Performance Analysis of DC-DC Converter with MHz Band Transformer Employing Finite Element Method

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Keywords: DC-DC converter, transformer, finite element method, equivalent circuit

This paper presents the performance analysis method for the DC-DC converter with the MHz band transformer. In this method 3D electromagnetic field analysis employing finite element method (FEM), in which the displacement current is taken into consideration, is coupled with the circuit analysis.

Fig. 1 shows the analyzed prototype model of the MHz band transformer in this study. This model has two rectangular parallelepiped cores (Mn-Zn ferrite) arranged side by side and the winding block. The electric power of 42 V sinusoidal wave is applied to the primary winding, and the load of 50 Ω is connected to secondary winding. Although this transformer can be built up more easily than usual transformers, it has to be operated at high frequency because of having only a few turns of windings.

Fig. 2 shows the comparison of the computed and measured efficiency of the transformer when the operating frequency is varied from 0.1 MHz to 10 MHz. These results show the validity of this computation, and the efficiency of this transformer is pretty low when the operation frequency is less than MHz band, especially less

than 0.5 MHz.

Nextly, the transformer is replaced by the equivalent circuit of the operating frequency from the results of FEM analysis. The equivalent circuit of the transformer is shown in Fig. 3. Finally, performances of DC-DC converter as shown in Fig. 4 are calculated.

Fig. 5 shows the comparison between computed and measured results of waveform of output voltage of the converter when the load is 50 Ω . As shown, the calculated results show good agreement with measured ones.

Fig. 3. The equivalent circuit of the transformer

Fig. 1. MHz band transformer in this study

Fig. 2. Comparison of the computed and measured efficiency

Fig. 4. The equivalent circuit of the DC-DC converter

Fig. 5. Comparison of the load characteristics between calculated and measured results

Performance Analysis of DC-DC Converter with MHz Band Transformer Employing Finite Element Method

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This paper presents the performance analysis method for the DC-DC converter with the MHz band transformer. In this method 3D electromagnetic field analysis employing finite element method (FEM), in which the displacement current is taken into consideration, is coupled with the circuit analysis. The performances of the transformer, such as input/output power and efficiency, are computed, and the validity of this method is confirmed through comparison of the computed and measured results. Furthermore the performances of a DC-DC converter with the transformer are calculated using the equivalent circuit of the transformer obtained from the results of FEM analysis. As the results, it is found that the calculated and measured input/output performances are in good agreement.

Keywords: DC-DC converter, transformer, finite element method, equivalent circuit

1. Introduction

In designing power electronics devices, it is very important to grasp the accurate waveforms of input/output voltage and current in order to estimate the efficiency and the power factor. Therefore, it is useful to study the effective dynamic analysis method through a numerical approach. Authors have presented some methods to analyze comparatively low-frequency transformers using 3-D FEM analysis taking account of external circuits ⁽¹⁾⁽²⁾. But it seems that few papers focused on the numerical method for the MHz band transformer have reported.

This paper describes the analysis method for dynamic performances of the DC-DC converter with the MHz band transformer. Input/output power and efficiency are calculated when the sinusoidal wave voltage is applied, the load is 50 Ω, and operating frequency is varied from 0.1 MHz to 10 MHz. These results show the validity of this computation. Furthermore the performances of a DC-DC converter with the transformer are calculated by the circuit analysis using the equivalent circuit of the transformer obtained from the above FEM analysis. The validity of this method is verified through the comparison with the measured results.

2. Finite Element Analysis of The Transformer

2.1 Analysis Method The fundamental equations of the magnetic field are expressed as follows:

$$\text{rot } \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \dots\dots\dots (1)$$

$$\text{rot } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \dots\dots\dots (2)$$

$$\text{div } \mathbf{B} = 0 \dots\dots\dots (3)$$

$$\text{div } \mathbf{D} = \rho \dots\dots\dots (4)$$

where, $\mathbf{H}$ is magnetic field strength, $\mathbf{J}$ is current density, $\mathbf{D}$ is dielectric flux density, $\mathbf{E}$ is electric field strength, $\mathbf{B}$ is magnetic flux density, ρ is charge density. Material constitution equations are expressed as follows:

$$\mathbf{B} = \mu \mathbf{H} \dots\dots\dots (5)$$

$$\mathbf{D} = \varepsilon \mathbf{E} \dots\dots\dots (6)$$

$$\mathbf{J} = \sigma \mathbf{E} \dots\dots\dots (7)$$

where, μ is magnetic permeability, ε is relative dielectric constant, σ is conductivity. The magnetic flux density $\mathbf{B}$ is expressed as follows by vector potential $\mathbf{A}$.

