Development of 13-V, 5000-A DC Power Supply with High-Frequency Transformer Coupling Applied to Electric Furnace

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Abstract—**This paper describes a low-voltage and large-current DC power supply with a high-frequency transformer coupling, which is applied to electric furnaces. The power supply is simply composed of a full-bridge inverter, an amorphous-core step down transformer and a Schottky diode rectifier. The magnetizing frequency of the transformer is raised up to 15 kHz and the maximum output rating of this system is 13 V and 5000 A. The most important key feature of this system is reduction of line inductance and leakage inductance in the whole power circuit, which exist mainly in wire harnesses, the transformer windings, the output DC bus, etc. Even such inductance of micro-Henry order detrimentally affects the total output power to the load because a long overlapping period in commutation of the final rectifying stage can be caused by the large current and such minute inductance. The maximum total efficiency between the utility AC power source and the load is 89.9% and the maximum total input power factor at the front end stage of the prototype is 83.5%, respectively. Although the output voltage and the current of the system are considerably low and large, the confirmed experimental results demonstrate rather excellent performance and feasibility of the developed system, compared with conventional thyristor-based power supplies.**

Keywords-DC power supply; low-voltage and large-current; high-frequency transformer; Schottky diode rectifier; line inductance; leakage inductance; overlapping period.

I. Introduction

The authors have been investigating a low-voltage and large-current DC power supply system for an electric furnace, which is used for sintering. Sintering is often performed by a direct resistive heating method and requires a low-voltage and extremely large-current power supply, e.g., nearly ten volts and several thousand amperes. In such applications, thyristor-based rectifiers have commonly been employed to generate such low voltage and large current. However, the efficiency and the input power factor of the thyristor-based system are at most 60% and 40%, respectively. To make matters worse, large transformers and large smoothing reactors in the output DC bus are required to achieve power conversion because of low frequency of utility power source, which results in disadvantages in physical dimensions and weight of the whole power supply system.

In order to overcome the problems described above, it is absolutely necessary to raise the operation frequency of the power converter to kHz-order. Recent high-speed power switching devices such as IGBTs and MOSFETs are desirable for current ripple and acoustic noise reduction as well as physical downsizing of the system by enlarging their operating frequency. The most important point to develop such low-voltage and extremely large-current power converter using high-frequency AC coupling is reduction of the line inductance and the leakage inductance at every part of the whole power conversion circuit, i.e., wire harness, the transformer windings, the output DC bus, etc. Since such inductance prevents to transfer the effective power to the load and causes a long overlapping period in commutation of the final rectifying stage, even μH-order of the inductance should be eliminated from the power conversion circuit. In this paper, 13-V, 5000-A DC power supply is described and its experimental results are presented to show advantages in operation performances over the conventional power supply systems.

II. Outline of Low-Voltage and Large-Current DC Power Supply System for Electric Furnace

Sintering is a kind of techniques that create contacts and bonds between minute particles by heating the molded powder material below its melting point. This technique allows producing ultra hard and high-melting point materials, which are considerably difficult to process, and is remarkably useful to create functional composites, functionally graded materials, etc. The powder materials, which are often boron, tungsten carbide, alumina, etc., are filled in a mold case with applying a certain amount of pressure and draw thousand amperes of DC current for heating up. Since the mold case filled with the powder materials has as low resistance as several mΩ, only tens-volt output of the DC power supply is sufficient for the thousand amperes of current draw. However, enlarging the magnetizing frequency of the step down transformer, which is inserted in the power conversion process, detrimentally affects the power transfer to the load mold because voltage drop of the line inductance and the leakage inductance caused by the high frequency and the extremely large current is never negligible.

