Abstract—This paper describes the design and implementation of a three-phase resonant converter with low ripple and high control accuracy. Based on a three-phase LCC-type resonant converter—which has advantages of low ripple, high-efficiency, and high-power density compared with a single-phase converter—a high-voltage power supply with low ripple (<0.1%) was designed. In addition to the general merits of an LCC-type resonant converter operating at continuous conduction mode—including soft switching, low conduction loss, and current source characteristics—the proposed scheme uses only one phase under a light-load condition by having different leg designs of the gate drive circuit and snubber parameters. This allows the design to overcome the operational constraints of the general LCC-type resonant converter. The distinctive design of the three-phase converter structure provides high efficiency and low ripple not only during rated operation, but also under light-load conditions. In order to analyze the high performance of the proposed scheme from no load to rated load, a PSPICE simulation was carried out. Comparison results with a conventional LCC-type resonant converter based on a single-phase structure are analyzed from the viewpoints of output ripple, losses, and operable load range. Using the proposed converter, a 20-kV, 20-kW high-voltage dc power supply design and implementation was presented with a superior gate drive circuit. Finally, the superiority of the proposed converter was verified through a simulation and experimental results. It was experimentally confirmed that the developed power supply achieves high performance in terms of efficiency (98%), operable load range (0.5–20 kV), and low ripple (0.05%), with a high power density.

Index Terms—High-voltage power supply, LCC resonant converter, three-phase resonant converter.

I. INTRODUCTION

In the field of pulsed power applications, such as linear accelerators, the importance of a low output voltage ripple and a high-precision, high-voltage dc power supply as the primary source has been emphasized because the output voltage ripple affects system performance [1]–[20]. For example, research on a capacitor charger with a low voltage ripple has been carried out to improve the stability of klystron-modulators [16]. In another example, the solid-state voltage ripple has been carried out to improve the stability of the modulator system.

To control the high-precision output of a high-voltage capacitor charger, the following method has been suggested: a subcharger is used in parallel, operating with relatively low rated output but with high switching frequency, to be in charge of voltage control in the maximum charging voltage along with the main charger, for the purpose of rapidly charging a capacitor with a large capacity to a lower level (between 5% and 10% of the maximum charging voltage) [22]. In a study to develop a power supply with low-pulse voltage droop and high-voltage pulse reproducibility, the vernier and bouncer methods were suggested. For these applications, low ripple and high precision control are necessary in the high-voltage dc power supply [23]–[30]. To lower a ripple, a method that increases the switching frequency or output filter capacity value can be used. However, as the capacity of the power supply increases, it limits the increase in switching frequency owing to a switching loss that is generated by semiconductor devices. On the other hand, raising the output filter capacitor allows the output voltage ripple to be minimized, but a load is still vulnerable to an electric arc that can be generated frequently in the application field when using an RF tube, such as a magnetron, gyrotron, or radar. In other words, the power supply at the period of arc generation is tripped with a failure condition, but all of the energy saved in the output filter capacitor is transmitted to the load side, and the load can get damaged [31]–[33]. To troubleshoot this problem, a method is now being used that compulsively blocks arc energy by connecting the switch with a fast switching operation characteristic between the power device output and load. This method, however, is rather inefficient with regard to system volume and cost [5], [34]–[36].

This paper describes a multiphase resonance-type converter that satisfies the requirements of the power supply, including output voltage ripple, control precision, and low arc energy.

This resonance-type converter can be designed to reduce ripples through multiphase operation and zero voltage (ZV) turn-ON. This converter can also have a reduced turn-OFF loss, which can increase the switching frequency. To control low voltage and power, a switching leg can be designed. By using multiphase switching legs that are independently driven, the switching frequency increases, and losses occur only at a single leg. This results in operation with high efficiency in the full-load control area. Furthermore, the disadvantages of a resonance-type converter—operating with a relatively low
switching frequency in the operational area, with a light load or more through multiphase operation—can be lessened and high control precision and low ripple can be achieved in the full-load area, by using an independent high-frequency switching operation for a switching leg, separately designed at a light loading area.

