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Paper

Experimental Verification of Self-Supplying Power Circuit using One-Turn Transformer for Gate Drive Unit

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This paper proposes a power supply circuit for gate drive units (GDUs) that uses a one-turn transformer, which gives advantages in terms of cost and loss reduction. The structure of the proposed one-turn transformer consists of a primary winding in which the number of turns is one and a secondary winding in which there are multiple number of turns. The proposed one-turn transformer is connected in series with a switching device of the main circuit in order to obtain power for the GDUs. The proposed power supply circuit can be applied to all types of main circuit topologies such as a multilevel converter topology or matrix converters, in addition to a conventional six-arm inverter. In this paper, the design method of the one-turn transformer and its characteristics are described based on an equivalent circuit and fundamental experimental results with a step-down chopper. Besides, the proposed power supply circuit for GDUs is tested in a two-level three-phase inverter. Secondly, the obtained power for GDUs from the proposed one-turn transformer with three connection points is investigated by harmonics analysis from the viewpoint of core size and other parameters. Finally, experimental results confirm that the GDU in the two-level three-phase inverter with switching frequencies of 12.5 kHz and 16 kHz is operated by the proposed self-supplying gate power supply circuit without an external power source.

Keywords: self-supplying power circuit, gate drive unit, one-turn transformer

1. Introduction

A gate drive unit (GDU) is generally used for power converters in order to operate the switching devices such as IGBT, MOS-FET and others [(1)–(4)]. The GDUs require additional power supply units because the electric potential of emitter of the switching device is different depending on the switching device in the main circuit.

Generally, an isolated DC-DC converter is used for a gate power supply; however extra cost is implemented. There are some design approaches for cost reduction, such as a charge pump circuit [(5)], a bootstrap circuit [(6)(7)], and a self-supplying power circuit using voltage across a switch [(8)–(17)] and thermoelectric devices [(18)–(20)]. For example, the bootstrap circuit has a simple configuration. The charge pump circuit can reduce the volume of a capacitor for voltage supply by increasing the switching frequency of a charge circuit, furthermore these two circuits can be applied easily to a conventional inverter topology. However, when these two circuits are applied to other main circuit topologies such as matrix converters or multilevel converters, the number of parts in the gate power supply will increase [(8)], furthermore the voltage rating of the components in the gate power supply depends on that of the main circuits.

Meanwhile, the multilevel converters for industrial applications has been attractively researched because medium-voltage ratings of the industrial applications have been risen to 3.3 kV or 6.6 kV [(21)–(23)]. In such multilevel converters, galvanic isolation is required for each GDU. In order to achieve isolation of the GDU safely, a coreless transformer and a wireless power transfer are utilized [(12)(13)]. However, in Ref. (12), it is concerned that many isolation systems are required. That is, downsizing of the gate power supply circuit is prevented. In addition, in Ref. (13), transmission efficiency of power for a GDU is low because of low coupling factor between a transmitting coil and receiving coils. Moreover, in both methods, a specified external power supply such as a switching power supply is required.

On the other hand, various self-supplying power circuits for GDUs have been proposed, which are roughly classified into two types. One type of them is not electrically isolated between a main circuit and a self-supplying power circuit [(8)–(16)]. Another type is electrically isolated between them [(17)–(20)].

In the type which is not electrically isolated between the main circuit and the self-supplying power circuit for GDUs, there are two types. One type of them utilizes a snubber circuit as the self-supplying power circuit. In Refs. (9), (10), stored energy in the snubber circuit is effectively utilized

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for the power of GDUs. Another type newly adds a self-supplying power circuit for GDUs to the main circuit[(8)(11)–(16)]. However, both types require circuit components with high voltage rating depending on the voltage of the main circuit because the self-supplying power circuit is connected in parallel to terminals of a switching device of a main circuit.

Meanwhile, as the type which is electrically isolated between the main circuit and the self-suppling circuit, in Ref. (17), a forward converter and a flyback converter are connected to a switching device in the main circuit in parallel. The forward converter is operated as a start-up converter when the switching device of main circuit turns on. The flyback converter is operated as a steady state converter while the switching device of main circuit is off-state. The primary voltage of a transformer in the forward converter corresponds to the on-state voltage of the switching device of main circuit. The number of turns in the primary side of the transformer is only one, which is simple configuration. However, the large number of turns of the secondary side of the transformer is required in order to obtain the required voltage for the GDU from the low voltage in the primary side of the transformer in the forward converter. As a result, size of the transformer of the start-up converter becomes large. In addition, a transformer in the flyback converter requires a number of primary windings because the transformer in the flyback converter needs to convert the high voltage across the switching device to the gate drive voltage which is low. As a result, size of the transformer of the steady-state converter also becomes large. Moreover, in Refs. (18)–(20), isolated self-supplying power circuits for GDUs which use a thermoelectric device, have been proposed. In these methods, the thermoelectric device is installed to a surface of a motor or an inverter and its circuit component in order to generate power for GDUs by utilizing the temperature difference of the thermoelectric device due to the heat from the motor or the inverter. Not only these methods can get power due to the heat but also temperature rising of the motor and inverter can be suppressed. However, the thermoelectric device is expensive and its efficiency is low.

This paper presents a new isolated self-supplying power circuit for GDUs, which utilizes the current fluctuation of main circuit as energy source of power for GDUs in order to solve above-mentioned problems. The concept of proposed isolated self-supplying power circuit is realizing at least one isolated power supply for a GDU by passing only one turn of main circuit line to a magnetic core. This method is very simple. That is, a designer can determine the number of one-turn transformers depending on the required number of isolated power supplies for GDUs and its power which are determined by specifications and configurations of main circuits. In addition, charge pump circuits and bootstrap circuits are unnecessary to the secondary side of the one-turn transformers by realizing multiple isolated power supplies for GDUs with multiple one-turn transformers. Multiple one-turn transformers are required in modular multilevel converters (MMCs) and matrix converters However, the proposed self-supplying power circuit using the one-turn transformer for GDUs has advantages in terms of the voltage rating and the size compared with conventional methods because the voltage rating in the primary side and secondary side of the one-turn transformer is low. Therefore, the proposed gate drive power supply delivers the following features; (i) The proposed circuit is isolated from the main circuit. (ii) The voltage rating of the components does not depend on the main circuit. (iii) An easy configuration that is composed of a one-turn transformer and a rectifier. (iv) A complicated control is unnecessary.