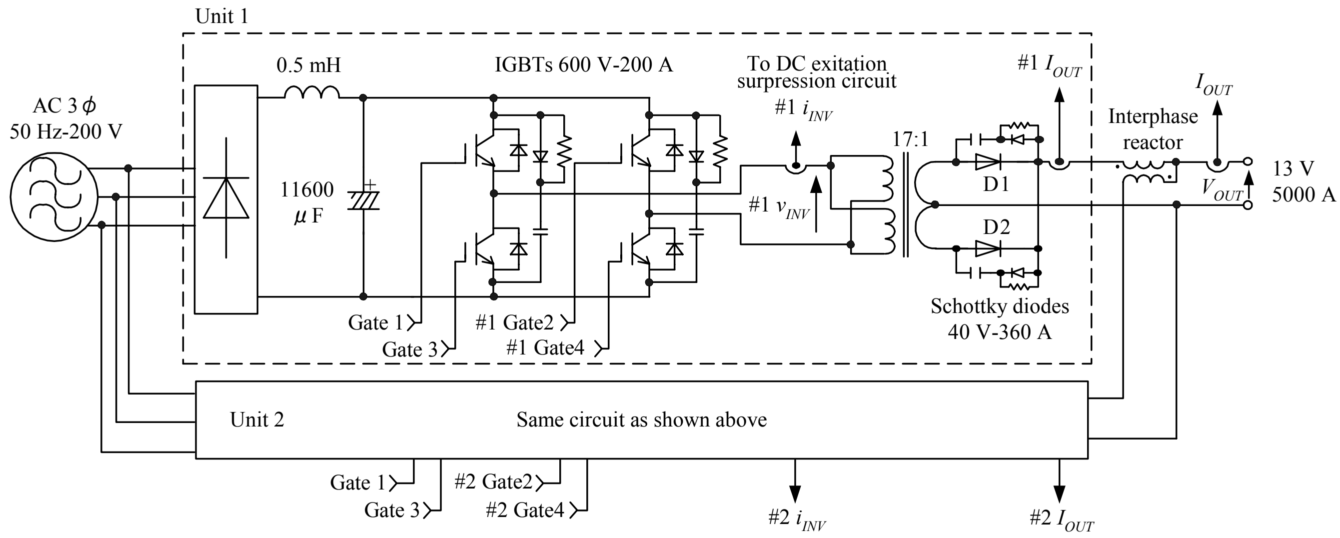

Fig. 2. Schematic diagram of 13-V, 5000-A DC power supply.

Fig. 1. Overview of sintering system.

Fig. 3. Photograph of current balancer at output DC bus.

To make matters worse, the leakage inductance of the transformer windings and the output DC bus causes an overlapping phenomenon in commutation of the final rectifying stage, where all the rectifying Schottky diodes turn on at the same time. This overlapping phenomenon generates zero-voltage across the output DC bus and makes the output voltage limitation applied to the load rather low. Therefore, it is indispensable to reduce the total line inductance and the leakage inductance that exist in everywhere of the power conversion circuit, e.g., the wire harness, the transformer windings, the output DC bus, etc.

Fig. 1 shows an overview of the whole sintering system. There are a vacuum chamber on the left hand side, a host controller in the middle of the photograph, and the 13-V, 5000-A DC power supply behind the host controller. The developed DC power supply occupies less than quarter space of the thyristor-based system. The mold case in the vacuum chamber is connected to the DC power supply through a sandwich DC bus of 3-m long, 200-mm wide and 10-mm thick copper bars. This sandwich structure allows effective reduction of the line inductance of the output DC bus.

III. Circuit Configuration and Control Method

A. *Power Conversion Circuit Configuration*

Fig. 2 shows a schematic diagram of the power circuit of the developed 13-V, 5000-A DC power supply for the sintering system. This DC power supply consists of two identical units connected in parallel with each other that has a 13-V, 2500-A rating per unit. Output terminals from the both units are connected at the final output DC bus through a current balancer (an inter-phase reactor) shown in Fig. 3. The current balancer is composed of a single rectangular-shaped iron-core, where an output line from each unit just passes through one time. Principal electrical specifications of the whole DC power supply system are listed in TABLE I. The front end of the DC power supply is composed of an ordinary three-phase diode full-bridge and a LC filter. On the other hand, a single-phase

TABLE I SPECIFICATIONS OF 13-V, 5000-A DC POWER SUPPLY SYSTEM.

