Parallel High-power Inverting Power Supply for DJ1 Locomotive

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Abstract *–To solve the problem that the original charger of DJ1 locomotive cannot adapt to voltage fluctuation of Daqin railway catenary, this paper designs a novel locomotive-carrying parallel high-power inverting power supply based on UC3854 BoostPFC circuits and UC3846 DC/DC converting circuits. The parallel and series connection modes are adopted into two sets of PFC circuits and two sets of DC/DC converting circuits respectively. With aid of output voltage feedforward technology and multiplier/divider, PFC circuits adopt average current-mode control to realize normal operation within wide output voltage range. Inverting unit adopts peak current-mode control and voltage-current double closed-loop control to improve line regulation and dynamic response speed. To avoid grid interference, over/under voltage and over current existing in power operation process, this paper also designs a special filtering circuit and a whole machine fault-protecting circuit based on TMP86FH09NG. The three-month operation of 11kVA prototype verifies that this power supply has high reliability and perfect dynamic/static performance, and satisfies reliable and safe running requirements of locomotive.*

Keywords *–locomotive-carrying power supply, Boost PFC circuit, DC/DC converting circuit, MOSFET parallel .*

I. INTRODUCTION

Since the 1990s, the DJ1 AC drive electric locomotives have been imported into our country from Germany to be as main locomotives for ten-thousand-tons haulage transportation at Daqin railway. The large voltage fluctuation of Daqin railway catenary results in high fault rate of original charger of DJ1 locomotive. Recently, DJ1 locomotives in foreign countries have been facing large replacements. If our country still uses original chargers, then expensive price, long supply period and inconvenient after-sale maintenance cause economic burden and difficult replacement of locomotive and bring influence on locomotive operation. Thus, it is urgent for Chinese-built locomotives to replace foreign ones.

Based on the mentioned above, a novel parallel high-power inverting power supply is designed in this paper. In this power supply, the BoostPFC circuits are adopted to change AC voltage with voltage fluctuation to be 400V DC voltage, and then 400V DC voltage is changed to be 110V DC voltage by DC/DC converting circuits. Compared with original charger, this power supply is characterized that: 1) it has wider working voltage range and can satisfy wide voltage change request; 2) BoostPFC circuits are adopted to ensure DC output voltage of inverter stable; 3) inverter of power supply adopts peak current-mode control and voltage-current double closed-loop control to improve line regulation and dynamic response speed. The three-month operation of 11kVA prototype verifies that this power supply has high reliability and perfect dynamic/static performance, and satisfies reliable and safe running requirements of locomotive.

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II. HARDWARE DESIGN

A. Design of main circuit

The main circuit adopts AC/DC/AC/DC conversion program, and it comprises rectifying circuit, voltage-boosting circuit, inverting circuit and output rectifying-filtering circuit, shown in Fig. 1.

Two sets of PFC circuits adopt parallel connection mode. The boost circuit working under CCM (continuous current mode) is adopted to boost DC voltage which has been rectified and has some fluctuation, and then to obtain stable 400V DC output voltage. The PFC circuits can raise power factor and suppress harmonic current. The rectifying-filtering capacitance is moved onto the output terminal of rectifying-boosting circuit (electrolytic capacitance C1 and C3 in Fig. 1) to keep input voltage U_i semi-sinusoidal waveform and to satisfy requirement that input current waveform should track input voltage waveform.

The 55V output voltage of each DC/DC converting circuit becomes reliable 110V DC voltage by connecting two circuits under the series mode. Due to high input voltage of DC/DC converting circuits, inverter adopts full-bridge topological structure. The high DC voltage is isolated and stepped down by the high-frequency transformer to be square-wave AC voltage with a certain frequency. The full-wave rectification with LC filtering is adopted in the output rectifying-filtering unit to effectively filter out high-order harmonic in output PWM waveforms and to satisfy the request of low output ripple so that other eletrical equipments cannot be disturbed. The MOSFET is selected as switch tube.

B. PFC control and drive circuit

To adapt to the change request of wide voltage, the UC3854A/B control chip is used to build PFC control circuit. Fig. 2 shows PFC control and drive circuit. This circuit comprises control chip UC3854A/B and external components. It makes AC input current waveform completely track AC input voltage waveform, and keeps input current waveform sinusoidal and same phase with input voltage to realize voltage boost and power factor correction.