First, this paper describes the characteristics of the one-turn transformer with an equivalent circuit. Then, the design method of a transformer is established. Secondly, the power supply characteristic for the GDU is investigated by experiment with a step-down chopper. Thirdly, connection points of the proposed transformer in a two-level three-phase inverter is discussed. Finally, the experimental results from the two-level three-phase inverter with the proposed self-supplying gate power circuit is demonstrated.

2. Analysis of Equivalent Circuit

This chapter discusses an equivalent circuit of the self-supplying type of gate power circuit by using a transformer. Then, the adequacy of the equivalent circuit is verified by simulation results and experimental results.

2.1 Identification of Equivalent Circuit Parameters

Figure 1 shows an example of the proposed self-supplying power circuit which is connected to a step-down chopper. A transformer using an one-turn winding to the primary side is used in the proposed self-supplying power circuit for the GDU. A diode rectifier is an example converter to obtain DC voltage for the GDU. The output power P_2 is supplied to the GDU. Note that a resistor is connected instead of a GDU in order to investigate simply the characteristics of the proposed circuit. The power consumption of the proposed power circuit is lower than the conventional self-supplying power circuit using voltage across the switch because the isolated voltage for GDUs in the proposed circuit is implemented by a transformer which has low-voltage rating.

Figure 2 shows an equivalent circuit with the secondary side model of the transformer. The equivalent circuit is com-

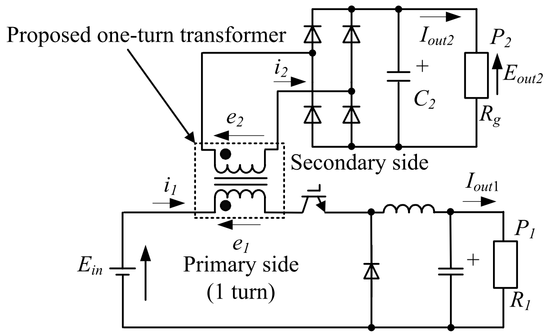


Fig. 1. Experimental circuit for the proposed self-supplying using one-turn transformer

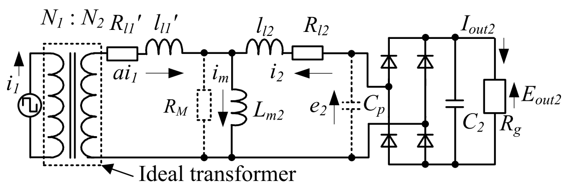


Fig. 2. Equivalent circuit converted to the secondary side of the transformer

posed by an ideal transformer and T-type equivalent circuit, which is expressed by a magnetizing inductance, leakage inductances and winding resistances. In addition, a p-n junction capacitance of the diode in the diode rectifier is considered as C_p. In this paper, C_p is connected to the terminal of the secondary side of the one-turn transformer. The position of C_p is different from the actual p-n junction capacitance. However, it is confirmed that C_p shown in Fig. 2 is operated as well as the p-n junction capacitance of the diode in the diode rectifier in simulation. On the other hand, a current source is connected as the primary current to the primary side of the transformer. In addition, even though the number of turns of the primary winding in the proposed circuit is only one, the number of turns of the primary winding is defined as N_1 in order to generalize the equivalent circuit shown in Fig. 2.

The identification of the circuit parameters is obtained as following. Firstly, the short-circuited inductance L_{sc2} on the secondary side is measured by a LCR meter when the primary side terminal is shorted. In addition, the secondary side self inductance L_2 is obtained by a LCR meter when the primary side terminal is opened. Then, the coupling factor k of the transformer is defined by (1).

$$k = \sqrt{1 - L_{SC2}/L_2} \cdots\cdots (1)$$

The magnetizing inductance L_{m2} in the equivalent circuit is obtained by (2).

$$L_{m2} = kL_2 = \sqrt{k^2 (N_2/N_1)^2 L_1 L_2} \cdots\cdots (2)$$

where N_1 is the number of turns of the primary winding, N_2 is the number of turns of secondary winding.

On the other hand, the secondary leakage inductance L_{l2} are expressed by (3).

$$l_{l2} = (N_2/N_1)^2 L_1(1 - k) = L_2(1 - k) \cdots\cdots (3)$$

2.2 Comparison of Experimental Waveforms with Simulation Waveforms Figure 3 shows the waveforms of the secondary side output voltage e_2 and the secondary side current i_2 with the primary current i_1. The experimental conditions are; the switching frequency of the step down chopper f_{sw} = 10 kHz, the switching duty ratio D = 35%, output current I_{out1} = 10 A, the coupling factor k = 0.92, the number of secondary winding turn N_2 = 20 turn, magnetizing inductance L_{m2} = 440 μH.

A leakage inductance of the one-turn transformer threatens the increase of surge voltage of the switching device and EMI in the main circuit. Actually, reducing leakage inductance of the one-turn transformer is required by considering the surge voltage of switching device in the main circuit. On the other hand, in high power applications assumed in this paper, in order to prevent the main circuit from malfunction by short-circuit, a current sensor is inserted between a DC link capacitor and a switching device in the main circuit for detection of short-current. Moreover, a fuse might be inserted to prevent ramification of malfunction of switching device in the main circuit. As a result, inductance of current path where the current sensor or the fuse is inserted, is increased. Therefore, it might be not a serious problem to inserting one-turn transformer to current path in the main circuit in terms of the surge voltage of switching device in the main circuit.