A detailed discussion of the analysis, design, and implementation of the developed 20-kV, 20-kW high-voltage power supply is presented. This discussion focuses on the power supply’s efficiency, load range, low ripple, and reliability. The simulation and experimental results verify the superiority of the proposed converter.

II. ANALYSIS OF THE PROPOSED CONVERTER

A. Single-Phase LCC-Type Resonant Converter

The LCC-type resonant converter has a number of advantages, including a current source characteristic and intrinsic voltage boost-up function. This type of converter is widely used for designing high-voltage power supplies. Let us compare a converter in the form of LCC (that has a parallel resonant capacitor with relatively small capacitance) to a series resonant capacitor at the secondary side of a series resonant converter (SRC) operating in continuous conduction mode (operating above resonance). The LCC-type converter has the same basic characteristics as the SRC, and can reduce conduction losses by lowering the crest factor. This is done by improving the resonant current waveform under the influence of a parallel resonant capacitor. This can reduce the switching loss by effectively increasing the capacitance of a lossless snubber capacitor that is used to reduce switching losses.

Using the following analysis of the operation mode, the characteristics of the single-phase LCC-type resonant converter are examined. Under the steady state, the designed single-phase LCC-type resonant converter can be divided into eight modes within each operating cycle, as shown in Fig. 1.

In mode 1, switch \( S_1 \) is turned ON, and the input current flows through the resonant tank. Resonance current flows while charging the parallel resonant capacitor. The resonant current rises rapidly as it is influenced by the parallel resonant capacitor, which has relatively small capacitance values. The increase in energy stored in the resonant inductor owing to the resonant current rising rapidly in mode 1, compared with the SRC, will lead to an increase in the free-wheeling energy that sustains mode 3 and mode 4. Mode 2 begins as the charging of the parallel resonant capacitor is completed, and the resonant current flows through the load.

Switch \( S_1 \) is turned OFF, and mode 3 begins. In this mode, the lossless snubber capacitors are charged and discharged to reduce turn-OFF losses. The lossless snubber capacitors are connected in parallel. Switch \( S_1 \) is charged by the freewheeling energy, and the lossless snubber capacitor connected in parallel to switch \( S_2 \) is discharged.

In mode 4, the charging and discharging of the lossless snubber capacitor are completed, and the resonant current begins to flow through the diode connected in parallel to the switch. In this mode, the voltage across switch \( S_2 \) becomes almost zero. Switch \( S_2 \) is turned ON under a ZV condition, and then a switching half-cycle begins. Modes 5–8 can be analyzed using a similar procedure to the one mentioned previously. The resonant inductor current and capacitor voltage have a polarity that is opposite to that of mode 1–mode 4. The operation waveform based upon each mode is shown in Fig. 2.

It is clear that the turn-OFF loss—which depends on the time duration of mode 3 and mode 7—can be reduced by increasing the value of the snubber capacitance. However, the snubber capacitor energy stored before turning ON the switch should be discharged in order to achieve ZV turn-ON. Thus, increasing the snubber capacitance is a constraint because the energy stored in the resonant tank is also limited, especially under light-load conditions.

By having ZV turn-ON and small turn-OFF losses, the single-phase LCC-type resonant converter is effectively applied to a high power supply using an IGBT with a small saturation voltage compared with a MOSFET. The LCC-type converter can achieve high-frequency power supply with high efficiency. However, the single-phase LCC-type resonant converter has losses that occur as the switching frequency increases under a light-load condition. In addition, when increasing the


**B. Proposed Asymmetric Multiphase LCC-Type Resonant Converter**

In order to resolve the constraints of the single-phase LCC-type resonant converter described earlier, this paper proposes an asymmetric multiphase converter, as shown in Fig. 3. This proposed converter uses a number of switching legs, including one particular leg for the light-load operation condition.