Power source	AC 3 ϕ , 50 Hz, 200 V
Inverter frequency	15 kHz
Output voltage	0-13 V
Output current	0-5000 A
Load	1-2 mΩ

TABLE II SPECIFICATIONS OF HIGH-FREQUENCY STEP DOWN TRANSFORMER.

Capacity	30 kVA
Core size	100 mm×155 mm×85 mm
Primary windings	Thickness 0.2 mm, Width 22 mm, 8 Parallel
Secondary windings	Thickness 0.2 mm, Width 22 mm, 35 pieces laminated, 8 Parallel
Turn ratio	$N_1 : N_2 = 17 : 1$

inverter consists of a 600-V, 200-A IGBT full bridge generating a 15-kHz rectangular voltage and is connected to the step down high-frequency transformer. The average output voltage of the inverter can be adjusted by controlling its voltage pulse width. The transformer has 30-kVA capacity, of which turn ratio is 17:1. The secondary circuit of the transformer has a center tap structure and is composed of 8 parallel one-turn windings. 40-V, 360-A Schottky diode modules are employed in the final rectifying stage to reduce the conduction loss caused by their forward voltage drop. A pair of the diode modules is connected to each secondary winding, so the total number of the diode modules is 16. Each pair has a snubber circuit to absorb surge voltages during its switching moment.

B. Control Method

Fig. 4 illustrates a simplified block diagram of the controller. Basically, this controller regulates the output DC bus current to the load with a current feedback loop by adjusting the average voltage across the primary windings of the two transformers. The controller provides the same gate signals to both of the 13-V, 2500-A units. The only difference is that the gate signals to Unit 2 are modified by the output current error between the two units. A 50-% duty, 15-kHz reference rectangular pulse is generated to operate the inverters and to magnetize the transformers. The gate signals "Gate 1" and "Gate 3" are commonly provided from the reference rectangular pulse generator to the both units. On the other hand, the gate signals "Gate 2" and "Gate 4" are created by the phase shifter, of which inputs are the original reference rectangular pulse and the current regulator output. Both of "Gate 2" and "Gate 4" signals also have 50-% duty but have relative phase shift with respect to the reference rectangular pulse. According to the relative phase shift amount governed by the current regulator output, the conduction duration, i.e., the voltage pulse width or the average output voltage, of each inverter is determined to balance the output current from the two units. In addition, each 13-V, 2500-A unit has an anti-DC-

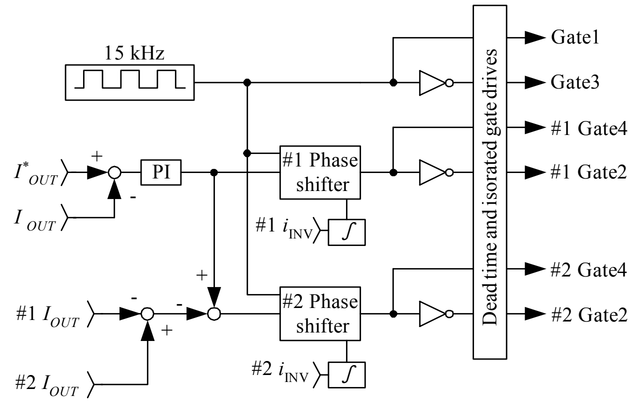

Fig. 4. Block diagram of 13V-5000A DC power supply controller.