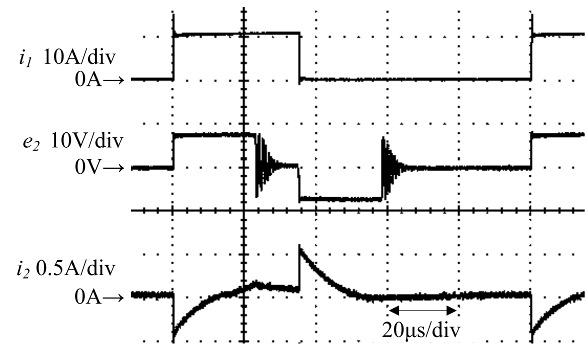


Fig. 3. Operation waveforms of proposed circuit (f_{sw} = 10 kHz, N_2 = 20 turn, D = 35%, I_{out1} = 10 A)

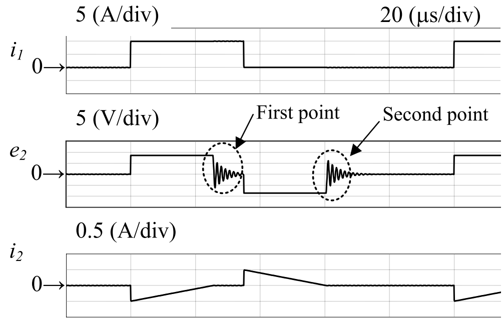


Fig. 4. Operation waveforms of equivalent circuit (f_{sw} = 10 kHz, N_2 = 20 turn, D = 35%, I_{out1} = 10 A)

On the other hand, it cannot be concluded that increasing stray inductance in the path which switching current flow through in the main circuit cause increasing EMI compared with the case without the proposed self-supplying power circuit. Voltage gradient of switching device dv/dt is reduced by increasing the stray inductance of the switching device. According to Ref. (26), amplitudes of spectrum of common-mode voltage is reduced by reducing the voltage gradient of switching device dv/dt. That is, increasing the stray inductance of the switching device might reduce EMI. Further investigations are needed for this issue as a future work, which is not a subject in this paper. Therefore, it is not discussed in detail.

Figure 4 shows the simulation waveforms of the equivalent circuit shown in Fig. 2. From Fig. 4, the simulation waveforms are similar to the experimental waveforms including that the secondary voltage waveform e_2 oscillates at two points which are when the positive voltage is reduced to zero and when the negative voltage is returned to zero.

The principle of oscillation in e_2 at the first point which is when the positive voltage is reduced to zero, is different from that in e_2 at the second point which is when the negative voltage is returned to zero. The first point, the short-circuit inductance L_{sc2} appears in the secondary side because the primary current is flowed. Therefore, a resonance between the short-circuit inductance L_{sc2} and C_p occurs during the first point. The resonant frequency f_{pon} during the first point is obtained by (4).

$$f_{pon} = \frac{1}{2\pi\sqrt{L_{SC2}C_p}} \cdots\cdots (4)$$

On the other hand, the self inductance L_2 appears at the second point. This is because the primary side can be assumed to be an opened circuit the since the primary current is zero at the second point. Therefore, a resonance between the self inductance L_2 and C_p occurs during the second point. The resonant frequency f_{poff} during the second point is obtained by (5).

$$f_{poff} = \frac{1}{2\pi\sqrt{L_2 C_p}} \cdots\cdots (5)$$

Thus, these resonant waveforms are generated by the capacitance C_p, which is connected in parallel with the input of the rectifier. In addition, it is noted that the oscillations are gradually reduced by the iron loss which corresponds to a resistance R_M. The simulation waveforms agree well with the experimental waveforms including the oscillation by considering C_p and R_M. Therefore, the validity of the equivalent circuit shown in Fig. 2 is confirmed.

3. Output Power on Secondary Side of Transformer

This chapter discusses the relationship between the output power P_2 and parameters of the one-turn transformer. The output power of the transformer depends on parameters of core materials and the switching frequency if the number of turns on the primary side is only one.

The output power P_2 is calculated by the output voltage E_{out2} and the output current I_{out2} which is an average current of the gate resistance R_g for one switching cycle. At first, the output current I_{out2} of the proposed circuit is formulated by a simple operation model.

Figure 5 shows the current waveforms in the equivalent circuit. Each waveform are as follows; ai_1 is the primary current which is converted to the secondary side, i_m is the exciting current which flows through the magnetizing inductance L_{m2}, and i_2 is the secondary side current of the transformer. In addition, I_1 is the peak current of the main circuit. I_2 is the peak value of i_2. Note that a is the turn ratio of the transformer, which is given by (6).

$$a = \frac{N_1}{N_2} \cdots\cdots (6)$$

I_2 is expressed by (7) using I_1 and (6).

$$I_2 = \frac{N_1}{N_2} I_1 = aI_1 \cdots\cdots (7)$$

Figure 5 assumes that the resistance in the transformer can be neglected and the primary current is constant during one switching cycle. The exciting current is increased because the primary current is commutated to the magnetizing inductance. Thus, the secondary side current of the transformer becomes a triangle shape. The peak value of the secondary side current is defined as aI_l.

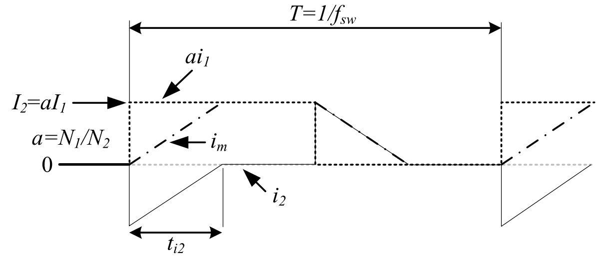


Fig. 5. Current waveform of the equivalent circuit

Then the output current I_{out2} is obtained by (8) from the area of the triangle waveform i_2.

$$I_{out2} = \frac{aI_1 t_{i2}}{2} \frac{1}{T} 2 = aI_1 t_{i2} f_{sw} \cdots\cdots (8)$$

where t_{i2} is the current flow time, T is the switching period, and f_{sw} is the switching frequency.

Next, the output voltage of the proposed circuit E_{out2} is discussed. The output voltage E_{out2} shown in Fig. 2 is given by (9).

$$E_{out2} = L_{m2}\frac{di_m}{dt} + l_{l2}\frac{di_2}{dt} \cdots\cdots (9)$$

Now, differentials of the current are approximately obtained by (10) and (11) from Fig. 5.

$$\frac{di_m}{dt} = \frac{aI_1}{t_{i2}} \cdots\cdots (10)$$

$$\frac{di_2}{dt} = -\frac{aI_1}{t_{i2}} \cdots\cdots (11)$$

Therefore, the output voltage of the proposed circuit E_{out2} is obtained by (12) by substituting (10) and (11) into (9).

$$E_{out2} = L_{m2}\frac{aI_1}{t_{i2}} - L_{l2}\frac{aI_1}{t_{i2}} = aI_1(L_{m2} - l_{l2})\frac{1}{t_{i2}} \cdots\cdots (12)$$

Thus, the output power P_2 of the transformer is obtained by multiplying (8) and (12) as expressed by (13).

$$P_2 = E_{out2}I_{out2} = (L_{m2} - l_{l2})(aI_1)^2 f_{sw} \cdots\cdots (13)$$

Thus, the relationship between the output power P_2 and the self inductance converted to the secondary side L_2 is expressed by (14) by substituting (2) and (3) into (13).

$$P_2 = (2k-1)L_1 I_1^2 f_{sw} = (2k-1)L_2(aI_1)^2 f_{sw} \cdots\cdots (14)$$

When a toroidal core is used in the transformer, the relationship between parameters of the transformer and the self inductance converted to the primary side L_1 and the self inductance converted to the secondary side L_2 is obtained by (15) and (16), respectively.

$$L_1 = N_1^2 \mu_0 \mu_e \frac{A_e}{l_e} \cdots\cdots (15)$$

$$L_2 = N_2^2 \mu_0 \mu_e \frac{A_e}{l_e} \cdots\cdots (16)$$

where μ_0 is the space permeability, μ_e is the effective permeability, A_e is the effective cross section, and l_e is the effective magnetic path length.

