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Low-Voltage and High-Current DC Power Supply Using Direct Power Control

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Abstract

This paper describes a low-voltage and high-current DC power supply with a direct-power-controlled (DPC) AC-AC converter, which is applied to electric furnaces. The AC-AC converter operates as positive current-source rectifier and negative one employing the DPC switching table, in order to generate square wave of an output current at the primary of a high-frequency step down transformer. Then DC current is drawn by another rectifier at secondary of the transformer. According to the simulation results, it is confirmed that the DC current can be controlled up to 2500A, and the input power factor is improved to more than 90% at the 15kW, 2500A operation condition.

Keywords: DC power supply, AC-AC direct converter, direct power control

1. Introduction

A conventional DC power supply for the electric furnace has been developed and used successfully to create ultra hard material by means of sintering [1]. However, the basic circuit topology of the power supply includes an AC-DC-AC conversion, which is a combination of a capacitor input type rectifier and a full-bridge inverter. Hence, the total input power factor has limitation because of a choke coil and an electrolytic capacitor in the DC bus. In this study, the converter has been altered to the AC-AC direct converter. Then total input power factor is improved.

2. Outline of Furnace

Sintering is a kind of techniques that create contacts and bonds between minute particles by heating powder material below its melting point. The powder materials are filled in a mold case with applying a certain amount of pressure and draw thousand amperes of DC current for heating up. The mold case filled with the powder materials has as low resistance as several milli-ohms. Therefore only tens-volt output of the DC power supply is sufficient for the thousand amperes of current draw.

3. Circuit Configuration and Principal of Operation

3.1 Main circuit configuration

Figure 1 shows a schematic diagram of a main circuit of the DC power supply for sintering. This DC power supply consists of a utility three-phase power supply, an LC filter, an AC-AC direct converter, a high-frequency step down transformer, and a high-current rectifier. One of the bi-directional switches, which are needed in the AC-AC direct converter, is composed of two 2-in-1 IGBT modules connected antiparallel. The frequency is converted directly from three-phase 50Hz to single-phase 15kHz to excite the transformer. The transformer has 30kVA capacity, of which winding turn ratio is 17:1. A secondary circuit of the transformer has a center tap structure and is composed of eight one-turn windings. Schottky diode modules, which connected to each secondary winding, are employed in the final rectifying stage. Each diode has a snubber circuit to

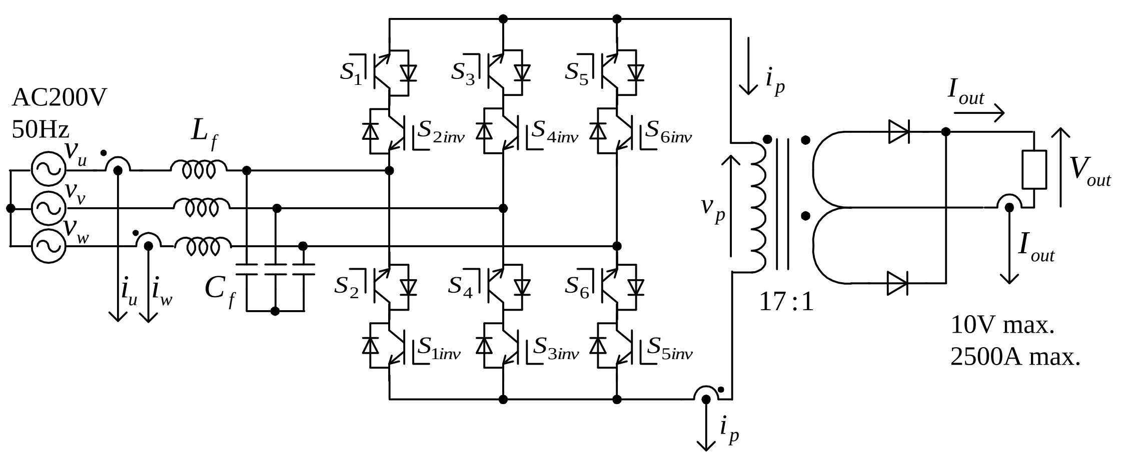
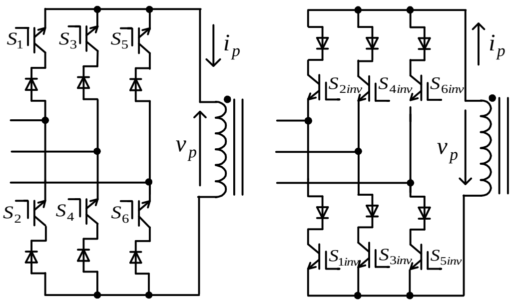
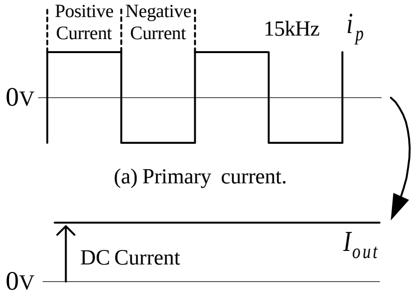


Figure 1. Schematic diagram of DC power supply using AC-AC converter.