To reduce the ripple of the output voltage without increasing the components of the output filter, a method for driving the multiphase converter in parallel is typically used. It is clear that the single-phase LCC-type resonant converter can also reduce the ripple of the output voltage by using a symmetric switching leg in multiphase. However, as mentioned previously, this has the disadvantage of creating a switching loss in many switching elements owing to the increase in the switching frequency in each switching leg under a light-load condition. In addition, all switching legs operate in the full-load range, and light-load operation becomes difficult owing to the increase in the controllable minimum operating voltage. It is possible to reduce the value of the snubber capacitor to handle the range of load operation. However, this causes the efficiency of the converters to decrease by increasing the turn-OFF loss of the semiconductor devices. The basic concept of the asymmetric multiphase converter proposed in this paper is shown in Fig. 3. It becomes possible for one particular leg, which operates separately under a light-load operation in a multiphase switching leg, to operate separately by employing smaller values of the snubber capacitor (C1, C4), unlike other switching legs. In other words, with the load that the multiphase converter can control efficiently, every switching leg, including one particular leg, operates with a phase difference to control the large output and to reduce the ripple. During light-load operation, when the simultaneous movements of multiphase switching legs are not controllable, the output voltage can be controlled by the isolated operation of one particular, separately designed leg.

In general, all switching legs operate with a phase delay for reducing the output ripple, and the switching frequency increases as the load decreases. In case of a less than specific light-load condition, the behavior of the switching legs—with the exception of the switching leg responsible for the light load—stops. The switching leg responsible for the light load takes charge of the load, so the switching frequency of the switching leg responsible for the light load decreases, which adjusts the output. By contrast, as the load increases again, the switching frequency of the switching leg responsible for the light load is reduced. And, if the load is more than the specified light load, all of the switching legs work again, and the entire switching frequency increases again and adjusts the output. As previously described, the proposed converter was designed to independently operate one switching leg at a light load. Therefore, if low voltage and power are controlled, the losses as the switching frequency increases occur in only one leg, enabling the converter to operate with high efficiency in the full-load control area.

In addition, unlike the other switching legs, because the snubber capacitor of a particular leg with a small value can be charged and discharged via a small resonance current in light-load operation, ZV switching is possible under the full-load condition. Further, because the control characteristic of the resonant converter increases the switching frequency as the load decreases, it is possible to maintain a low output voltage ripple even when one particular leg operates separately during light-load operation.

As an example, assume that the output voltage has a ripple of 120 kHz when the three-phase converter operates with a switching frequency of 20 kHz at rated current, and that one particular leg operates separately from 60 kHz and higher in light-load operation. In this case, the output voltage would have a ripple of 120 kHz and higher. Therefore, it is clear that there will be no large increase in the output ripple. Even three phases can convert into a single phase with a fixed output filter. Therefore, even if high-precision output
control is required—in devices, such as a gyrotron, klystron, magnetron, or radar power supply—high-precision control is possible without increasing the size of the filter capacitor. This can effectively protect the load because the energy of the filter capacitor passed to the load side can be minimized in case of an arc occurrence, while keeping the ripple of the output voltage small.

Without complex control, this paper proposed to change the behavior of the converter only by changing the design of the capacitance of the lossless snubber capacitor of the legs responsible for light load operation and the component of gate drive circuit by proposing a gate drive circuit with flexible dead time. In the high-frequency switching of light-load operation, relatively small lossless snubber capacitors were selected, compared with the capacitors of other switching legs, for soft switching. In addition, a method for configuring a more reliable system through hysteresis band control is proposed, and the features and advantages of the proposed power supply are verified through various experiments.

C. Gate Drive Circuit

As mentioned earlier, the operation of the proposed converter can be implemented in the form of a blocking gate signal from the controller in a particular area by detecting the power supply’s operating load area. However, this paper proposes a superior gate driver circuit with flexible dead time in the simple structure, as shown in Fig. 4, and implements the operation of the proposed converter by using the characteristics of flexible dead time.