Thus, the output power P_2 is obtained by (17) by substituting (15) into (14) or by substituting (16) into (14).

$$P_2 = (2k-1)N_1^2 I_1^2 f_{sw} \mu_0 \mu_e \frac{A_e}{l_e} \cdots\cdots (17)$$

Therefore, the output power P_2 is proportional to the square of the number of turns of primary winding N_1 and the primary current I_1. In addition, the output power P_2 is proportional to the switching frequency f_{sw}. Moreover, P_2 depends on the parameters of the core. From Eq. (17), it should be noted that the output power P_2 does not depend on the number of turns on the secondary side N_2.

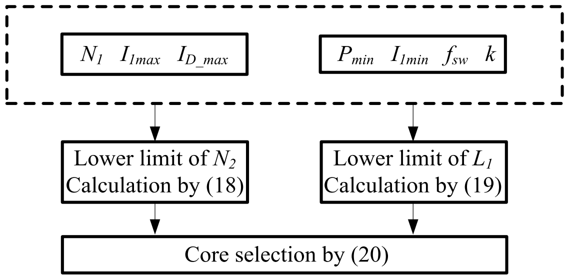


Fig. 6. Design flow chart for one-turn transformer

Table 1. Circuit specifications

Item	Value
Number of turns (Primary side) N_1	1
Coupling factor k	0.9
Minimum primary current I_{1min}	7.2 (A)
Maximum primary current I_{1max}	24.0 (A)
Switching frequency f_{sw}	10 (kHz)
Minimum power P_{min}	0.3 (W)
Maximum diode current I_{D_max}	2 (A)

4. Design of Transformer in Proposed Circuit

This chapter discusses the design of the one-turn transformer. In addition, an example of design for the one-turn transformer is shown in section 4.3. It is noted that the configuration of the secondary side of the one-turn transformer is not a subject in this paper. Therefore, a well-known circuit configuration is used in the secondary side of the one-turn transformer. Similarly, configuration of the main circuit as the primary side of the one-turn transformer is not a subject the authors claim as the novelty of this paper. The configuration of the main circuit is just an application of the proposed self-supplying power circuit with the one-turn transformer., Therefore, only the design method of the one-turn transformer and its characteristics are discussed.

4.1 Design Flow Chart for Transformer Figure 6 shows the design flow chart of the transformer. Each of the parameters of the transformer is decided based on the circuit specifications given in Fig. 6. The given circuit specifications are following; the maximum current of the main circuit is I_{1max} which equals to the maximum value of I_1, the minimum current of the main circuit is I_{1min} which equals to the minimum value of I_1, the switching frequency is f_{sw}, the minimum power of operation for GDU is P_{min} which is the minimum value of P_2, and the maximum allowable current of diode for rectifier is I_{D_max} which equals to both I_2 expressed by Eq. (7) and the peak value of i_2 shown in Fig. 2 and Fig. 5. Besides, the number of turns on the primary side is N_1 and the coupling factor of the transformer is k.

If above-mentioned specifications are given to (6), (7), (14), and (17), required parameters in order to design the transformer of the proposed circuit are as follows; 1) the number of turns of the secondary winding N_2, 2) the self inductance converted to the primary side L_1, 3) core parameters μ_e, A_e, and l_e.

First, the number of turns on the secondary winding N_2 has a lower limit in order to meet the requirement of I_{1max} and I_{D_max}. The required number of turns on the secondary winding N_2 is calculated by substituting I_{1max} and I_{D_max} into (7) instead of I_1 and I_2, as expressed by (18).

$$N_2 \geq \frac{N_1 I_{1\,\max}}{I_{D-\max}} \cdots\cdots (18)$$

Secondly, the self inductance converted to the primary side L_1 has a lower limit in order to obtain P_{min}. The required self inductance converted to the primary side L_1 is calculated by substituting P_{min} and I_{1min} into (14) instead of P_2 and I_1, as expressed by (19).

$$L_1 \geq \frac{P_{\min}}{(2k-1){I_{1\,\min}}^2 f_{sw}} \cdots\cdots (19)$$

Finally, the core of the transformer is selected to satisfy (18) and (19). However, if N_2 is decided by (18), the self inductance converted to the primary side L_1 expressed by (19) is decided by only the parameters of the core. That is, a core which satisfies (20) should be selected based on (15).

$$\mu_e \frac{A_e}{l_e} \geq \frac{L_1}{N_1^2 \mu_0} \cdots\cdots (20)$$

Hence, the transformer of the proposed circuit is designed by (18), (19), and (20).

4.2 Design Example of One-turn Transformer

Table 1 shows an example of the circuit specification. The number of turns on the primary side N_1 is one in order to realize a simple configuration of the gate power supply circuit. The lower limit of number of turns on the secondary windings N_{2min} is calculated by (21), the lower limit of the self inductance on the primary side L_{1min} is calculated by (22), respectively.

$$N_{2\,\min} \geq \frac{N_1 I_{1\,\max}}{I_{D-\max}} = 12 \cdots\cdots (21)$$

$$L_{1\,\min} \geq \frac{P_{\min}}{(2k-1) I_1^2 f_{sw}} = 0.73\,\mu H \cdots\cdots (22)$$

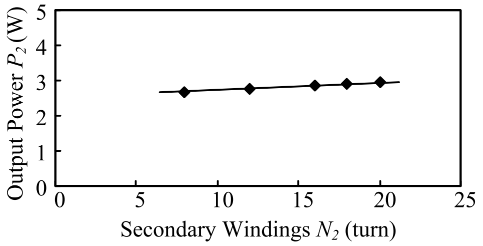
Therefore, the core that satisfies conditions in (21) and (22) is selected. Thus, the core which has following parameters was selected according to (20); $A_e = 150\,\mathrm{mm}^2$, $l_e = 56.5\,\mathrm{mm}$, and $\mu_e = 229$. Using this core, L_1 of 0.79 μH is obtained with N_2 of 12 turns.