(a) Positive current-source rectifier.
(b) Positive current-source rectifier.

Figure 2. Operation of AC-AC converter.



(a) Primary current.
(b) Secondary current after rectification.

Figure 3. Generation of DC current.

absorb surge voltages at its switching moment.

3.2 Control method based on DPC

In general, a current-source rectifier operates to keep current constantly to the load. The AC-AC direct converter, which is illustrated in Figure 2, selects (a) for positive current, and (b) for negative current. A primary current i_p of the transformer is a square wave of the current of which frequency is 15kHz, then the rectifier at the secondary of the transformer produces DC current I_{out}, as shown in Figure 3. A switching pattern of the current-source rectifier is determined so that the output current follows to a current reference. A DPC technique is applied to this control to select an optimum switching state of the converter.

3.3 Control of DPC based current-source rectifier

The DPC technique is applied to the current-source rectifier because of its extremely high-speed response. Figure 4 indicates a block diagram of the DPC based control circuit. As shown in Figure 4, instantaneous active power P and instantaneous reactive power Q are calculated from the voltages and the currents of the utility power source as

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} v_a & v_b \\ v_b & -v_a \end{bmatrix} \begin{bmatrix} i_a \\ i_b \end{bmatrix}, \tag{1}$$

where v_a and v_b are two-phase voltages and i_a and i_b are two-phase currents obtained by three-phase to two-phase transformation.

In general, it is necessary to dump the LC resonance with a power feedback compensation, which is composed by differential elements sk_d.

An instantaneous active power command P^* is calculated by using a detected output current I_{out} and an output voltage reference V_{out}^* which is an output of the PI controller to regulate I_{out}. On the other hand, the instantaneous reactive power command Q^* is provided from outside of the controller, and is normally set at zero to achieve a unity total power factor operation.

Control errors $\Delta P=P^*-P$ and $\Delta Q=Q^*-Q$ are quantized with hysteresis comparators, generating two-level signals S_p and S_q [2]. A phase angle of the power-source voltage vector is also quantized to six sectors q_n, where a-axis and b-axis denote real and imaginary parts of the vector, respectively. The quantized

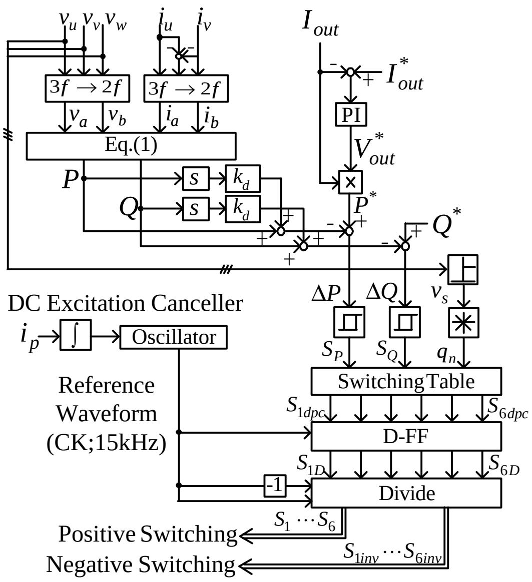


Figure 4. Block diagram of direct power controller.

Table 1. Optimum switching state.

S_P	S_Q	q_1	q_2	q_3	q_4	q_5	q_6
1	0	P O N	O P N	N P O	N O P	O N P	P N O
1	1	P N O	P O N	O P N	N P O	N O P	O N P
0	0	S O O	O O S	O S O	S O O	O O S	O S O
0	1	O N P	P N O	P O N	O P N	N P O	N O P

Table 2. State of switching.

	P	N	O	S
High side device (S_1, S_3, S_5)	ON (1)	OFF (0)	OFF (0)	ON (1)
Low side device (S_2, S_4, S_6)	OFF (0)	ON (1)	OFF (0)	ON (1)

phase q_n is mathematically expressed as

$$\frac{p}{6}(2n-3) \le q_n < \frac{p}{6}(2n-1) \quad \because \; n = 1, 2, \cdots, 6\,. \tag{2}$$

By using the quantized signals S_p, S_q and q_n, the most appropriate switching state of the rectifier is uniquely determined to restrict the control errors ΔP and

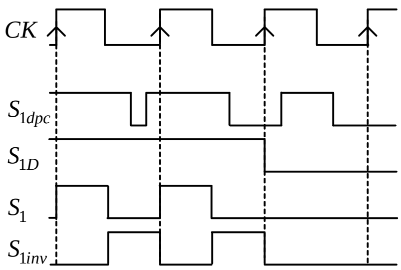


Figure 5. Switching pattern of S_1 and S_{1inv} (for n=1).

