A 2.5 MHz High-Frequency Output Inverter Based on Frequency Multiplying Technique with a Multi-Core Transformer using Mn-Zn Ferrite Materials

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This paper proposes a 2.5 MHz high-frequency output inverter based on a frequency multiplying technique with a multi-core transformer using Mn-Zn ferrite materials. The upper limit of the operation frequency for these materials is lower than the output frequency of 2.5 MHz. First, the operation principle of the proposed circuit is explained. Second, a difficulty of using Mn-Zn for transformers at the frequency of 2.5 MHz is discussed. Third, a numerical analysis shows that the proposed circuit can output the frequency over the upper limit of the operation frequency of Mn-Zn ferrite. Finally, through continuous operation, where the proposed circuit outputs approximately 650 W, it is experimentally confirmed that Mn-Zn ferrite can be used without large iron loss at the output frequency of 2.5 MHz. Thus, the proposed circuit can overcome the difficulty of using Mn-Zn for transformers at the frequency of 2.5 MHz.

Keywords: high-frequency output inverter, frequency multiplying, iron loss, Mn-Zn ferrite

1. Introduction

Linear amplifiers have been used as power converters which output MHz frequency. However, the linear amplifiers are theoretically low efficiency, thus a cooling system for the linear amplifiers becomes large and this results in that the whole system is bulky (1)-(3). On the other hand, semiconductor devices can be operated at MHz frequency which can be operated in high efficiency by applying a soft switching technique using capacitive passive components (capacitors, parasitic capacitances of semiconductor devices) and inductive passive components (inductors, a leakage inductance of transformers) (5)-(10). This results in downsizing of the cooling system. Therefore, low loss passive components which can be operated at MHz frequency, are required for the semiconductor devices operated at the switching frequency of MHz.

However, the operation frequency of magnetic materials used for inductors and transformers has an upper limit. First, a real part of complex permeability is decreased in the region where the operation frequency of magnetic materials is over the upper limit (14)-(15). This results in increasing an iron loss. From the above reasons, the switching frequency of power converters is limited by the upper limit of operation frequency of magnetic materials even though the semiconductor devices can be operated at the high frequency. Therefore, it is difficult to achieve power converters which output the high frequency over the upper limit of operation frequency of magnetic materials by the switching operation of semiconductor devices, not the linear amplifier operation.

This paper deals with Mn-Zn ferrite whose upper limit of operation frequency is approximately 1 MHz (16), as an example of magnetic materials. The purpose of this paper is to verify the fundamental principle of the proposed circuit which outputs 2.5 MHz over the upper limit of operation frequency of Mn-Zn. The authors have been proposed a power converter based on the switching operation of semiconductor devices which outputs the frequency over the upper limit of operation frequency of magnetic materials (17). A five-phase half-bridge inverter is used in the proposed circuit, the operation frequency of magnetic core is 500 kHz which is one-fifth of the output frequency. In addition, the real part of complex permeability of Mn-Zn is kept almost constant in the frequency below 500 kHz. Therefore, 2.5 MHz is chosen as the output frequency from the viewpoint of the frequency characteristic of permeability in Mn-Zn. First, the operation principle of the proposed circuit is explained. Second, a difficulty of using Mn-Zn for transformers at the frequency of 2.5 MHz is discussed. Thirdly, numerical analysis shows that the proposed circuit can output the frequency over the upper limit of operation frequency of Mn-Zn ferrite. Finally, by conducting the continuous operation where the proposed circuit outputs approximately 650 W, it is experimentally confirmed that Mn-Zn ferrite can be used without large iron loss at the output frequency of 2.5 MHz.