The proposed gate drive circuit has several advantages, including implementing flexible dead time by sensing the ZV condition of the switch, and a transformer for gate isolation that is easily designed by entering the operating switching frequency of half-duty.

By analyzing the following operation mode, the operational principle of the proposed gate drive circuit is described.

At mode 1, a turn-ON signal (+Vpulse) is applied to the gate drive circuit. The voltage across the switch is not ZV. Capacitor C1 is gradually charged through series resistor R1 and parallel resistor R2 and, as a result, the turn-ON signal of the gate drive circuit does not turn ON the switch. Mode 2 is the case where the turn-ON signal (+Vpulse) is input in the gate drive circuit. The voltage becomes zero. Diode D2 is forward-biased, and capacitor C1 is charged through resistance R5 and diode D2. Compared with resistance R1, resistance R5 is designed to have a very small value so that MOSFET M1 is quickly turned ON under a ZV condition. If the voltage of capacitor C1 is charged to more than the threshold voltage of MOSFET M1, then M1 is turned ON and gate voltage is applied through resistance R6 and diode D3 so that the switch is turned ON.

Mode 3 is a turn-OFF mode. If the turn-OFF signal (−Vpulse) is input in the gate drive circuit and MOSFET M2 is turned ON, the switch is turned OFF while quickly discharging the charged gate capacitor voltage. At this time, MOSFET M1 is turned OFF as well. Further, by being recharged to minus voltage through resistance R3 and diode D1, the voltage of capacitor C1 can conduct the operation of mode 1 in the next switching cycle.

As shown above, by having the operation wait until the voltage across the switch of mode 1 becomes zero—the situation where current flows in the diode connected in parallel at both ends of the switch of mode 4 of the converter operating mode (that is, the operation of mode 2 enables the turn-ON of the switch in a condition that switch both ends becomes zero voltage)—flexible dead time functionality is achieved. Because of these modifications—making the switching leg responsible for the light load, having a lossless snubber capacitor, and setting the predetermined value of R1 to determine maximum dead time in the gate drive circuit differently from other switching legs—the operation of the proposed converter is implemented by letting only the switching leg responsible for a light load do the switching operation under the light-load condition.

III. DESIGN AND SIMULATION OF THE PROPOSED CONVERTER AND GATE DRIVE CIRCUIT

The proposed converter in this paper is implemented as a power supply of a gyrotron, radar, magnetron, or linear accelerator. Table I lists the specifications for these

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Input Voltage</td>
<td>380 Vac ± 10%</td>
</tr>
<tr>
<td>Output Voltage, V&lt;sub&gt;out&lt;/sub&gt;</td>
<td>1–20 kV</td>
</tr>
<tr>
<td>Output Current, I&lt;sub&gt;out&lt;/sub&gt;</td>
<td>~ 1 A</td>
</tr>
<tr>
<td>Maximum Output Power, P&lt;sub&gt;max&lt;/sub&gt;</td>
<td>20 kW</td>
</tr>
<tr>
<td>Control Accuracy, Error&lt;sub&gt;acc&lt;/sub&gt;</td>
<td>±0.1% Precise Voltage and Current Control</td>
</tr>
<tr>
<td>Output Voltage Ripple, V&lt;sub&gt;ripple&lt;/sub&gt;</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Arc Energy, E&lt;sub&gt;arc&lt;/sub&gt;</td>
<td>&lt;5 J</td>
</tr>
<tr>
<td>Maximum Efficiency, η&lt;sub&gt;max&lt;/sub&gt;</td>
<td>&gt;96%</td>
</tr>
<tr>
<td>Maximum Power Factor, PF&lt;sub&gt;max&lt;/sub&gt;</td>
<td>&gt;0.92</td>
</tr>
<tr>
<td>Protections</td>
<td>Over-Temperature</td>
</tr>
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<td></td>
<td>Over-Current</td>
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<td>Over-Voltage</td>
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applications, and Table II lists the design parameters according to the specifications in Table I. The entire scheme of the 20-kV, 20-kW dc power supply, with the proposed converter and gate drive circuit implemented, is shown in Fig. 5.