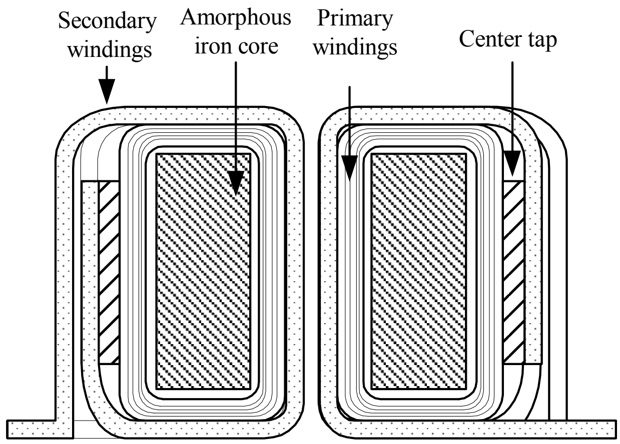

Fig. 5. Cross section diagram of high-frequency step down transformer.

excitation function for the transformer. This function is individually achieved by slightly changing the duty of "Gate 2" and "Gate 4" signals around 50%, detecting the DC component of each inverter output current.

C. High-Frequency Transformer and Final Rectifying Stage

The specifications of the high-frequency transformer are listed in TABLE II. As can be seen in the table, power density of the prototype is much higher than that of conventional common transformers, owing to its enlarged magnetizing frequency of 15 kHz. The transformer has an amorphous core of which maximum flux density is 1.5 T and the average length and the cross sectional area of its magnetic path is 359 mm and 2450 mm^2, respectively. The primary winding consists of 8 parallel thin copper sheets of which maximum current density is designed to be 4.3 A/mm^2 and the number of turn is 17. The secondary winding has a laminated structure using 35 sheets of the same copper plates. The number of turn of these secondary windings is only one and its maximum current density is 4.1 A/mm^2 at 2500-A output per unit. Fig. 5 illustrates a cross section of the transformer. The secondary windings are wound around the amorphous core, closely overlapping the primary windings around the core to avoid increase of the leakage inductance as well as to improve the magnetic coupling

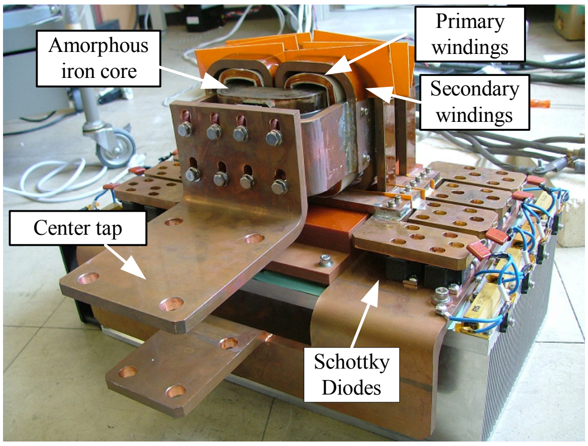

Fig. 6. Photograph of transformer and final rectifying stage.

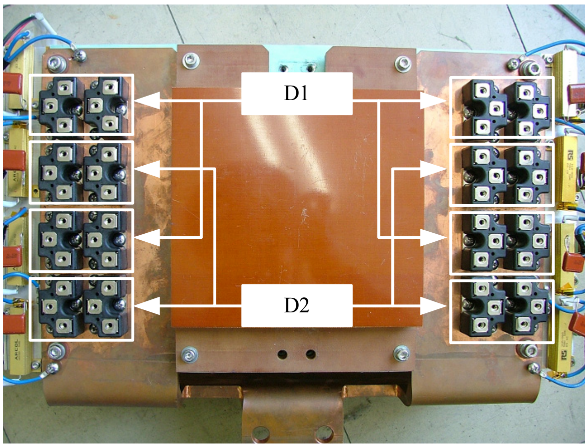

Fig. 7. Photograph of final rectifying stage and secondary copper plate.

coefficient. The secondary windings are closely placed over the primary windings to achieve the same goal, i.e., deduction of the leakage inductance. Every junction between the center tap and the secondary windings is welded to reduce the contact resistance. A parameter measurement test result indicates only 3.9- μH leakage inductance in the prototype transformer.

