Design of a Novel Underground Coal Mine 127V Power Supply

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Abstract. In view of the current disadvantages of the large size, high cost and low power factor of custom transformers in China’s coal mine 127V power supply system, a novel type of unit-power factor rectifier based on OCC (One-Cycle Control) is proposed to supply the underground coal mine lighting system. The power supply consists of three stages, including a Vienna rectifier, a high frequency isolated DC-DC converter and an inverter. However, the first two stages of the control circuit use a coordinated control. The circuit is simple to control, unit power factor operation can be realized without the multiplier and input voltage detection and half of the voltage stress of the switching device can be reduced as well. The paper analyses in detail the basic working principle and double closed-loop control strategy of the new rectifier circuit. The correctness is fully verified by simulations.

1. Introduction

With the increasing application of power electronic devices and the large number of non-linear loads in the power system, power supply power quality issues have become increasingly prominent. Therefore, in recent years, power quality control technology centered on power electronic converters has attracted increasingly attention [1-3]. Research on harmonic suppression and reactive power compensation techniques applied in power systems, and power factor correction (PFC) techniques have become one of the most important research fields in the field of electrical engineering.

The traditional coal mine underground lighting power supply is mainly powered by 127V AC power supply, which is usually obtained with a special transformer transformation. In view of the current disadvantages of the large size, high cost and low power factor of custom transformers. In addition, the efficiency of the transformer varies with the load and is difficult to calculate. Based on the above drawbacks and deficiencies, this paper proposes a novel circuit based on OCC strategy for powering underground coal mine lighting systems. The power supply consists of three stages, including a Vienna rectifier, a high frequency isolated DC-DC converter and an inverter. However, the first two stages of the control circuit use a coordinated control. The circuit is simple to control, unit power factor operation can be realized without the multiplier and input voltage detection and half of the voltage stress of the switching device can be reduced as well. This novel underground coal mine 127V power supply replaces the traditional transformer-based power supply effectively. The paper analyzes in detail the basic working principle and double closed-loop control strategy of the new
rectifier circuit. The correctness is fully verified by simulations and experimental results from a 300W three-phase Vienna rectifier prototype.

2. Novel Underground Lighting Power Supply Main Circuit

The novel underground lighting power supply circuit proposed in this paper is shown in Figure 1. The AC/DC rectification part of this circuit uses a three-phase three-wire VIENNA circuit structure. Because it requires only three switching devices to operate at unity power factor, it can effectively reduce losses and increase energy utilization. The withstand voltage of the circuit switch in Vienna is only half of the DC voltage. Therefore, under the same output voltage conditions, half the voltage stress of the switch can be reduced. In addition, the circuit has a three-level structure, so a smaller filter inductor can be used when the current ripple requirement is constant.

![Vienna Rectifier DC-DC converter inverter](image)

**Fig.1** Power supply topology of novel underground lighting

There are two main reasons for increasing the high-frequency isolation DC-DC conversion stage: First, through the electrical isolation between the pre-class and post-class, it can increase the safety of coal mine power supply operation. More importantly, the VIENNA circuit must operate in boost mode to operate reliably. Considering the grid voltage to be ± 10% or ± 20% fluctuation, the DC side voltage should follow this fluctuate. This is very detrimental to the subsequent reversal. After adding the high-frequency isolation DC-DC converter stage, it can ensure that the DC-DC output of the novel power supply can maintain the output voltage of 200V DC no matter how the input supply voltage fluctuates. And this voltage level can exactly meet the 127V inverter circuit.

Because the power supply for the coal mine lighting system is AC-powered, an inverter circuit must be connected in series on the DC side to provide a stable AC power supply for lighting. For the output inverter stage, there is no practical difference between the three-phase 127V output and the single-phase 127V output based on the actual situation underground coal mine. A circuit topology in which the traditional three-phase inverter topology is changed to single-phase inverter is proposed. This not only solves the problem of possible unbalanced three-phase power, but also greatly reduces the number of switches. This strategy further improves the output efficiency of the inverter stage.