2. Conventional and Proposed Circuits

2.1 Conventional Circuit

Figure 1(a) shows the
conventional circuit, which consists of a half-bridge inverter, a single transformer, a resonant inductor, a resonant capacitor, and a load. For sake of simplicity, the leakage inductance \( b \) is used as the resonant inductor and is represented at only the secondary side of the transformer. The half-bridge inverter is driven by a constant 50% duty cycle. The sinusoidal voltage and current are generated by series resonance on the secondary side of the transformer. The switching frequency of the conventional circuit is equal to the output frequency. Therefore, the operation frequency of the single transformer becomes the output frequency.

2.2 Proposed Circuit based on Frequency Multiplying Technique

Figure 1(b) shows the proposed circuit, which consists of a multi-phase half-bridge inverter, a multi-core transformer, a resonant inductor, a resonant capacitor, and a load. The transformer in the proposed circuit has a structure where the primary windings are connected in parallel and the secondary windings are connected in series, then the whole of transformer is named “multi-core transformer” in this paper. Similar to Fig. 1(a), the leakage inductance of each transformer \( l/5 \) is shown at only the secondary side in Fig. 1(b). Therefore, the leakage inductance of the multi-core transformer, in other words, the resonant inductance is \( l \).

Figure 2 shows the principle of the proposed frequency multiplying method. The five-phase inverter is operated with phase shift control. The phase difference is \( 2\pi/5 \) rad. Duty ratios of each gate signal are 0.5. One terminal of each primary winding in the multi-core transformer is connected to the corresponding output terminal of the five-phase inverter, and the other terminals of all primary windings are connected to the dc neutral point. On the other hand, the secondary side of each transformer is connected in series. Consequently, the secondary side voltage of the multi-core transformer is the sum of the secondary side voltage of each transformer in principle, as shown in Fig. 2. That is, the output frequency on the secondary side of the multi-core transformer is five times of the switching frequency. This results in reducing the operational frequency of magnetic cores in the multi-core transformer compared with that of conventional high frequency output inverters. The switching frequency of five-phase inverter is also one-fifth of the output frequency. As a result, the proposed circuit can use magnetic materials whose upper limit of operation frequency is lower.

2.3 Flux in Magnetic Core

Fig. 3 shows the relationship between currents and the flux in the proposed circuit. Fig. 3(a) shows the equivalent circuit of a single transformer used in the multi-core transformer, which consists of a leakage inductance at the primary side \( l_1 \), an iron loss resistance \( R_{\text{core}} \), an armature inductance \( L_n \), an ideal transformer, a leakage inductance at the secondary side \( l_2 \), a resonant capacitor, and a load resistance. It is noted that the number of turns ratio of the single transformer is 1:1. The secondary side is assumed to be a sinusoidal current source provided that a quality factor of resonant circuit is designed to be high. Fig. 3(b) illustrates the flux in the single transformer. The equivalent secondary current \( i' \) whose frequency is the output frequency flows through the primary winding to cancel the flux induced by the load current \( i_{\text{load}} \) at the secondary winding. Therefore, no flux, which has the output frequency component caused by the load current, occurs in the magnetic core. This is the same as the flux due to a differential current is zero since it is cancelled even though the differential current flows in a common mode choke.

Here, the primary current of the multi-core transformer \( i_{\text{trans}} \) is expressed by (1).

\[
i_{\text{trans}} = i_1 + i_{\text{load}} \quad \quad \quad \quad \quad \quad \quad \quad (1)
\]

where \( i_1 \) is the magnetizing current. The magnetizing current has a triangular waveform since the output voltage of the inverter is a square waveform. The flux in the magnetic core is also a triangular waveform whose
fundamental frequency is the switching frequency of the inverter. Therefore, although the flux in the magnetic core includes the output frequency component, the amplitude of the fifth-order component of the flux is one twenty-fifth of the fundamental frequency component. Therefore, the main component of the iron loss which comes from the triangular flux waveform is due to the switching frequency. In addition to this, because the flux induced by the load current is cancelled as previously explained, the iron loss of the output frequency component almost does not occur in the multi-core transformer of the proposed circuit†.