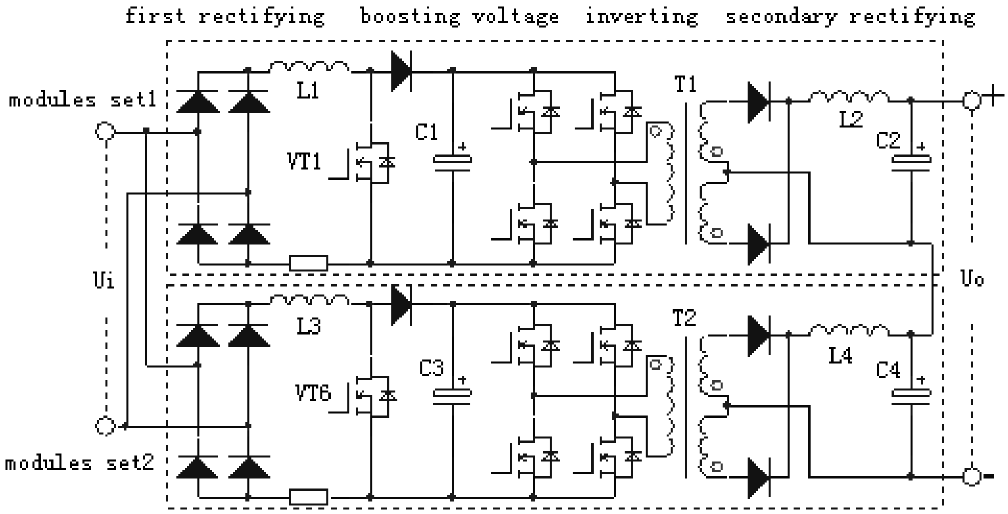

Fig. 1. Main circuit of parallel inverting power supply

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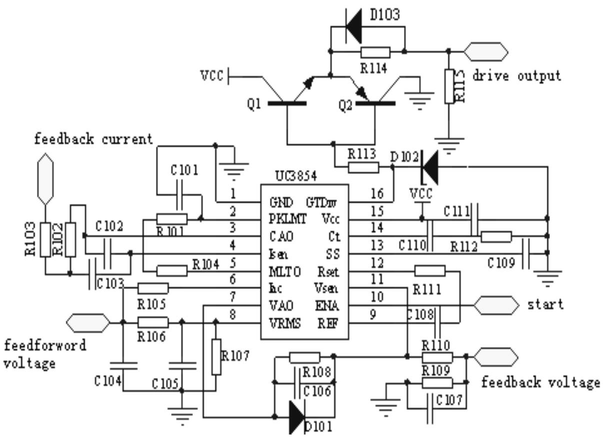


Fig. 2. PFC control and drive circuit.

The UC3854A/B adopts average current-mode control and is applicable in high-power switch converter. It comprises four parts: output voltage error regulator (VER), multiplier/divider (MULT/DIV), switch tube on/off form and drive circuit and current error regulator (CER), shown in Fig. 3. The output of MULT/DIV is $LM = \frac{A \times B}{C}$, where C is the square of feedforward voltage V_s. C is divided to ensure that input power P_i is independent of V_{in} under high power factor condition. The working principle is analyzed and derived as follows.

The output of multiplier is:

$$V_i = K_m \times V_f \times V_e = K_m \times K_{in} \times V_{in} \times V_e \tag{1}$$

where K_m is gain factor of multiplier and K_{in} is narrow scale factor of pulsating voltage.

According to V_{in} and current-detecting resistance R_0 (seen in Fig. 3), the current control loop establishes I_{in}:

$$I_{in} = K_i \times \frac{V_i}{R_0} \tag{2}$$

where K_i denotes attenuation multiple of V_{in}.

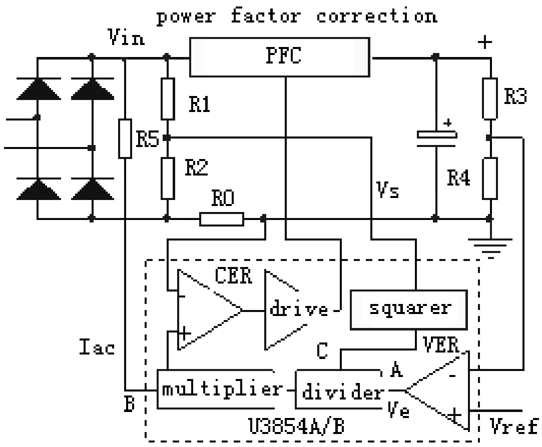


Fig. 3. Principle diagram of power factor correction.