A. Structure of 20-kV, 20-kW Asymmetric Three-Phase LCC-Type Resonant Converter

The proposed converter is designed with a three-phase structure that takes into account the ripple rate and output voltage and power. As mentioned earlier, the LCC-type resonant converter is composed of a series of resonant inductor (Lr) and a capacitor (Cr) with a parallel capacitor (Cp).

In the designed power supply, the additional parallel capacitor is not used, as shown in Fig. 5. Capacitors (Cp1-n–Cp4-m) that are connected in parallel with a series of stacked high-voltage diodes (Dhv1-n–Dhv3-m) are designed not only for voltage balancing, but also to play the role of a parallel capacitor. When the high-voltage diode stack commutates from a reverse to a forward bias, the transformer secondary winding current flows in order to discharge the voltage across the parallel-connected capacitor. At this transition interval, the series combination of (Cp1-n–Cp4-m) affects the resonant frequency in the same way as a parallel capacitor (Cp).

Because of the voltage-boosting property of a parallel capacitor, the LCC-type resonant converter facilitates the design of a high-voltage transformer by reducing the turn ratio. In addition, the converter helps prevent distortion, owing to the effect of parasitic capacitance. As shown in Fig. 5, three transformers are connected with the voltage-doubled rectifiers, which consist of a series of stacked diodes (Dhv1-n–Dhv3-m), voltage-balancing capacitors (Cp1-1–Cp4-6) that are also operated as the parallel capacitor (Cp), and filter capacitors (Cf1–Cf6). In addition, a high-voltage sensing circuit is designed that uses resistors (Rs1–Rsm) and a capacitor (Cs1–Csm) divider.

B. Control of 20-kV, 20-kW Asymmetric Three-Phase LCC-Type Resonant Converter

As shown in Fig. 5, the designed 20-kV, 20-kW dc power supply has two PI controllers that have separate PI gains—one for the output voltage and the other for the output current. The controllers are connected through diodes. This design is accompanied by the limitation of a single output, with one output controlling the other. Depending on the value of the control signal, the frequency of the switching signals is

<table>
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<tr>
<th>TABLE II</th>
<th>SUMMARY OF DESIGN PARAMETERS</th>
</tr>
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<tr>
<td>Resonant Capacitor (Cr)</td>
<td>8 nF</td>
</tr>
<tr>
<td>Resonant Inductor (Lr)</td>
<td>35.6 mH</td>
</tr>
<tr>
<td>Parallel Capacitor (Cp)</td>
<td>(0.756 nF * 2 in parallel)</td>
</tr>
<tr>
<td>Fundamental Resonant Frequency</td>
<td>9.43 kHz</td>
</tr>
<tr>
<td>Second Resonant Frequency</td>
<td>19.7 kHz</td>
</tr>
<tr>
<td>Snubber Capacitor (C1-6)</td>
<td>150 nF / 15 nF</td>
</tr>
<tr>
<td>Transformer Turns Ratio</td>
<td>14:274:274:274</td>
</tr>
<tr>
<td>Output Filter Capacitor (Cf)</td>
<td>6.67 nF</td>
</tr>
<tr>
<td>High-Voltage Sensing Resistors (Rs)</td>
<td>50 MΩ (25 MΩ in series)</td>
</tr>
<tr>
<td>High-Voltage Sensing Resistors (Cs)</td>
<td>0.05 nF</td>
</tr>
</tbody>
</table>

Fig. 5. Scheme of the proposed asymmetric three-phase LCC resonant converter.
modulated with a 50% duty cycle. After the signal is phase shifted, it is transferred through the AND gate, and it is applied to the gate transformer (Tr-gate1–Tr-gate3) for switching. The protection signal generated from the protections—including the over-current, over-voltage, and over-temperature—is also transferred through the AND gate to the stop gating signal for emergency stop.