4.3 Evaluation of Design Method by Experiment

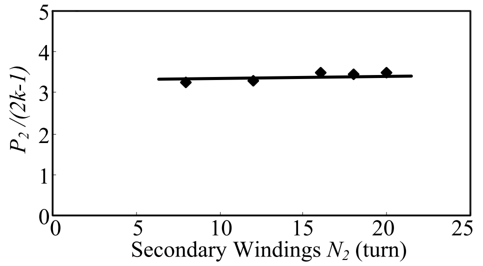
The validity of the design method is evaluated by a basic experimental circuit shown in Fig. 1. In experiment, the transformer which was designed in the previous chapter, is used.

Figure 7(a) shows the relationship between the output power P_2 and the number of turns on the secondary side N_2. It is confirmed that the output power P_2 is increasing as the N_2 increased even though the output power P_2 theoretically does not depend on the number of turns on the secondary side N_2 as mentioned in the chapter 3. This reason is that the coupling factor k actually becomes higher by increasing N_2 while the coupling factor k is independent from N_2 in (17) theoretically.

On the other hand, Fig. 7(b) shows the relationship between the value of the output power P_2 divided by (2k − 1) to exclude the variation of k and the number of turns on the secondary winding N_2. From Fig. 7(b), it is confirmed that the



(a) Output power P_2.



(b) Output power P_2 divided by (2k−1).

Fig. 7. Characteristics of the number of turns on the secondary side (f_{sw} = 10 kHz, D = 35%, I_{out1} = 21 A)

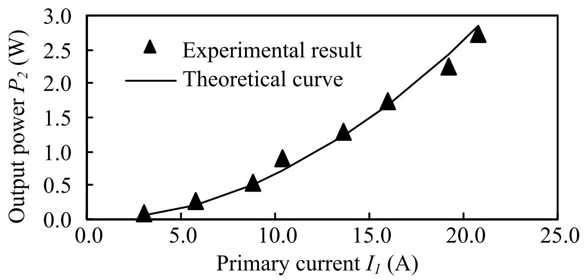


Fig. 8. Output power P_2 for the primary current I_1 in the range of 3 A–21 A (f_{sw} = 10 kHz, N_2 = 12 turn, D = 35%, R_1 varies)

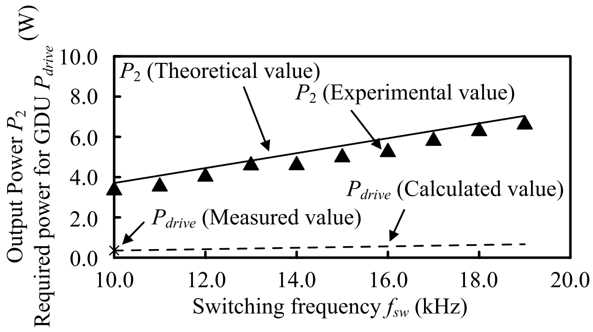


Fig. 9. Output power P_2 and required power for GDU P_{drive} for the switching frequency f_{sw} in the range of 10 kHz–19 kHz (N_2 = 12 turn, D = 35%, I_{out1} = 23.5 A)

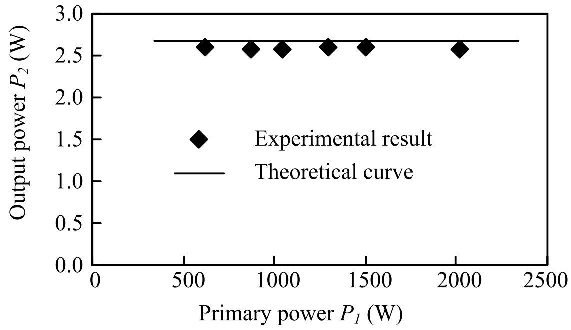


Fig. 10. Output power P_2 for the primary power P_1 (f_{sw} = 10 kHz, N_2 = 12 turn, D = 35%, I_{out1} = 20 A, E_{in} and R_1 vary)

value of $P_2/(2k-1)$ is almost independent from the number of turns on the secondary side even though the coupling factor k varies. Therefore, it is confirmed that the output power P_2 is independent from N_2 by removing the variation of k.

Figure 8 shows the relationship between the output power P_2 and the peak current of the main circuit I_1 based on the experimental result and the theoretical analysis from (17). In this experiment, I_1 is varied by changing the value of R_1 in the step-down chopper shown in Fig. 1. From the result, it is confirmed that the output power P_2 is proportional to the square of the primary current I_1 in experiment, which agrees with the theoretical analysis.

Figure 9 shows the relationship among the output power P_2, the switching frequency f_{sw} and the required power per one GDU P_{drive}. The variation range of the switching frequency is from 10 kHz to 19 kHz. The power consumption per one GDU was experimentally measured at only the switching frequency of 10 kHz. It was 0.35 W which includes not only the power consumption of a gate resistance but also power consumption of a photocoupler, zener diodes, and so on. Using this measurement value, the required power for the GDU at other switching frequencies was calculated by assuming that the required power for the GDU is proportional to the switching frequency. The experimental result confirms that the proposed method can obtain an enough output power P_2 to operate the GDU for the entire variation range of the switching frequency.

Figure 10 shows the output power P_2 for the output power of the main circuit P_1. In this experiment, the output power of the main circuit P_1 is changed by adjusting a DC link voltage E_{in} and the load resistance R_1 in the step-down chopper, while the load current of the main circuit I_{out1} is constant. Therefore, the primary current of the transformer of the proposed circuit is also constant. From the result, it is confirmed that the output power P_2 is constant even through the output power of the main circuit P_1 is changed if the primary current of the transformer of the proposed circuit, the switching frequency, and the duty ratio are fixed. That is, the enough output power of the gate power supply using the proposed self-supplying power circuit can be obtained if the load current of the main circuit is large or the switching frequency is high, however the output power of the main circuit is small.