Put (1) into (2) to obtain:

$$I_{in} = \frac{K_i \times K_m \times K_{in} \times V_{in} \times V_e}{R_0} \tag{3}$$

If conversion efficiency of PFC is η=1, then obtain:

$$P_o = P_i = I_{in} \times V_{in}$$
$$= K_i \times K_m \times K_{in} \times V_{in} \times V_e \times \frac{V_{in}^2}{R_0} \quad (4)$$

It is seen from (4) that when V_e is fixed, P_i and P_o will change with V_{in}^2 change. If the divider is used to make V_{in} divide C ($C = (K_{in} \times V_{in})^2 = K_{in}^2 V_{in}^2$), then obtain:

$$P_o = P_i = \frac{K_i \times K_m \times K_{in} \times V_e \times V_{in}^2}{K_{in}^2 \times V_{in}^2 \times R_0}$$
$$= \frac{K_m \times K_i \times V_e}{K_{in} \times R_0} = K_m \times K_i \times K_f \times \frac{V_e}{R_0} \quad (5)$$

where $K_f = \frac{1}{K_{in}}$.

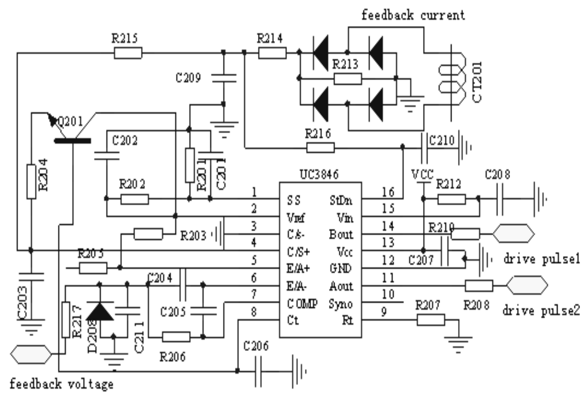
It is seen that at the premise that power factor must be improved, when V_e is constant, P_i and P_o will not change with V_{in} change. That is, after loop gain of the control circuit goes through voltage feed forward technology and multiplier/divider, the loop gain is independent of voltage V_{in} change, thus the control circuit can normally work in full input voltage range and it has fast dynamic response and load regulation characteristic. Therefore, this circuit can be applied into locomotive grid with large voltage fluctuation.

C. Control and drive circuits of the inverting unit

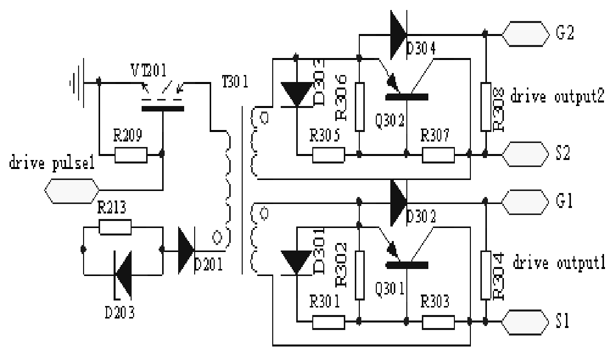
The inverting unit of the power supply adopts UC3846 control chip and adjusts the output pulse width according to feedback current. UC3846 adopts peak current-mode control. Compared with the voltage control mode, this mode is double closed-loop control system where the voltage outer loop controls the current inner loop and control bandwidth is wide. It has following advantages that: 1) it has good linear regulation rate and fast input-output dynamic response; 2) it has function of limiting programmable pulse current in each cycle, strong ability of limiting peak current and function of self-balancing flux in full-bridge circuit; 3) parallel of a number of powers is easy to realize automatic current sharing. However, when the rising rate of current is not big enough and there is no slope compensation, once duty ration is bigger than 50%, the control loop will become unstable and its anti-interference ability will become poor. Thus, peak current signal should be given with slope compensation.