3. OCC Coordinated Control Strategy

3.1. Theoretical Derivation of OCC

The power factor correction converter adopting the OCC technique has a simple control strategy, does not need to generate an input current reference, does not require the multiplier, a phase-locked loop or a sampled input power supply voltage. It also has many advantages such as good dynamic and steady-state performance, and it has received extensive attention from scholars at home and abroad [4-6]. The following is a detailed analysis and discussion of a novel underground coal mine lighting power supply that used OCC strategy.
The schematic and its average model of switching period for the three-phase VIENNA rectifier are shown in Fig. 2(a) and 1(b), respectively. In Fig. 1(a), $U_o$ is the output voltage in DC side. In the average model shown in Fig.1(b), the average voltages at nodes A, B, C with respect to the neutral point “O” equal to the phase voltages minus the voltages across the inductors $L_a$, $L_b$, $L_c$ (assuming $L_a = L_b = L_c = L$), which are given by

$$\begin{align*}
u_{AO} &= u_a - jwL \cdot i_A \\ 
u_{BO} &= u_b - jwL \cdot i_B \\ 
u_{CO} &= u_c - jwL \cdot i_C \\ 
\end{align*}$$

Where $i_A$, $i_B$, $i_C$ are inductor currents and $\omega$ is line angular frequency. In COCC strategy, when switching frequency is much higher than line frequency, the voltages across the inductors are usually seen as small enough to be neglected, therefore equation (2) can be obtained

$$\begin{align*}
\nu_{AO} &\approx u_a = \sqrt{2}V_{in} \cdot \sin(\omega t) \\
\nu_{BO} &\approx u_b = \sqrt{2}V_{in} \cdot \sin(\omega t - 120^\circ) \\
\nu_{CO} &\approx u_c = \sqrt{2}V_{in} \cdot \sin(\omega t + 120^\circ) \\
\end{align*}$$

Where $V_{in}$ is the RMS value of the phase voltages. For a three-phase rectifier with unity-power-factor, the control goal is described by

$$\begin{align*}
u_a &= R_e \cdot i_A \\
\nu_b &= R_e \cdot i_B \\
\nu_c &= R_e \cdot i_C \\
\end{align*}$$

Where $R_e$ is the emulated per-phase resistance of the rectifier when viewed from the ac-input side reflecting the output power-level. The COCC key equations for three-phase Vienna rectifier is shown below (derivation of (4) can be found in [7])

Fig. 2 (a) A three-phase star-connected VIENNA rectifier and (b) its switching cycle average model
\[
\begin{align*}
V_m (1-d_a) &= R_s \cdot i_A \\
V_m (1-d_b) &= R_s \cdot i_B \\
V_m (1-d_c) &= R_s \cdot i_C
\end{align*}
\] (4)

where \(R_s\) is the equivalent resistance of current sensor and \(V_m = U_o R_2/2R_s\). \(d_a, d_b\) and \(d_c\) are duty ratio of switches \(S_A, S_B\) and \(S_C\), respectively.

3.2. Implementation of OCC

According to the conventional OCC control equation, the control block is shown in Fig.3. The control system is composed of a voltage compensator and an OCC controller. In the voltage compensator, the error between the reference voltage and sensed dc-link voltage is regulated through a PI controller. The output signal \(V_m\) is the input of a carrier generator. The output of the carrier generator is connected to the input of three comparators, and the triangular waveforms synthesized by the carrier generator is compared with the sampled input currents. PWM signals are then generated to control the on and off state of the 3 switches in the three Vienna converter modules and force the average inductor currents over one switching cycle to follow the corresponding phase voltages. Both digital and analog circuits can achieve the above control goal.

3.3. Rectifier – High Frequency Isolation DC-DC Coordinated Control Strategy

To improve the control efficiency and reduce the high-voltage side capacitance, this paper proposes a rectifier high-frequency isolation DC-DC coordinated control strategy. This strategy uses a fixed duty cycle open-loop control of high frequency isolated DC-DC circuits. The high-frequency isolation DC-DC converter at this time can be equivalent to a proportional link with a proportional coefficient \(k\) related to the duty ratio and transformer ratio. The relationship between the primary voltage and the secondary voltage of the high-frequency isolation DC-DC converter is:

\[
U_{out} = kU_{in}
\] (5)

Therefore, the output voltage of the Vienna circuit can be controlled by controlling the high-frequency isolation DC-DC output side voltage. This control method not only greatly simplifies the control structure, but also greatly reduces the DC output side capacitance of the Vienna converter. Figure. 4 shows the system control block diagram based on this control method.
Fig. 4 Coordinated control block diagram