$$\mathbf{B} = \text{rot } \mathbf{A} \dots\dots\dots (8)$$

The following equation is obtained by substituting equation (5) and (8) into equation (1).

$$\text{rot} \left(\frac{1}{\mu} \text{rot } \mathbf{A} \right) = \text{rot}(\nu \text{rot } \mathbf{A}) = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \dots\dots\dots (9)$$

where, ν is reluctivity. And the following equation is obtained by substituting equation (8) into equation (2).

$$\mathbf{E} = - \left(\frac{\partial \mathbf{A}}{\partial t} + \text{grad } \phi \right) \dots\dots\dots (10)$$

where, ϕ is electric scalar potential.

The fundamental equation of the magnetic field in time domain can be expressed by using equation (7), (9) and (10).

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Fig. 1. MHz Band Transformer in this study

(a) 3-D shape of the transformer

(b) Cross section of the transformer

Fig. 2. Analyzed model

$$\text{rot}(\nu \text{rot } \mathbf{A}) = \mathbf{J}_0 + \mathbf{J}_e + \frac{\partial \mathbf{D}}{\partial t} \dots\dots\dots (11)$$

$$\mathbf{J}_e = -\sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \text{grad } \phi \right) \dots\dots\dots (12)$$

where, $\mathbf{J}_0$ is forced current density, $\mathbf{J}_e$ is eddy current density. In this model, non-linear magnetic materials are not used, then the fundamental equation of the magnetic field can be expressed in frequency domain as follows:

$$\text{rot}(\nu \text{rot } \mathbf{A}) = \mathbf{J}_0 + \mathbf{J}_e + j\omega \mathbf{D} \dots\dots\dots (13)$$

$$\mathbf{J}_e = -\sigma(j\omega \mathbf{A} + \text{grad } \phi) \dots\dots\dots (14)$$

where, ν , $\mathbf{A}$, $\mathbf{J}_0$, $\mathbf{J}_e$ and $\mathbf{D}$ are complex numbers. In this analysis, the displacement current $j\omega \mathbf{D}$ in equation (13) is taken into consideration. ω is the angular frequency.

2.2 Analyzed Model Fig.1 shows the analyzed

Fig. 3. Complex permeability characteristic of Mn-Zn ferrite

(a) Input power

(b) Output power

(c) Efficiency

Fig. 4. Comparison of the performance between computed and measured results

prototype model of the MHz band transformer in this study. This model has two rectangular parallelepiped cores (Mn-Zn ferrite) arranged side by side and the winding block. Fig. 2 shows the basic construction of the transformer. The cores A and B are made of Mn-Zn ferrite, which conductivity and the relative dielectric constant are 5 S/m and 12, respectively. The characteristics of the relative permeability versus frequency of Mn-Zn ferrite are shown in Fig. 3. The winding block consists of two turns of primary and the secondary windings, respectively. They are made of copper bar which conductivity is 5.8×10^7 S/m, and are inserted into the holes of cores. The electric power of 42 V sinusoidal wave is applied to the primary winding, and the load of 50Ω is connected to secondary winding. Although this transformer can be built up more easily than usual transformers, it has to be operated at high frequency because of having only a few turns of windings. The maximum flux density in the core is less than 1mT under the condition mentioned above, therefore the linear analysis is employed using the complex permeability shown in Fig. 3.

2.3 Performances of MHz Band Transformer The input power is calculated from the current peak and the phase difference between the voltage and the current. The output power is calculated from the current of the load. Fig. 4 shows the comparison of the computed and measured input/output power and efficiency when the applied voltage is 42 V sinusoidal wave, the load is 50Ω , and operating frequency is varied from 0.1 MHz to 10 MHz. These results show the validity of this computation, and the efficiency of this transformer is pretty low when the operation frequency is less than 1 MHz, especially less than 0.5 MHz.