For higher reliability, the switching frequency hysteresis band control can be added. As the switching frequency, the hysteresis band control block can choose from the single-phase operation and the three-phase operation. A detailed explanation is presented in the experimental results part of this paper.

C. Simulation of 20-kV, 20-kW Asymmetric Three-Phase LCC-Type Resonant Converter

In order to verify the design parameters and to evaluate the characteristics, a PSPICE simulation of the converter was performed. The PSPICE simulation model of the 20-kV, 20-kW dc power supply, with the converter and gate drive circuit implemented, is shown in Fig. 6. Simulation results of the converter performance with switching frequencies of 20 kHz and 120 kHz, under the condition of a rated load of 20 kΩ—to validate the performance of the 20-kV, 20-kW dc power supply with the converter and gate drive circuit implemented—are shown in Figs. 7 and 8, respectively. The output voltage in Fig. 7 is 20 kV with all three phases working. The output voltage in Fig. 8 is 700 V with only one switching working, in one leg that is responsible for the light load. Fig. 9 shows the simulation results of the switching loss per switching frequency. A smaller lossless snubber capacitor was used for soft switching in a leg that is responsible for light loads compared with other legs (the other legs only work with loads that are greater than light loads, in consideration of the loss efficiency). The result confirmed that the switching loss in the light-load leg was relatively large. However, only the light-load leg was operated in the frequency range of ~80–100 kHz. The losses in other
legs were confirmed to be close to 0. Hard switching was observed in the light-load leg in a weak frequency above 140 kHz with an output voltage of 500 V. Therefore, the switching frequency range of the converter is found to be between 20 and 130 kHz, with output voltages from 500 V up to 20 kV, while the converter performed normally. Additional simulation of a single-phase LCC-type resonant converter was conducted to validate the design and superiority of the proposed converter of this paper. Table III shows the design parameter and results. The single-phase LCC-type resonant converter designed to be compared was also designed to have identical output voltage and power and high efficiency as the converter of this paper. Simulation results—per output voltage according to the switching frequency changes in both the single-phase LCC-type resonant converter and the three-phase LCC-type resonant converter of this paper under the condition of a rated load of 20 kΩ—are shown in Fig. 10. In the single-phase structure, hard switching was observed with a 70-kHz switching frequency and <6-kV output voltage. The output was limited to <6 kV. On the other hand, the converter developed by this paper was able to work over a wide range of output voltage, from 500 V to a maximum of 20 kV.

### IV. Experimental Results

Fig. 11 shows the resonant current waveform and output voltage in rated output at a rated load of 20 kΩ, and under the condition of a maximum output voltage of 20 kV. The resonant peak current was measured as 65 A, and the switching frequency was 20 kHz. Fig. 12 shows each inverter output voltage waveform of a leg, for light load and for other legs. The inverter output voltage slope of a leg for a light load is quite different from the slope of other legs because of the smaller lossless snubber capacitor used for the light-load condition. It was confirmed that there is no hard-switching condition with each slope.

Figs. 13 and 14 show the output voltages under the conditions of maximum switching frequency under a 20-kΩ-rated load condition and no-load condition. The minimum
output voltage was measured as 500 V under a 20-kΩ-rated-load condition, and the minimum controllable output voltage was measured as 700 V under a no-load condition. This was found to have satisfied the condition of less than the design specification (the minimum output voltage of 1 kV, as explained earlier). For the control patent experiment of the converter implemented, the output voltage and switching frequency when the proposed converter operates (single operation of the single-phase leg in the light-load area, operation of all three-phase legs when operated at a load more than the light load) and when a single-phase leg operates independently, were compared under conditions of a 20-kΩ rated load and no load. The results are shown in Figs. 15 and 16. The switching frequency where the converter changes from three-phase operation to single-phase operation under a 20-kΩ-rated-load condition (using the component of the gate drive circuit and the converter implemented) is ~90 kHz. It was found that operation changes at ~80 kHz under a no-load condition. That is, the point where the implemented converter changes from three phase to single phase, and single phase to three phase, occurs at a switching frequency of 80–90 kHz, depending on the load.

