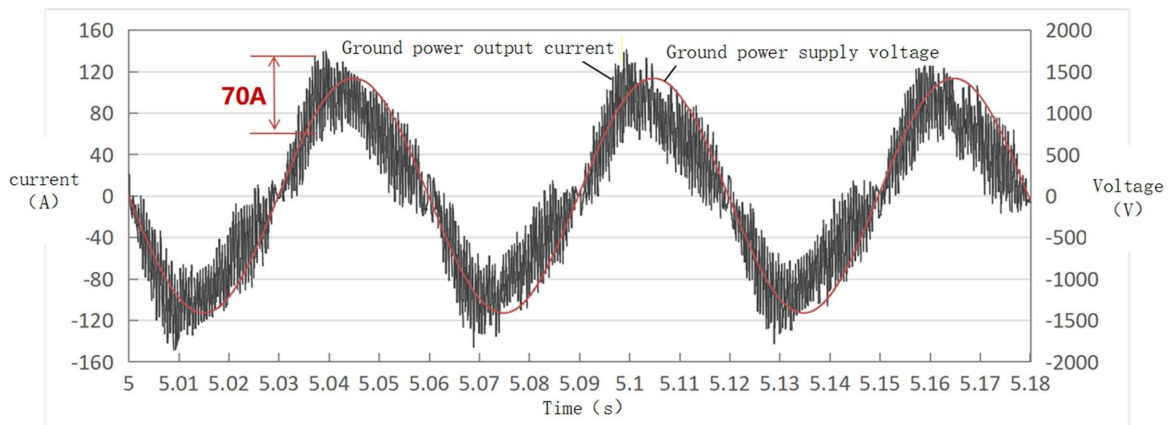
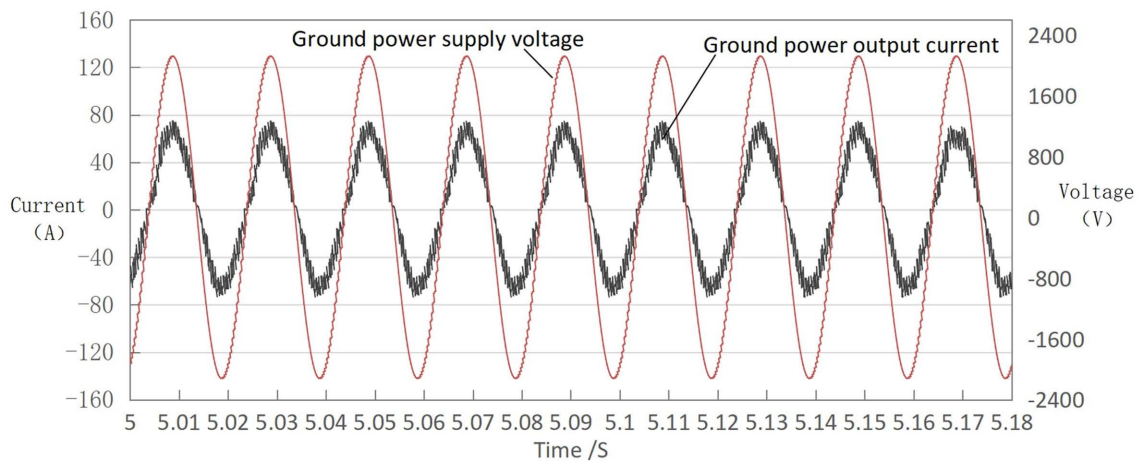


Figure 11. Operating waveforms under different ground power supply modes.

Figure 12 shows the output voltage and current waveforms of the ground power supply when the external power supply is used. Because the equivalent inductance (including the leakage inductance of the step-down transformer) of the AC 1500 V/50 Hz power supply mode is greater than the corresponding value of the AC 1000 V/16.7 Hz power supply mode, the harmonic distortion rate of the output current is significantly better than that of the AC 1500 V/50 Hz power supply mode. **Figure 12(a)** shows the waveform of the AC 1000 V/16.7 Hz power supply mode, and **Figure 12(b)** shows the waveform of the AC 1500 V/50 Hz power supply mode. At the same time, it can be seen that the maximum pulsation peak value of the output current of the external power supply under the two power supply modes does not exceed 100 A (pulsation peak value refers to the current pulsation value in the action cycle of a single switch. **Figure 11(a)** shows the pulsation peak value at 5.03 s, which is 70 A).



(a) AC 1000 V/16.7 Hz, $L = 5$ mH power supply mode



(b) AC 1 500 V/50 Hz, $L = 5$ mH power supply mode

Figure 12. Output current waveforms of the external power supply under different power supply modes.

Set the inductance drop of the external power supply system to 4 mH, and the output current waveform under the AC 1000 V/16.7 Hz power supply mode is

shown in **Figure 13**. It can be seen that the maximum pulsation peak of the output current has reached 110 A, exceeding the pulsation limit of 100 A, which does not meet the system design requirements.

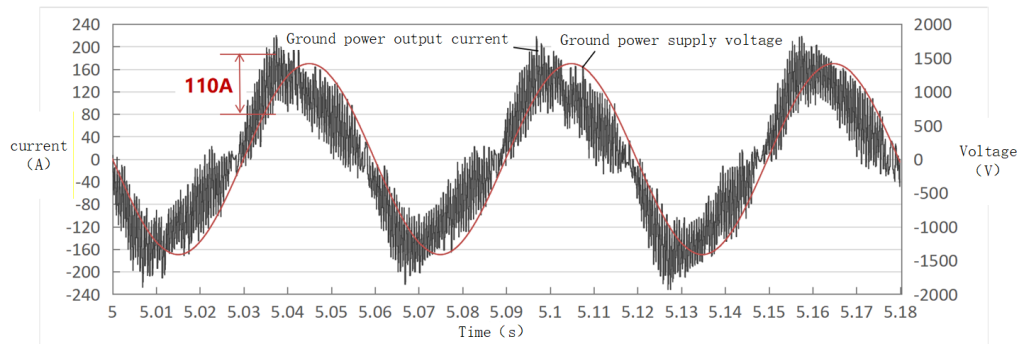


Figure 13. AC 1000 V/16.7 Hz, L = 4 mH output current waveforms of the external power supply system.

6. Conclusions

In view of the special demand that a certain type of export EMU needs to be compatible with two external power supply modes, this paper analyzes the advantages and disadvantages of different external power supply main circuit schemes, and puts forward an improved combined external power supply scheme with obvious advantages in volume and quality. Through theoretical analysis and calculation, the key parameter design and inductance design requirements under extreme conditions, such as power supply voltage fluctuation, are determined; At the same time, the corresponding control and protection strategies are proposed to ensure the intelligent and safe operation of the external power supply system. Finally, the feasibility and correctness of the proposed scheme are verified by simulation tests.

This scheme conforms to the interconnection design concept of the European multi-standard power supply mode, and provides a certain reference for the subsequent design of the external power supply scheme of export EMUs.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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