In Figure 4, $U_{\text{dcref}}$ is the output voltage of the high-frequency isolation DC-DC converter and $U_{dc}$ is the output voltage of the high-frequency isolated DC-DC converter. $U_m$ is generated by the PI controller and the carrier generator generates the amplitude $U_m$ carrier. Among them, $R_s$ is the electric current sampling resistance, $i_{ix}$ is one of three-phase current, namely X can be A, B or C. Through this control, the DC output voltage of the rectified power supply can be stabilized and the input current of the power supply can follow the grid voltage to realize the purpose of unit power factor operation.

4. Parameter Calculation and Selection
Known three-phase power supply line voltage is 380V, the peak value of its input line voltage is 537V. Considering the 20% voltage fluctuation in the coal mine power supply system, the maximum voltage at the input side of the Vienna rectifier is:

$$380 \times \sqrt{2} \times (1 + 20\%) \approx 645V \tag{6}$$

To ensure stable operation of the rectifier in Vienna in boost mode, the DC voltage at the output of the Vienna rectifier can be set to 700V. Currently, the voltage stress on the switch tube in the H-bridge converter in the circuit of Fig. 2 is the output voltage of the DC side 700V. In the Vienna circuit, the voltage stress experienced by the switching device is half of the voltage on the DC side, which is 350V. Considering the safety margin, the maximum withstands voltage of the switch tube multiplied by 1.5, then the highest voltage the Vienna rectifier switching device withstands is 525V. The high-voltage isolated DC-DC converter H-bridge switching device withstands a maximum voltage of 1050V.

From the above, the switch tube with a withstand voltage of 1200V can meet the requirements for the normal operation of the circuit. Among them, IGBTs can use IXYS Company’s M II100 -12A3, and output rectifier diodes use IXYS’s fast recovery diode M0280RA200. According to the current development level of power electronic devices, the circuit can be fully applied to the 380V/127V voltage transformation in underground coal mines.

5. Experiment and Simulation
To prove the effectiveness of the circuit, the circuit was simulated with reference to the actual industry. Its main parameters are shown in Table 1.

| Parameters                        | Value   |
|-----------------------------------|---------|
| Three-phase input line voltage    | 380     |
| Vienna rectifier switching frequency | 10khz   |
| High frequency DC-DC switching frequency | 20khz   |
| Inverter frequency               | 20khz   |
| Load side capacitance            | 4700uf  |
| Load resistance                   | 0.16Ω   |
| The output voltage                | 127v    |

Tab.1 Simulation of the main parameters
The simulation results are shown in Figures 5, 6 and 7. In figures 5 and 6, after the system enters the steady state, the AC output voltage is stable at 127V and the input current is a sine wave with a difference of 120 degrees from each other. From figures 7 we can see that the A-phase current and the A-phase voltage have the same phase and we can know that the input is operated with unit power factor. To verify the stability of the control, the resistance of the load was halved from 0.32Ω to 0.16Ω at 0.2 seconds and the stability of the disturbance observer system was manufactured. The current is still operating at the unit power factor and the output voltage can quickly return to the set value, which proves that the control effect is good. The THD analysis of the current is shown in FIG. 8 and reaches 1.9% at 0.28 seconds. The feasibility and effectiveness of the overall OCC control strategy for the two power conversion stages of the rectified power supply are proved.

6. Conclusion
The problems associated with conventional power frequency transformers include: bulky and difficult to move, explosion-proof costs, low power factor and low resistance to load fluctuations. This article first designed a novel type of underground 127V lighting power supply, which is composed of Vienna rectifier, cascaded high-frequency DC-DC and inverter. Then proposed a coordinated control strategy based on Vienna rectifier and high frequency DC-DC. To achieve both the suppression of voltage fluctuations and can effectively reduce the high-voltage side of the capacitor. Significantly reduced the industrial cost and power supply volume. In this paper, the basic working principle and double closed-loop control strategy of this novel power supply are analyzed in detail and the circuit parameters is calculated and selected. Finally, the novel underground lighting power supply circuit was verified by MATLAB simulation and prototype experiment. Simulation results verify the feasibility, validity and correctness of this novel circuit topology and its corresponding control strategy.

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