5. Evaluation of Proposed Circuit as Gate Drive Unit

By the chapter 4, the output power of the transformer of the proposed circuit is only consumed in the resistor R_g. In this chapter, the obtained output power is utilized in order to drive GDUs in prototype circuits.

Assumed main circuits of the proposed self-supplying power circuit in this paper are modular multilevel converters (MMCs), basic multilevel converters and matrix converters which have some advantage such as high efficiency and low harmonic distortion of the output voltage in high-voltage and high-power applications. In addition, in this paper those converters are assumed be interconnected to the grid which has constant frequency such as 50 or 60 Hz. Although the duty ratio in those power converters is changed depending on the phase of grid voltage, the period of low duty ratio and high duty ratio is often small compared the period of grid frequency. In addition, the current of switching device periodically becomes small since the grid voltage is AC. Therefore, for practical use, a button battery or a small capacitor can be used as the energy storage component to the secondary side of one-turn transformer. Consequently, the proposed self-supplying power circuit can start up even in the above-mentioned situation including a light load condition. In addition, lack of power for GDUs is compensated by the energy storage component.

Considering the above-mentioned situation, hence, in this paper an auxiliary power supply is used in the secondary side of the one-turn transformer for simplicity of experiment. The auxiliary power supply is operated only when the power for GDUs from the main circuit is not enough for GDUs. On the other hand, the start-up procedure of the proposed self-supplying power circuit is explained at the end of chapter 5 since the start-up operation of the proposed self-supplying power circuit is not a subject in this paper.

For simplicity of experiment, a step-down chopper which has constant and reasonable duty ratio, is firstly tested. Next, a two-level three-phase inverter is experimentally tested under control with a pulse-width modulation (PWM) method whose duty ratio is periodically changed.

5.1 Fundamental Operation in DC Chopper

Figure 11 shows an evaluation circuit of the proposed circuit. In this chapter, the operation of a GDU using the proposed self-supplying power circuit is confirmed by experiment. A well-known circuit configuration as one of examples is used in the secondary side of the one-turn transformer for simplicity of experiment. The circuit configuration of the secondary side of one-turn transformer is not a subject the authors claim as the novelty of this paper.

The supplied voltage for the GDU is more than 24 V. When the output voltage of the proposed self-supplying power circuit is less than 24 V, the proposed self-supplying power circuit starts to operate by using the auxiliary DC power source (e_{aux}) as shown in the DC part of Fig. 11. It should be noted that only the proposed circuit supplies the power to the GDU when the DC power supply current i_{aux} is zero. The positive gate voltage for on-state period is set to 16 V. On the other hand, negative gate voltage for off-state period is set to −7 V.

Figure 12 shows the operation waveforms of the GDU with the proposed self-supplying power circuit; V_{ge} is the voltage between a gate and an emitter, the supply current i_{sub1} is from the proposed self-supplying power circuit, and the current i_{aux} is from the auxiliary power supply. The experimental conditions are following; the output current of the step-down chopper I_{out1} = 7.8 A, the switching frequency f_{sw} is 16 kHz, the switching duty ratio = 35%. In Fig. 12(a), the current for the GDU is supplied from the auxiliary power supply e_{aux} without the proposed self-supplying power circuit. On the other hand, in Fig. 12(b), the current for the GDU is i_{sub1} from the proposed circuit. The same gate voltage waveforms are obtained in Figs. 12(a) and (b). These experimental results confirmed that the proposed circuit can normally supply enough power for the GDU if the voltage is supplied initially

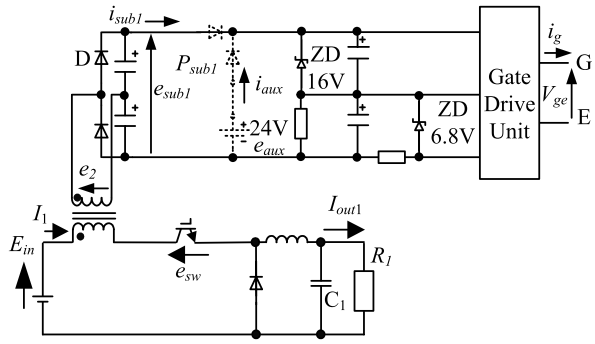
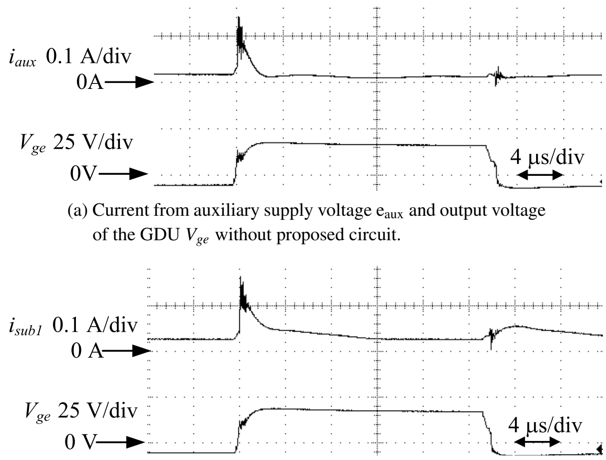


Fig. 11. Experimental circuit of self-supplying power circuit



(a) Current from auxiliary supply voltage e_{aux} and output voltage of the GDU V_{ge} without proposed circuit.

(b) Current from proposed self-supplying circuit and output voltage of the GDU V_{ge} with proposed circuit.

Fig. 12. Operation waveforms of the GDU using the proposed self-supplying circuit at step-down chopper

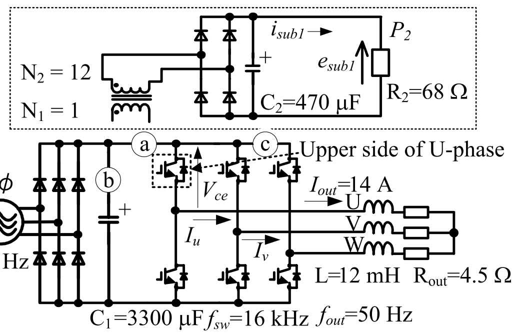


Fig. 13. The possible connection points of the one-turn transformer in a two-level three-phase inverter. (Only the power to the upper side of U-phase is provided by the proposed self-supplying circuit)

by the auxiliary power supply.