Under a nonlinear load condition showing severe load fluctuations, the proposed converter can repeat the change of three-phase operation and single-phase operation at ~80–90 kHz. For higher reliability, a switching frequency hysteresis band control can be selected. In this paper, we carried out the experiment by changing the switching frequency from three-phase operation to single-phase operation at 60 kHz, and changing the switching frequency from single-phase operation to three-phase operation at 40 kHz. The experimental results of the switching frequency hysteresis band and control characteristic, under a 20-kΩ-rated-load condition and no-load condition, are as shown in Figs. 17 and 18. In the area that has a load more than a light load, all switching legs operate. As the load decreases, the switching frequency increases. As shown in Fig. 17, under a 20-kΩ-rated-load condition,
Fig. 18. Hysteresis band control characteristic test results under no-load condition.

Fig. 19. Hysteresis band control characteristic test results under no-load.

Fig. 20. Efficiency measurement depending on the load.

a light load—that is, <5-kV condition (with a switching frequency of 60 kHz or higher)—the operation of the remaining switching legs, except for the switching leg responsible for the load light, is stopped. Because only the switching leg responsible for the load light takes charge of the load, the switching frequency of the switching leg responsible for the light load is reduced again, to ~50 kHz, which adjusts the output. By contrast, under a condition of a load more than a light load, where output increases—that is, under a condition of more than 7 kV (with a switching frequency of 40 kHz or less)—all switching legs operate again, and all switching frequencies increase again, up to ~50 kHz, which adjusts the output. As shown in Fig. 18, the conversion of all switching leg actions and the three-phase single leg action occur at output voltages of ~16 and 13 kV, respectively, under a no-load condition. Fig. 19 shows the result of measuring the output voltage by switching the frequency after applying the hysteresis band control under a 20-kΩ-rated-load condition. The output range is wide, from a minimum output voltage of 500 V to a maximum output voltage of 20 kV, as the switching frequency varies from 20 to 128 kHz. Fig. 20 shows the results of measuring the efficiency while adjusting the output. A high efficiency of up to 98% is achieved, with 90% efficiency from ~50% load of ~9 kW.

V. CONCLUSION

This paper presented an asymmetric multiphase resonant converter applicable to a high-voltage power supply. The proposed converter demonstrated high-performance with respect to output voltage ripple and control precision focusing on applications, such as the gyrotron, radar, magnetron, and linear accelerator. The proposed scheme overcomes the constraints of the single-phase LCC-type resonant converter by decreasing the output ripple, having a wide operable load range, and having high efficiency for the overall load range. The operational principle of the proposed converter and gate drive circuit was explained. This explanation included asymmetric switching leg operation, flexible dead time control, and hysteresis band control. The superiority of the asymmetric multiphase resonant converter was verified, compared with the single-phase converter. Based on the analysis of the proposed converter, the design and implementation of a 20-kV, 20-kW high-voltage power supply using an asymmetric three-phase LCC-type resonant converter were presented. Finally, the developed high-voltage power supply was tested with a resistor load. The results showed a maximum efficiency of 98% and a controllable load range from 500 V to 20 kV with 0.05% output ripple. In addition to the switching frequency modulation, the hysteresis band control method was suggested to improve reliability, depending on the frequency characteristic of the LCC-type resonant converter. This paper showed the application of the three-phase resonant converter with regard to power supplies. One advantage of this proposed converter is that it can be structured into a multiphase type in order to increase the performance and output power with regard to the ripple. This can be done without increasing the filter capacity, which is related to the arc energy.

REFERENCES


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