The full-bridge control circuit of inverter is shown in Fig. 4(a), and its main component is UC3846. In Fig. 4(a), R_{207} and C_{206} make up the oscillation circuit and its oscillation frequency is $f = \frac{2.2}{R \times C}$. To prevent the shoot-through phenomenon of upper and lower H-bridge arms, we should set dead time to make sure all switch tubes off. The dead time is determined by the falling edge of oscillator. UC3846 current control is given with slope compensation through Q_{201} and R_{204} from pin-8 and the duty ratio is limited less than 50% to suppress harmonic oscillation and ensure control circuit stable. The current signal of main circuit goes through the current transformer CT_{201} , the bridge rectifier and capacitance-resistance filter to be regarded as current feedback signal of UC3846. The feedback voltage of main circuit is regulated by voltage loop PI controller comprising C_{204} , R_{206} and voltage error amplifier.

The switch tube of each H-bridge arm adopts parallel mode with a number of MOSFETs. When UC3846 is used to drive a number of parallel MOSFETs, the drive capability is not enough and rising edge and falling edge of pulse are not steep enough. Thus, turn-on and turn-off speed of MOSFET will be affected. Fig. 4(b) shows the drive circuit of nonadjacent upper and lower H-bridge arms. This drive circuit has such advantages as high switching frequency, large drive power, simple structure and low cost etc. and it can meet the request of driving a number of parallel MOSFETs.



(a) Control circuit of inverting unit



(b) Drive circuit of inverting unit

Fig. 4. Control and drive circuits of inverting unit.

III. ANTI-INTERFERENCE AND FAULT PROTECTION CIRCUIT

To make power supply overcome the interference from the grid, this paper designs piezoresistance, two-stage common-mode filtering and one-stage differential-mode filtering at the input terminal of power supply. They are effective for filtering out surge voltage, electrical fast transient pulse packet and other interferences from the grid. Fig. 5 shows input filtering circuit, in which Z_1, Z_2 and Z_3 are piezoresistances, D_1 is discharge tube, L_1 and L_4 are common-mode filtering coils, L_2 and L_3 are differential-mode filtering coils, and C_1, C_2, C_3 and C_4 are safety capacitances.

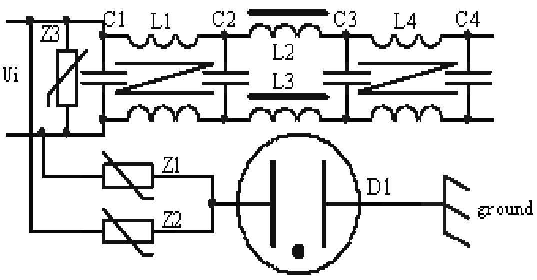


Fig. 5. Input filtering circuit.

Once circuit works abnormally, the power supply should stop operating immediately. To achieve this, apart from over/under voltage protection and over-current protection which are owned by single power supply control chip, this paper designs fault protection circuit based on SCM (single chip micyoco) TMP86FH09NG, shown in Fig. 6. This protection circuit comprises input over/under voltage, output over/under voltage and output over current protections to ensure reliable operation of power supply. In this paper, a communication circuit based on MAX232 and locomotive console is also designed and it can output operation and faults of power supply onto the locomotive display, so that it is convenient for the crew and maintainers to maintain and to know operation of power supply.