5.2 Connection Point of One-turn Transformer in Two-level Three-Phase Inverter Figure 13 illustrates several connection points of the proposed self-supplying using the one-turn transformer in a two-level three-phase inverter. In the two-level three-phase inverter, the one-turn transformer can be connected in series to (a) a DC-link part between the two-level three-phase inverter and a smoothing capacitor, (b) the smoothing capacitor, or (c) a switching device of each leg. In this paper, R-L loads are used to the two-level three-phase inverter for simplicity of experiment instead of the grid.

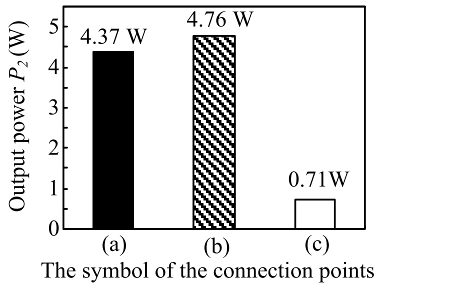


Fig. 14. Output power P_2 at the selected connection points of the one-turn transformer

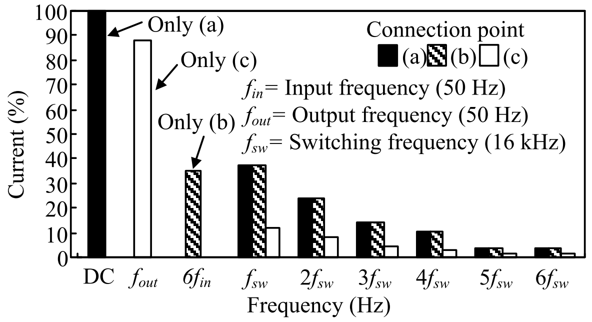


Fig. 15. Harmonics components of the primary current at each connection point

Figure 14 shows the output power P_2 of the secondary side for the connected points of the one-turn transformer. The obtained output power P_2 is more than 4 W when the primary side of the one-turn transformer is connected to the point (a) and (b). The proposed gate drive power supply can supply enough power to operate up to six GDUs since the power consumption of one GDU (shown in Fig. 9) used in the two-level three-phase inverter is smaller than the obtained output power P_2 shown in Figs. 14(a) and (b). On the other hand, the proposed circuit generates only 0.71 W when the primary side of the one-turn transformer is connected to the point (c). In order to clarify differences among the output power of the proposed self-supplying power circuit at the three connection points, harmonics components of the each primary current of the transformer is analyzed.

Figure 15 shows the harmonics components of the primary current at each connection point. The harmonics components of the switching frequency at the point (c) are smaller than other connection points shown in Fig. 13. In addition, although the amplitudes of the DC component and the six times component of the input frequency between the point (a) and (b), a same output power is obtained by the proposed circuit when the primary side is connected to the point (a) and (b) because the output power is dominated by the harmonics components of the switching frequency in the primary current. It should be noted that the output power P_2 is proportional to the switching frequency and the square of the primary current as expressed in (17). However, in the connection point (a), it is concerned that magnetic saturation occurs by the DC component of the input current of the two-level three-phase inverter. Therefore, a large core might be required if the proposed on-turn transformer is connected at the point (a). Therefore, the connection point (b) is superior to the connection points (a) and (c) because the connection point (b) can obtain the largest power using a small core among the three connection points.

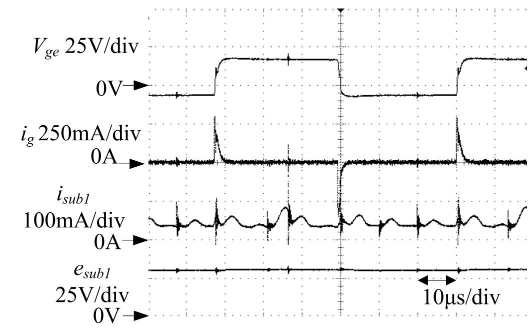


Fig. 16. Operation waveforms of the GDU with the proposed circuit

5.3 Application of Proposed Self-Supplying Power Circuit for Two-level Three-Phase Inverter In this section, the performance of the gate drive unit is evaluated. A two-level three-phase inverter is used as the main circuit, and the power to drive the GDU is supplied by the proposed gate power circuit. Note that the power is supplied to only the GDU for U-phase by the proposed gate power supply circuit where the primary side of the transformer is connected to point (b) which is the smoothing capacitor.

Figure 16 shows the operation waveforms of the proposed circuit shown in Fig. 13. From the top in Fig. 16, V_{ge} is the voltage between the gate and the emitter of a switching device of the two-level three-phase inverter, i_g is the gate current of the switching device, i_{sub1} is the supply current for the GDU and e_{sub1} is the power supply voltage for the GDU. The power supply voltage e_{sub1} is constant while the gate current i_g is operated in charge or discharge mode. Besides, the actual gate voltage almost agrees with the design value. It is noted that the auxiliary power source does not operate in this experiment because the output voltage of the proposed self-supplying power circuit is 27 V while the output voltage of the auxiliary power source is 24 V. It is confirmed that the voltage between the gate and the emitter V_{ge} does not contain a large distortion. Therefore, it is confirmed that the GDU is operated normally with the proposed self-supplying power supply.

Figure 17 shows the operation waveforms of the two-level three-phase inverter which are the collector-emitter voltage of the switching device V_{ce}, the U-phase output current I_u, the V-phase output current I_v, and the power supply voltage e_{sub1} for the GDU. Sinusoidal current waveforms are obtained in U-phase and V-phase output of the two-level three-phase inverter without any distortion. Besides, the gate power supply voltage shows a constant voltage. Therefore, the results confirmed that the two-level three-phase inverter can operate normally by using the GDU with the proposed self-supplying gate drive power circuit.