3. Difficulty of Using Mn-Zn for Transformers at 2.5 MHz

3.1 Property of Magnetic Material

Table I shows the specifications of the Mn-Zn ferrite magnetic material (PC40 T51*13*31, TDK Corp.) used in experiment.

Figure 4 shows the measured complex permeability of PC40 (T51*13*31). The detailed measurement method of the complex permeability is described in Appendix. In the frequency below 500 kHz, the complex permeability shows the satisfactory characteristic of soft magnetic materials suitable for cores of transformers because the real part of complex permeability is approximately 2000 which is almost constant, and the imaginary part of complex permeability is low. In addition, it is reported that the real part of complex permeability is sharply decreased in Mn-Zn ferrites because standing electromagnetic waves occur in the magnetic core depending on its size. This phenomenon is known as dimensional resonance (18). Dimensional resonance occurs in lower frequency as the size of magnetic cores is increased, the upper limit of operation frequency of magnetic cores is decreased in large-sized magnetic cores. Furthermore, at 2.5 MHz the real part of complex permeability is negative, and the imaginary part of complex permeability is large. For this reason, Mn-Zn cannot be used at 2.5 MHz.

3.2 Estimation of Iron Loss in Multi-core Transformer

Figure 5 shows the iron loss per volume under the sinusoidal excitation test given by the manufacturer (16). Although the actual waveform of magnetic flux density is triangular, for simplicity in estimating the iron loss, we use this data because triangular waveforms have low harmonic distortion. The iron loss data are plotted to a maximum of 1 MHz in the datasheet. Therefore, the iron loss of the conventional circuit is estimated by extrapolating the iron loss data to 2.5 MHz. In the datasheet, the minimum magnetic flux density is 50 mT. Therefore, in this paper, the iron loss is calculated with a magnetic flux density of 50 mT.

From Fig. 5, the iron loss per volume of PC40 at 50 mT and 500
kHz is 260 kW/m³, which is considered to be capable of being cooled by natural air cooling or forced-air cooling. On the other hand, the iron loss per volume at 50 mT and 2.5 MHz is estimated at 8400 kW/m³, which is considered to be difficult to cool. For this reason, at 2.5 MHz the magnetic flux density for PC40 is required to be designed to be significantly low. However, this is not a practical use for power transformers. That is, it is usually difficult to use Mn-Zn for power transformers at 2.5 MHz. In contrast, in the proposed circuit Mn-Zn can be used since the operation frequency of magnetic core is reduced and the flux caused by the load current with the frequency of 2.5 MHz is not theoretically generated as explained in Section 2.2.

4 Design of Experimental System

4.1 Design of Single-Core Transformer A prototype of the proposed circuit is verified experimentally. GaN-FETs are used for the five-phase inverter. First, in this paper PC40 whose shape is toroid was adopted as an example of a transformer design using Mn-Zn. Next, the iron loss per volume was designed to be 200 – 300 kW/m³ so that the magnetic core can be easily cooled by forced-air cooling. In this paper, T51*13*31 was selected as a PC40 material which satisfies above-mentioned conditions. The number of turns in the primary winding \( N_1 \) is expressed by

\[
N_1 = \frac{V_n}{B_m A_{ef}}
\]

where \( B_m \) is the maximum magnetic flux density, \( A_{ef} \) is the effective cross-sectional area, and \( f \) is the operation frequency. Hence, the number of turns in the primary winding \( N_1 \) is 12 so that the maximum magnetic flux density of multi-core transformer will be designed to be 50 mT at the input voltage of 283 V. On the other hand, the turns ratio of single-core transformer should be basically designed in order to match the output impedance of five-phase inverter and the load. However, the number of turns in the secondary winding \( N_2 \) is simply designed to be 12 for the confirmation of the fundamental operation of the proposed circuit. At the both primary and secondary side, wires of 0.5 mm in diameter is used in an eight-parallel winding to reduce the AC resistance of the wires.

