Research on the Verification Method of Flyback High-Frequency Transformer (FHFT) Based on Field-Circuit Coupling Model

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Abstract. In view of the current status of research on verification of the correctness and effectiveness of FHFT design, a field-circuit coupling based FHFT design verification method is proposed in this paper. This paper proposes a FHFT design verification method based on field-circuit coupling. The steps of FHFT verification using field-circuit coupling method are elaborated in detail. A three-dimensional physical model of FHFT based on AP method is established. The calculation of FHFT flux density and the verifying of transformer output waveform are completed by using the field-circuit coupling method of alternating iteration of non-linear magnetic field solution and circuit. On the basis of completing the flux density calculation, the field circuit coupling method is used to verify the output waveform of the transformer. It is found that the output waveform of FHFT is not an ideal square wave, but has some distortion, which is caused by neglecting the leakage inductance of transformer in the design process. This shows that the influence of transformer leakage inductance is very important and should be paid attention to.

1 The introduction

Flyback high-frequency transformer has the functions of energy transmission, electrical isolation, energy storage, and lifting voltage, etc. Its performance directly affects the performance of the whole inverter. Therefore, it is very important to verify the correctness and effectiveness of the design method of flyback high-frequency transformer.[1]

For the design of flyback high-frequency transformer, whether its performance parameters can meet the design requirements is the key. Therefore, it is very important to design and verify flyback high-frequency transformer. However, few studies have been made on the calibration method of design correctness of flyback high-frequency transformer.[2] This paper takes the design of flyback high-frequency transformer for vacuum degree measurement as an example, and elaborates the steps of verifying flyback high-frequency transformer with field-circuit coupling method. Firstly, a three-dimensional physical model of flyback high-frequency transformer for vacuum measurement based on AP method is established. Secondly, the principle of field-path coupling and the steps to calculate the transformer magnetic flux using field-path coupling method are described, including the establishment of the calculation model, the setting of material parameters, mesh generation,
excitation and the determination of the solution algorithm. Based on the magnetic flux density calculation, the output waveform of the transformer is checked by the field-circuit coupling method. Finally, the results are analyzed.

2 Design of single-ended flyback high frequency transformer

Single-ended flyback transformer is also called inductance energy-storage type transformer. Since there is only one switch tube in the topology structure, the homologous ends of the primary and secondary sides of the transformer are reversed, so it is called single-ended flyback transformer\(^3\). Flux design of flyback high frequency transformer is the key\(^4\).

According to the calculation results, EI30 magnetic core is selected. Relevant parameters are shown in table 1.

| The name of the parameter | The name of the parameter |
|--------------------------|--------------------------|
| material                | PC40 ferrite             |
| model                   | EI30                     |
| \(I_p\)                 | 0.4 (A)                  |
| \(I_{avg}\)             | 0.08 (A)                 |
| \(I_1\)                 | 0.15 (A)                 |
| \(I_2\)                 | 0.011 (A)                |
| \(L_p\)                 | 14 mh                    |
| \(L_s\)                 | 2.74 H.                  |
| The para-primary turns ratio is \(N\) | 14 |
| \(L_g\)                 | 0.176 cm                 |
| Number of primary turns | 61                       |
| Number of turns of secondary coil | 820 |
| Primary conductor diameter | The 0.219 mm |
| Secondary conductor diameter | The 0.058 mm |
| Number of primary loops | 2                        |
| Number of secondary loops | 13                       |

3 Calibration method for design of flyback high-frequency transformers for vacuum

Flyback high-frequency transformer calibration is mainly used to verify the magnetic flux and output waveform. Therefore, the paper establishes the three-dimensional finite element calculation model of the excitation high-frequency transformer, and adopts the field-circuit coupling method to verify the output waveform.

3.1 Flyback high-frequency transformer calculation model based on field-path coupling

3.1.1 The three dimensional computing model

The governing equation applied to the three-dimensional magnetic field is as follows:

\[
\frac{\partial}{\partial x} \left( \nu \frac{\partial A}{\partial x} \right) + \frac{\partial}{\partial y} \left( \nu \frac{\partial A}{\partial y} \right) + \frac{\partial}{\partial z} \left( \nu \frac{\partial A}{\partial z} \right) = -\mathbf{J}_s + j\omega \sigma \mathbf{A}
\]

where: \(\nu\) is the magnetic resistivity of the medium.
3.1.2 Boundary conditions

In order to make the calculation closer to reality, insulation conditions were applied to the outer surface of the coil module and the iron core module during the checking process. The specific mathematical formula was expressed as follows:

\[ n \times A = 0 \]  

(2)

3.1.3 Establishment of calculation model

The relevant parameters are set in the finite element method, and the modeling of transformer 3d model is completed[5]. The structural size parameters of the transformer model are shown in table 2.