The experimental result of the two-level three-phase inverter with the PWM control method shown in Fig. 17 is obtained by using the auxiliary power supply as energy storage component in the secondary side of the one-turn transformer. In the PWM control method, the duty ratio of inverter is changed from low value to high value according to the phase of output current. However, there is no large distortion and

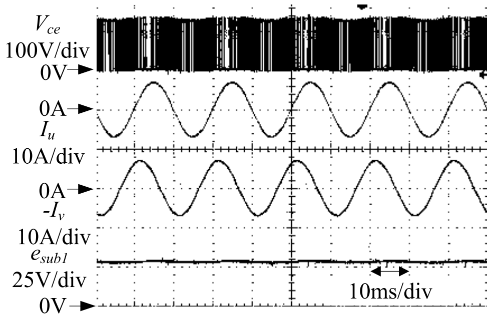
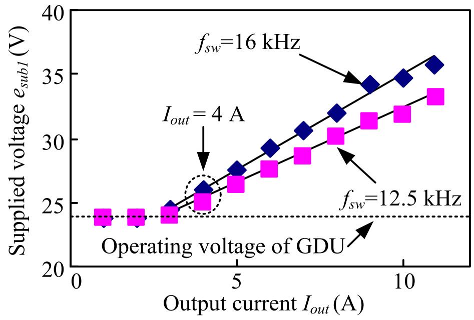
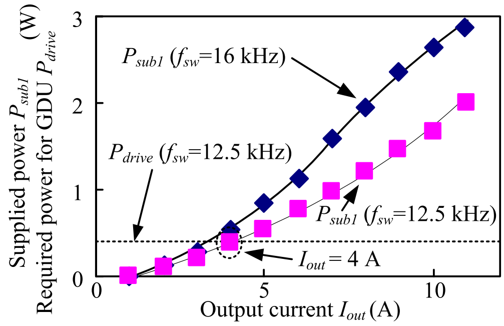


Fig. 17. Operation waveforms of the inverter with the GDU using the proposed self-supplying gate drive power supply circuit



(a) Gate power supply voltage for the output current of the two-level three-phase inverter.



(b) Supplied power of the gate drive power supply circuit for the output current of the two-level three-phase inverter.

Fig. 18. The relationship between the power supply voltage and the output power of the gate drive power supply circuit for the output current of the inverter

jump in the output current of the two-level three-phase inverter in the experimental result shown in Fig. 17. Therefore, it is revealed that the proposed self-supplying power circuit for the GDU can be applied for MMCs, basic multilevel converters and matrix converters by installing the energy storage component to the secondary side of the one-turn transformer. It is noted that the periods which are extreme low or high duty ratio are short compared with that of fundamental output frequency. On the other hand, converters with high voltage conversion ratio is not an application of the proposed self-supplying power circuit of the GDU because such converters require constantly extreme duty ratio. Therefore, it is noted that a special design is required for the proposed self-supplying power circuit when it is applied for such converters.

Figure 18(a) shows the relationship between the supplied voltage e_{sub1} of the GDU and the output current of the two-level three-phase inverter. Figure 18(b) shows the relationship between supplied power P_{sub1} of the GDU and the output current of the two-level three-phase inverter. In order to investigate the influence of the switching frequency to the supplied voltage e_{sub1} and the supplied power P_{sub1}, two switching frequencies of 16 kHz and 12.5 kHz are tested. The output current I_{out} is changed by adjusting the input voltage of the two-level three-phase diode rectifier shown in Fig. 13. The results confirmed that the GDU is operated by the proposed self-supplying gate power supply circuit at least at the switching frequency of 12.5 kHz when the output current is more than 4 A because both the obtained supplied voltage and supplied power are larger than the desired values shown in Fig. 18.

However, it should be noted that the gate power supply voltage increases in proportion to output current as expressed in (12). Moreover, the higher switching frequency results in the higher supplied voltage e_{sub1}. Therefore, practically, the proposed gate power circuit should be designed in a way that the supplied voltage e_{sub1} for GDUs is kept according to the operation range of the main circuit such as an output current and a switching frequency.

In summary, the features of the proposed self-supplying power circuit for the GDU are as follows;

(a) Energy source of the power for GDUs
The current fluctuation due to switching operation of the main circuit

(b) Main circuits assumed as applications
 (i) Basic multilevel converters
 (ii) Modular multilevel converters
 (iii) Matrix converters

(c) Applications of main circuits
Grid-tied inverters which has constant fundamental output frequency such as 50 or 60 Hz

(d) Advantages of the proposed self-supplying power circuit
 (i) Simple installation and structure in the primary side of an one-turn transformer
 (ii) Circuit components with lower voltage rating can be used compared with conventional self-supplying power circuit for GDUs. Therefore, the voltage rating of circuit components in the proposed self-supplying power circuit is drastically reduced compared with conventional charge pump circuits and bootstrap circuits.

Lastly, in this paper, the start-up operation of the proposed self-supplying power circuit is not a subject in this paper. However, the start-up procedure of the self-supplying power circuit for GDUs is one of the important issues. Therefore, the procedure of start-up operation of the proposed self-supplying power circuit is briefly explained as following.

(i) First, it is assumed that malfunction of switching devices of the main circuit by short-circuit is prevented even the power for the GDU is not provided. That is, the switching devices are completely off-state even the power for the GDU is not provided. This assumption is actually realized in many practical applications. In addition, the proposed self-supplying power circuit is assumed to be started up by an energy storage component connected to the DC part of the secondary side of the one-turn transformer. A button battery or a small capacitor can be used as the energy storage component.

(ii) Next, voltage is applied to the main circuit. Then, the energy storage component in the secondary side of one-turn transformer provides power to the GDU. After that, the operation of switching device in the main circuit is started. Finally, the startup of the proposed self-supplying power circuit is completed.

(iii) After the switching device in the main circuit starts to operate, the proposed self-suppling power circuit starts to provide power for the GDU. Then, the power from the energy storage component in the secondary side of the one-turn transformer is stopped.

6. Conclusions

This paper proposed the self-supplying gate power circuit for the gate drive unit which uses a one-turn transformer. The characteristics of the proposed gate power circuit were confirmed by the equivalent circuit and the experimental results as following;

(i) The output power of the one-turn transformer is almost proportional to the square of the primary current of the transformer and the switching frequency of the main circuit. On the other hand, the output power of the main circuit does not influence the gate drive performance.

(ii) Connecting the primary side of the transformer in series to the smoothing capacitor at the DC link of the two-level three-phase inverter is superior in terms of reducing the core size and obtaining the larger power for GDUs.

(iii) The same gate voltage was obtained by the proposed circuit in comparison to that of a conventional gate drive unit.

(iv) Sinusoidal output current waveforms were obtained in the two-level three-phase inverter with the proposed gate power supply circuit, as similarly to general inverters with conventional GDUs.

Thus, the validity of the proposed self-supplying gate power circuit was confirmed theoretically and experimentally.

It is expected that these results promote the discussion of the simplification of gate power supply circuits in matrix converters and multilevel converters in the future.

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