Fig. 6 shows a photograph of the transformer and the final rectifying stage with a heat sink which is cooled down by some electric fans. As shown in this figure, the final rectifying stage is securely mounted on the heat sink, inserting an insulation sheet with high thermal conductivity. Electrical insulation among the windings is sustained by polyimide tapings, which is much superior to any other materials in high thermal resistance and high insulation resistance. The final rectifying stage is composed of the Schottky diodes and a copper plate of the output DC bus. The Schottky diodes are directly mounted on the copper plate for effective heat conduction from the diodes because even slight forward drop (typically 0.45 V in this system) of the Schottky diodes causes a large conduction loss due to thousand amperes of current. Resistors used in the snubber circuits are also implemented on the heat sink for effective cooling. Fig. 7 is a photograph of the copper plate and the mounted Schottky diodes without the transformer. As

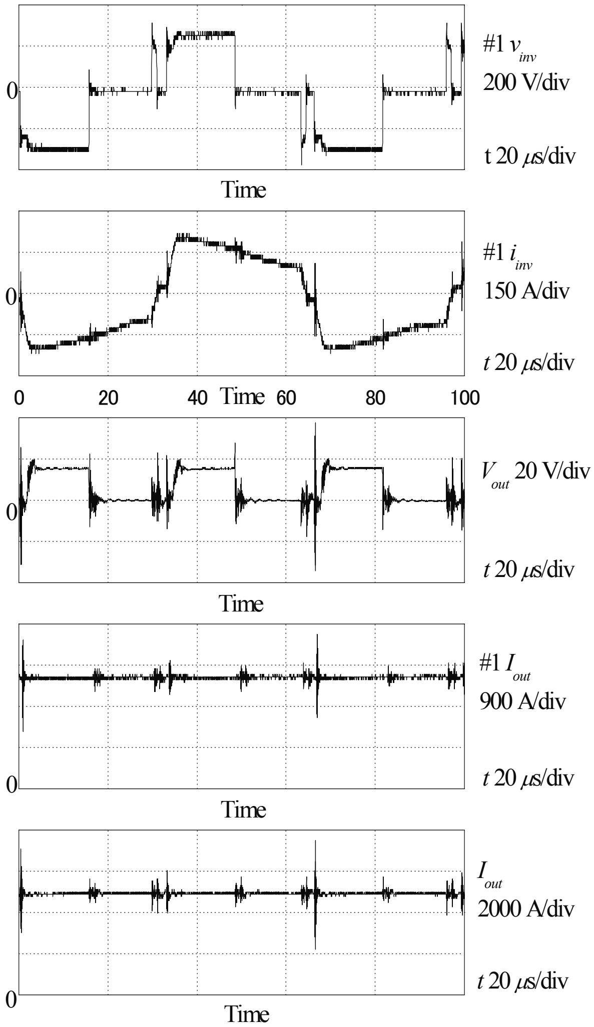

Fig. 8. Waveforms of 15-kHz inverter and output DC bus.

shown here, 16 diodes of 40-V and 360-A rating are placed side by side on the 10-mm thick copper plate. D1 or D2 in Fig. 2 corresponds to a set of the 8 parallel-connected Schottky diodes shown in this figure.

It is possible to reduce physical dimensions of the transformer core because of the high-frequency magnetization of 15 kHz. However, the overlapping period in commutating the final rectifying stage occupies more in a magnetization cycle, which detrimentally affects the output voltage and the output power from the DC bus. Since the overlapping phenomenon is caused mainly by the leakage inductance of the transformer, the magnetic coupling between the primary and the secondary windings must be enhanced by implementing the two windings around the core as closely as possible.

IV. Experimental Results of Prototype System

A. *Operating Waveforms at Rated Output*

Fig. 8 shows operating waveforms of the prototype system at the full load condition. From the upper to the bottom, the figure depicts an inverter output voltage of Unit 1, an inverter

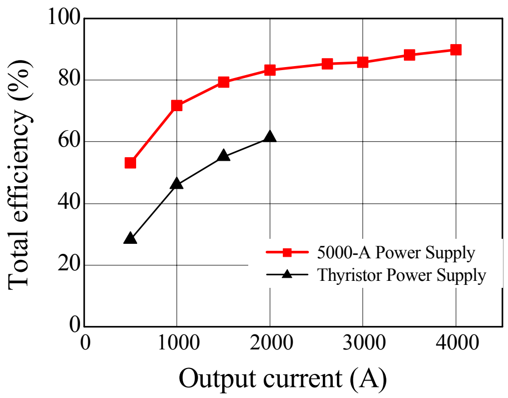

Fig. 9. Total efficiency.