ΔQ within the predetermined hysteresis bandwidth. In order to achieve this relay control operation, an optimum switching state table shown in Table 1 is employed to select a unique optimum switching state of the rectifier, according to a combination of the quantized signals S_p, S_q and q_n [2]. Table 2 indicates relationship between the switching states and the corresponding actual state of switching devices.

After S_{ndpc} (n=0-6) passes the D-FF, S_{nD} (n=0-6) is divided into switching patterns for the positive current-source rectifier (S_n (n=0-6)) and the negative one (S_{ninv} (n=0-6)), as shown in Figure 5. S_n and S_{ninv} make it possible to generate square shaped current at the primary of the transformer.

An important point of this control is that using only DPC switching table for the positive current-source rectifier can control both the positive current-source rectifier and the negative one. S_n and S_{ninv} have the same switching pattern, but the direction is opposite each other.

4. Simulation Results

Figure 6 and Figure 7 show operating waveforms of simulation results. In these simulations, the load was 15kW and the output current command was 2500A. As can be seen in Figure 6, i_u was controlled to be in phase with v_u, and power factor was more than 90%. Besides, I_{out} of 2500A was achieved, which is well-regulated to follow the command. I_{out} depends on i_p, and enlarged waveforms of i_p and v_p are shown in Figure 7. According to i_p, the positive current and negative current keep constant value, which means the positive current-type converter and negative one operate alternately to produce the square wave of the current. Then, DC current can be generated applying the DPC based AC-AC conversion technique.

5. Conclusion

In this paper, a control method of operation of the low-voltage and high-current DC power supply using the DPC based AC-AC converter was proposed. The basic operation of the AC-AC converter is based on positive current-source rectifier and negative one, generating the square wave of current i_p at primary of the transformer. Therefore, the rectified transformer output can generates a DC current to the load. As a result of simulated waveforms, generation of the DC current, using the AC-AC converter was confirmed. The input power factor was improved more than 90%. In the future works, the circuit proposed in the paper will be examined through various tests.

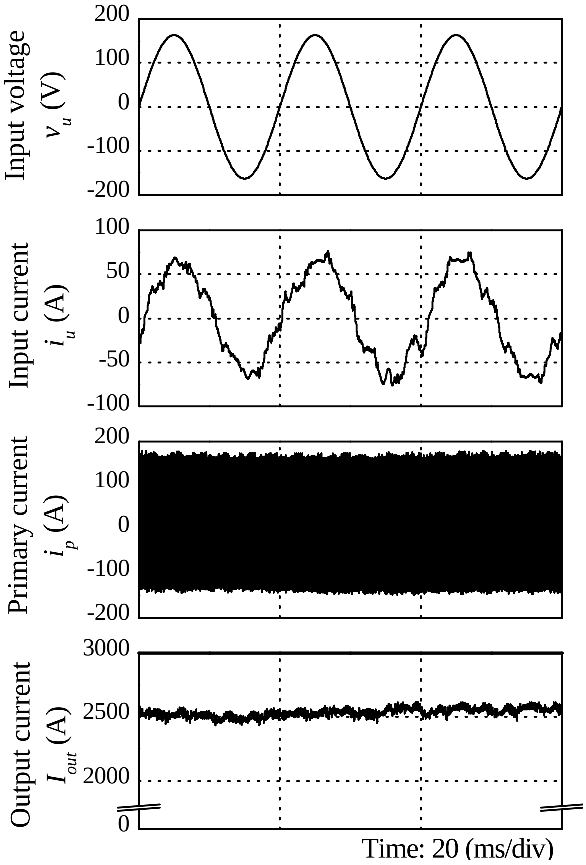


Figure 6. Waveforms of DC power supply.

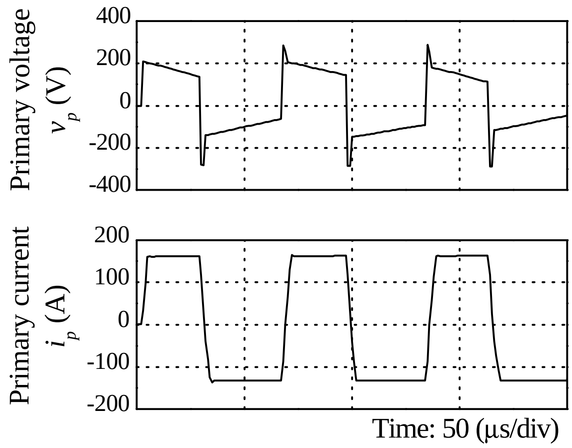


Figure 7. Waveforms of v_p and i_p.

Acknowledgments

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