4.2 Measurement of Single-core Transformer Parameters Figure 6 shows the impedance and phase of a single-core transformer used in the multi-core transformer. All single-core transformers were tested. The secondary open-circuit test and a primary short-circuit test were conducted to confirm whether the designed transformer works at the switching frequency of 500 kHz and the output frequency of 2.5 MHz.

Figure 6(a) shows the measurement results of the secondary open-circuit test. Firstly the impedance and phase frequency characteristics of the single-core transformer used for the multi-core transformer are measured under a secondary open-circuit test in order to show that the single-core transformer using PC40 can be used at 500 kHz and cannot be used at 2.5 MHz from the viewpoint of the frequency characteristics of complex permeability shown in Fig. 4. Although the resonance is seen around 1 MHz in Fig. 6(a), the cause of this resonance is not related to parasitic capacitances of the single-core transformer but related to the frequency characteristics of complex permeability shown in Fig. 4 because the phase is not reached to -90 degree. This indicates that the single-core transformer works at the switching frequency of 500 kHz, however, it cannot properly work at 2.5 MHz due to the frequency characteristics of complex permeability.

Figure 6(b) shows the results of the primary short-circuit test. The impedance and phase frequency characteristics of the single-core transformer are measured under a primary short-circuit test in order to show that the leakage inductance converted to the secondary side of the single-core transformer using PC40 can be used as the resonant inductance at 2.5 MHz. The leakage inductance converted to the secondary side is measured by assuming that the magnetizing inductance is sufficiently larger than the leakage inductance. No resonance occurs up to 10 MHz.
therefore, the leakage inductance functions as the resonance inductor at the output frequency of 2.5 MHz.

4.3 Measurement of Multi-core Transformer Parameters

Figure 7 shows the impedance and phase of the multi-core transformer measured from the secondary side when all primary windings are shorted together. Similar to Fig. 6(b), the measured impedance is inductive up to 10 MHz. That is, the leakage inductance of the multi-core transformer also can work at an output frequency of 2.5 MHz. The measured leakage inductance of the multi-core transformer was 3.3 μH at 2.5 MHz.

4.4 Design of Resonant Inductance and Capacitance

First, the quality factor in the resonant circuit $Q$ expressed by (3) is designed to be larger than one at the output power of 650 W so that a sinusoidal current will flow.

$$Q = \frac{1}{R_{\text{load}}} \sqrt{\frac{l_i}{C_r}} \quad \text{·········································· (3)}$$

where $R_{\text{load}}$ is the pure load resistance, $l_i$ is the resonant inductance, and $C_r$ is the resonant capacitance. It is assumed that $R_{\text{load}}$ is designed to be predetermined.

On the other hand, the resonant frequency of the series resonant circuit $f_r$ is designed by the following equation.

$$f_r = \frac{1}{2\pi \sqrt{l_i C_r}} \quad \text{·········································· (4)}$$

Next, a required capacitance of the resonant capacitor for the designed quality factor is calculated with a function of the leakage inductance by transforming (3). Besides, the required capacitance of the resonance capacitor for the designed resonant frequency is calculated with a function of the leakage inductance by transforming (4). The designed resonant frequency is usually lower than the output frequency in order to realize zero voltage switching (ZVS) in the inverter. As a result, a range of the required resonant capacitance which satisfies both the designed resonant frequency and the designed quality factor is found. Consequently, a minimum resonance inductance required for the proposed circuit is found. In this paper, the resonant inductance is realized by only the leakage inductance because the leakage inductance is larger than the minimum resonance inductance required for the proposed circuit. Therefore, no additional resonant inductor is connected.