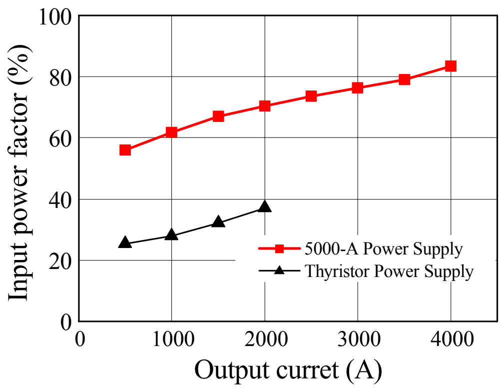

Fig. 10. Total input power factor on utility power source side.

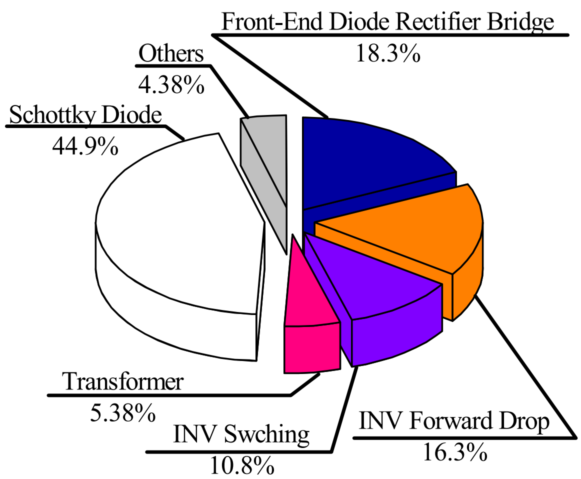

Fig. 11. Loss analysis result at 80-% (4000-A) load.

output current of Unit 1, a total output DC bus voltage, an output current of Unit 1 DC bus, and a total output DC bus current. As can be seen in these waveforms, the developed prototype achieves 5000-A DC current output. The voltage and the current waveforms of the inverter demonstrate 15-kHz operation and properly pulse-width-controlled inverter output. In addition, since the inverter current does not contain DC component, it can be confirmed that the DC magnetization of the transformer is successfully compensated by the controller. The output current waveform of Unit 1 DC bus is approximately 2500 A, which implies that both output currents of the two units are appropriately balanced by the electronic controller and the current balancing reactor. As described in the previous section, the load is connected to the DC power supply through the 3-m long sandwich DC bus. Although the sandwich structure is inherently effective to reduce the line inductance, 8.3-μH inductance is still measured; hence this inductance smoothes the output DC bus current as shown in Fig. 8. On the other hand, short pulse voltages are observed before every leading edge of the inverter output voltage waveform as indicated in Fig. 8. These pulse voltages are generated when the conduction path of the inverter changes due to a lock-out period to prevent a short circuit between the high-side and the low-side IGBTs.

B. Total Efficiency and Total Input Power Factor

Fig. 9 and Fig. 10 show total efficiency between the three-phase utility AC power source and the load, and total input power factor on the AC power source terminals, respectively. These figures also indicate characteristics of the conventional thyristor-based DC power supply for performance comparison. As can be seen in the operation characteristics, the developed prototype achieves the maximum efficiency of 89.9% and the maximum power factor of 83.5%, which perfectly surpasses those of the thyristor based system.

Fig. 11 represents a loss analysis result at 80-% (4000-A) load condition. Input and output power of the front-end full-bridge rectifier, the single-phase inverter, the step-down high-frequency transformer and the Schottky diode rectifier are measured with some digital power meters. The power losses of the transformer can be separated into a copper loss and a iron loss as known well. The copper loss was calculated, using the measured winding resistances and the measured current, while the iron loss was estimated on the basis of the no-load test result. Furthermore, the power loss of the Schottky diode rectifier is obtained from difference between the load power and the power dissipation of the transformer.