*Table 2.* Dimension parameter of flyback high-frequency transformer is modeled by vacuum degree.

| The name of the structure | The numerical |
|--------------------------|--------------|
| Magnetic core material   | Soft magnetic ferrite (PC40) |
| Magnetic core shape      | EI30 type magnetic core |
| Magnetic core size       | 30 * 26.8 * 10.7 (mm) |
| Number of primary turns  | 61 (turn) |
| Number of turns of secondary coil | 820 (turn) |
| Input excitation voltage | AC 279 (V) |

The physical parameters of the model are shown in table 3.

*Table 3.* Material parameters.

| material  | Relative permeability | Relative permittivity | Conductivity (S/m) |
|-----------|-----------------------|-----------------------|--------------------|
| air       | 1                     | 1                     | 0                  |
| copper    | 1                     | 1                     | 5.7 x 10^7         |

According to the transformer parameters in table 3 and the material parameters in table 3, the calculation model of high-frequency transformer is established.

3.2 Realization of field-path coupling method

The realization of the field-circuit coupling method is that the three-dimensional model of the transformer is treated as "field" and calculated by finite element method. At the same time, the winding is used as a component and applied voltage to form a circuit for circuit analysis, in which the voltage can be described by inductive potential (a function of magnetic field) and external circuit parameters. The calculation is constrained by the change of electromagnetic field and the topology of the external circuit at the same time. The solution of the nonlinear magnetic field and the circuit calculation are realized through alternating iteration to achieve field-path coupling.

The circuit model of the transformer in the finite element is shown in fig 1.
According to the transformer principle, the induced voltage $V_{in}$ is proportional to the change rate of its magnetic field, and the relationship between it and the magnetic flux $\Phi$ and the number of turns of the coil $N$ are shown as follows.

$$V_{in} = -N \frac{d\Phi}{dt} \quad (3)$$

As shown in fig 2, which is more in line with the actual working principle of the transformer, so as to ensure the checking accuracy.

### 3.3 Analysis of check results

#### 3.3.1 Magnetic flux density check calculation

The distribution of magnetic flux inside the transformer is directional. The distribution of magnetic flux density inside the transformer can be clearly seen from fig 3. In order to clearly show its distribution characteristics, profile images were selected for analysis.

It can be seen from the above figure that the magnetic flux density is mainly distributed on the magnet, and the magnetic flux density is large at the corner (the red region in the figure), while the magnetic flux density is small in the air region. Figure 4 shows that: during normal operation, the magnetic induction intensity at different positions of the high-frequency transformer does not exceed the maximum allowable magnetic induction intensity of 0.24t. Through the calculation of the magnetic field, the correctness of the transformer design is further verified.
3.3.2 Analysis of output voltage

On the basis of magnetic flux checking, the voltage waveform is checked. The input voltage is shown in fig 5, and the output voltage waveform is shown in fig 6.

![Figure 5. Input voltage waveforms](image1.png)

![Figure 6. Input and output voltage of waveforms.](image2.png)

In the design of flyback high frequency transformer, the primary guarantee is that the output voltage meets the design requirements. Fig 6 shows that the output of the transformer reaches 2.5kv and meets the design requirements.

Output voltage waveform in fig 6 along have certain rising or falling, this is due to the leakage inductance of the high voltage transformer winding, winding and high voltage wire between the distributed capacitance, the presence of these parasitic parameters, the front is steep square wave to the transformer, the transformer will be complex oscillation process, thus formed certain rising and falling. Therefore, the existence of leakage inductance of transformer has a great influence on the output waveform of flyback high-frequency transformer, and the influence of leakage inductance on the output waveform of flyback high-frequency transformer can only be found through the verification of waveform. The value of capacitance and resistance should not be too large. The output pulse waveform can be made more standard by selecting the appropriate resistance capacity structure.[6]

4 Conclusion

This paper establishes a three-dimensional model of flyback high frequency transformer based on field-path coupling. Taking the design of flyback high-frequency transformer for vacuum degree as an example, the calibration method is introduced in detail, and the following conclusions are obtained:

1) the field-path coupling method can correctly and efficiently verify the key parameters of flyback high-frequency transformer design—whether the magnetic flux density can meet the requirements. For flyback high-frequency transformers for vacuum degree, the verification results show that the maximum magnetic flux density does not exceed the maximum working magnetic flux density of 0.24t, which meets the design requirements.

2) the field-path coupling method can also verify the output voltage amplitude and waveform of the flyback high-frequency transformer. The calibration results show that the output voltage of the flyback high-frequency transformer reaches 2500V, which meets the design requirements.

3) the waveform calibration results of the flyback high-frequency transformer show that the waveform is not ideal. This is because the transformer leakage caused by the existence of measures to be taken. This can only be found through the verification of the problem.
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