From the above-mentioned design procedure, experimental condition is as follows: The input voltage $V_\text{in}$ is 283 V. The load resistance $R_{\text{load}}$ is 13.3 Ω. The quality factor is 3.9. The leakage inductance $l_i$ is 3.3 μH. The resonant capacitance is 1246.0 pF. The resonant frequency was designed to be 2.48 MHz lower than the output frequency of 2.5 MHz in order to achieve ZVS.

5. Experimental Verification

Figure 8 (a) shows the U-phase primary voltage and current of the multi-core transformer, and the load voltage and current. The experimental results confirm that the operation frequency of the transformer is 500 kHz, which is one-fifth of 2.5 MHz, whereas the frequency of the load voltage is 2.5 MHz. It is seen that no surge voltage occurs in the inverter output voltage due to ZVS. Moreover, the current that has a 2.5 MHz component flows on the primary side of the transformer in addition to the magnetizing current. However, the magnetic flux of 2.5 MHz is not generated in the PC40 material because the 2.5 MHz component in the primary current of the transformer flows to cancel the magnetic flux induced by the secondary current of the multi-core transformer as explained in Section 2.2.

Figure 8 (b) shows the primary currents of all phases in the
multi-core transformer. It is confirmed that the all currents are not distorted. In addition, it is seen that the phase and magnitude of the all currents is almost same since each transformer was assembled by the same manner. In this prototype, the leakage inductance at the primary side is designed to be smaller than that at the secondary side of the multi-core transformer so that the iron loss of the multi-core transformer will be reduced (19). In addition, the leakage inductance of each transformer is designed to be same (19).

Figure 9(a) shows the visual image of the multi-core transformer. The toroidal core is covered by an electric insulation tape, then the primary winding and secondary winding are wound. Fig. 9(b) and (c) show the thermal pictures of multi-core transformer at five minutes and 90 minutes after the start-up of experiment, respectively. In this experiment, the multi-core transformer is cooled by a fan which is placed in front of the magnetic core in the foreground. Therefore, the temperature of the surface of the magnetic core in the foreground is lower than that of the magnetic core in the background.

Figure 9(d) shows the rise in temperature of the surface of the multi-core transformer. The measuring point a, b, and c are the surface of the magnetic core, the primary winding, and the secondary winding, respectively. The ambient temperature was 24.1 °C. First, temperatures of the primary winding and secondary winding are almost same since the current values are almost same in addition to the specification of windings. Second, at t = 90 minutes, the temperature of the multi-core transformer was saturated. It is confirmed that the rise in temperature on the surface of the magnetic core in the proposed circuit is 37.6 °C which is lower than that of the winding temperatures. The result indicates that the rise in temperature on the surface of the magnetic core is affected by the heat due to the primary winding and secondary winding. As a result, it was experimentally confirmed that the proposed circuit using Mn-Zn ferrite can continuously output 2.5 MHz without the iron loss of multi-core transformer.

6. Conclusion

This paper proposed the 2.5 MHz high-frequency output inverter based on the frequency multiplying technique with the multi-core transformer using Mn-Zn ferrite materials with the upper limit of operation frequency which is lower than the output frequency of 2.5 MHz. First, the operation principle of the proposed circuit was explained. The flux caused by the load current is not generated in the magnetic core because the flux caused by the load current is cancelled by the current which flows through the primary winding in addition to the magnetizing current. Therefore, the iron loss caused by the output frequency is not theoretically generated. Next, the difficulty of using Mn-Zn for transformers at 2.5 MHz was discussed from the viewpoint of not theoretically generated. Next, the difficulty of using Mn-Zn ferrite in high-frequency output inverter at the frequency of 2.5 MHz.

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assumed to be the series circuit consists of the equivalent series resistance and the equivalent series reactance. Taking these into account, the impedance of the toroidal inductor is decreased. As a result, there is a possibility that the toroidal inductor cannot be assumed to be the series circuit consists of the equivalent series resistance and the equivalent series reactance. Taking these into account, the number of turns in the toroidal inductor for the measurement of complex permeability, was designed to be eight in this paper.

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