As illustrated in Fig. 11, the power loss of the Schottky diode rectifier occupies most part of the total losses. Although the forward voltage drop of the Schottky diodes is only 0.45 V, total conduction loss of the diodes reaches 1.3 kW. Synchronous rectifying using MOSFET instead of the Schottky diodes might be effective to reduce the conduction loss, but it is necessary to implement so many devices in parallel and gate drive circuits; hence this solution is impractical for low-voltage and large-current power supplies. As for losses of the inverter, the switching loss occupies approximately 11% of the total power dissipation due to 15-kHz operating frequency, while the conduction loss does near 16%. The saturation voltage between an emitter and a corrector of the IGBTs is typically 1.8 V, which increases the conduction loss of the inverter circuit. The power loss of the front-end rectifier is not negligible because it exceeds 18% of the total loss. However, the three-phase full bridge structure is very attractive to

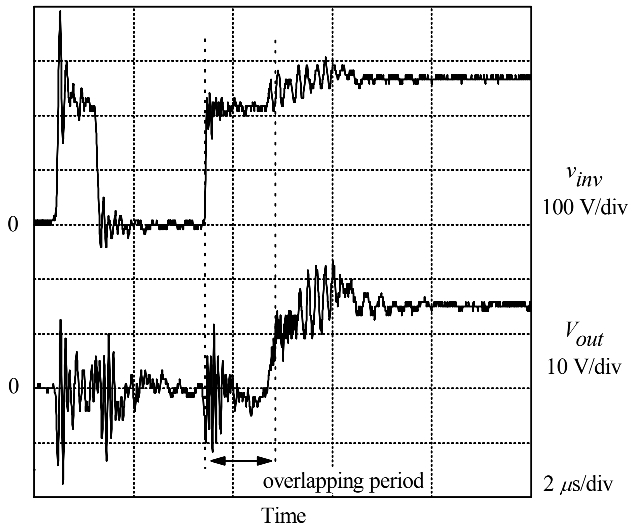

Fig. 12. Waveforms of overlapping period in commutation.

simplify the circuit configuration, so it is worthy to introduce this structure, sacrificing the conduction loss. To contrast with the power losses described above, it can be found that the transformer loss is suppressed down to approximately 5%. This fact proves that highly efficient power transfer is achieved through the prototype transformer and employing an amorphous core effectively reduces the iron loss in spite of 15-kHz magnetizing frequency.

C. Overlapping Phenomenon

Fig. 12 shows an overlapping period of the developed system at 80-% (4000-A) load condition. As can be observed in this figure, the output voltage is clamped at zero and its pulse width is shortened even though the inverter output volatage is applied to the transformer, which is the fatal drawback of the overlapping phenomenon. However, the overlapping period of the developed system is as short as 1.2 μs; thus it occupies only 1.8% of one inverter output cycle. This result proves feasibility of the total system configuration to reduce the line inductance as well as the leakage inductance, which greatly contributes availability of larger current and higher output power regardless of the low output voltage. The unique mechanical and electrical design of the transfomer and the final rectifying stage enables the developed system to deliver 13-V and 5000-A output.

V. CONCLUSION

In this paper, a prototype of the low-voltage and large-current DC power supply applied to an electric furnace was developed and its operation characteristics were experimentally examined. The unique configuration of the step down high-frequency transformer and the final rectifying stage enabled the DC power supply to reduce the line inductance and the leakage inductance, which was indispensable to shorten the overlapping period in commutation of the final rectifying stage. This technique made it possible to raise the operating frequency of the inverter and the magnetizing frequency of the transformer up to 15 kHz. In the experimental tests, 13-V, 5000-A DC current output was achieved and the 89.9-% maximum efficiency and the 83.5-% maximum total input power factor were confirmed. Every experimental result demonstrated higher superiority of the developed system to the conventional thyristor-based DC power supply.

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