3. Circuit Simulation of DC-DC Converter

3.1 Calculation of Circuit Parameters When this transformer is applied to a DC-DC converter, it is operated under the condition of the rectangular wave voltage. Then, it becomes difficult to apply this frequency domain analysis. In this method, the transformer is replaced by the equivalent circuit of the operating frequency from the results of FEM analysis, and the output performances of DC-DC converter are calculated by the circuit simulation. The line capacitance of the primary and secondary windings are negligible because of a few turns of windings, however, capacitance between these windings should be taken into consideration. The equivalent circuit of the transformer is shown in Fig. 5. The inductances and resistances are calculated from the results of FEM analysis using short-circuit and open-circuit models of the transformer, in which the load is replaced by copper bar for the short-circuit model, and the load is removed for open-circuit model. The resistances and the inductances are

Fig. 5. The equivalent circuit of the transformer

obtained from the results of impedance calculation of these models. The capacitance between windings is calculated from the following equation.

$$C = \epsilon_0 d / S \dots \dots \dots (15)$$

where, ϵ_0 is dielectric constant of vacuum, S and d are the facing area and the distance between primary and secondary windings.

3.2 Validity of the Equivalent Circuit of the Transformer The load characteristics of the transformer are calculated in order to confirm the validity of the equivalent circuit. Fig. 6 shows the comparison of the calculated and measured input/output power and efficiency when the applied

Fig. 6. Comparison of the load characteristics of the transformer between calculated and measured results

Fig. 7. The equivalent circuit of the DC-DC converter

Fig. 8. The equivalent circuit of the MOSFET

(a) Input Voltage of the transformer

(b) Input current of the transformer

(c) Output voltage of the converter

Fig. 9. Comparison of waveforms operated at 1 MHz between calculated results and measured results

voltage is 42 V sinusoidal wave, the operating frequency is 1 MHz, and the load is varied from 10 Ω to 255 Ω. These results show that the obtained equivalent circuit can be applied to all models from the light load to heavy load.

3.3 Performance Analysis of DC-DC Converter

The performances of DC-DC converter shown in Fig. 7 are calculated according to the procedure mentioned above. In Fig. 7, the reset circuit is added to primary circuit in order to prevent magnetic deviation in the core, and the operating frequency of the converter is synchronized with switching frequency of the FET. The input voltage of the transformer V_1 is rectangular waveform. Diode D1, D2 and D3 have the

Fig. 10. Comparison of the load characteristics between calculated and measured results

on-resistance R_{on} of 250 mΩ, the off-resistance R_{off} of 2 MΩ, and the threshold-voltage V_{th} of 0.3 V, respectively. FET is replaced by the equivalent circuit shown in Fig. 8. FET has R_{on} of 1 Ω, R_{off} of 1.6 MΩ, V_{th} of 3.47 V, and D4 has R_{on} of 290 mΩ, R_{off} of 1.6 MΩ and V_{th} of 0.6 V. Fig. 9 shows the comparison between computed and measured results of waveforms of input voltage/current of the transformer and output voltage of the converter when the load is 50 Ω.

As shown, these calculated results show good agreement with measured ones although measured input voltage gradually drops because the on-resistance R_{on} of FET increases caused by the heat from FET. In addition, when the load is varied from 50 Ω to 1000 Ω, the output voltage versus current is calculated. As the results, it is found that the calculated and measured results are in good agreement as shown in Fig. 10. It can be seen from this figure, this converter is operated in discontinuity mode when the light load is applied.

4. Conclusions

This paper presented the performance analysis method for the DC-DC converter with the MHz band transformer. In this method, 3D electromagnetic field analysis employing finite element method (FEM), in which the displacement current is taken into consideration, is coupled with the circuit analysis. The validity of this method was confirmed through comparison of the computed and measured results when the performances of the transformer were computed. Furthermore the performances of the DC-DC converter with the transformer were calculated using the equivalent circuit of the transformer obtained from the results of FEM analysis. As the results, it was found that the calculated and measured input/output performances were in good agreement.

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