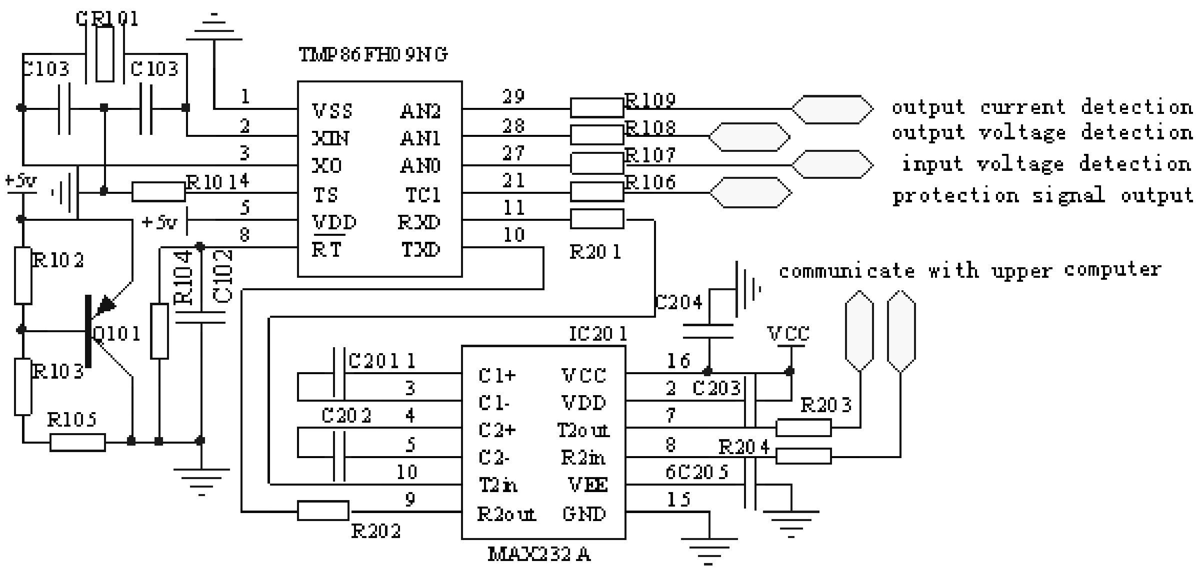
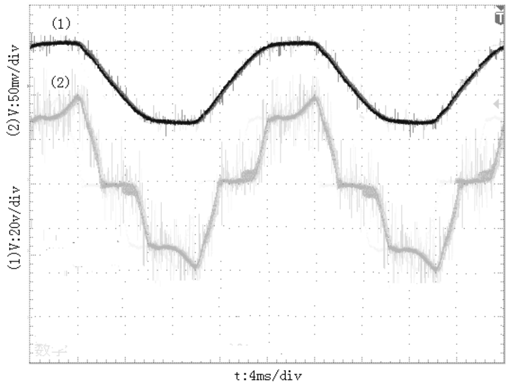


Fig. 6. Fault protection circuit

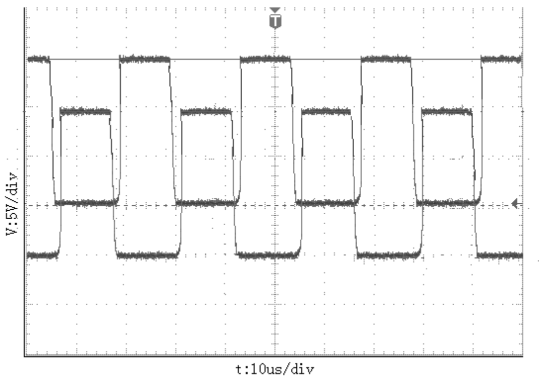
IV. WAVEFORMS OF PROTOTYPE

An engineering prototype is developed in this paper according to the program above. The principal parameters of this prototype are shown as follows: rated capacity 11kVA, output power 8.8kW, rated input voltage AC220V(50Hz), acceptable voltage fluctuation range 140~276V, rated output voltage DC110V, and conversion efficiency $\eta \geq 85\%$.

The batteries are used for load test. When power supply operates, the waveforms of each part are shown in Fig. 7. In Fig. 7(a), (1) denotes the AC input voltage waveform of power supply and (2) denotes the input current waveform of power supply. The input current waveform is quasi-sinusoidal and has the same phase with voltage waveform, thus waveform tracking has been realized and wide input voltage and power factor connections have been achieved. Fig. 7(b) shows drive waveform of switch tube in the inverter unit, where duty ratio is less than 50% and bridge-arm components are open only when the component of upper bridge arm is turned off.



(a) Input voltage and current waveforms of power supply



(b) Drive waveform of switch tube in inverting unit

Fig. 7. Experimental waveforms of prototype.

V. CONCLUSION

A novel locomotive-carrying parallel high-power inverting power supply is designed in this paper to solve the problem that the original charger of DJ1 locomotive cannot adapt to voltage fluctuation of Daqin railway catenary. The input voltage feedforward technology and multiplier/divider ensure normal operation of power supply in wide input voltage range. This power supply system has perfect protection for input over/under voltage, output over/under voltage and output over current. This power supply is with advantages of small volume, light weight and convenient maintenance. The three-month operation of 11kVA prototype verifies that this power supply has high reliability and perfect dynamic/static performance, and satisfies reliable and safe running requirements of locomotive.

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