A method of designing high-voltage power using transformer parameters

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Abstract: PWM high-frequency high-voltage power has different ratio in light load and heavy load; often seriously affect the equipment's indicators and reliability. In order to find out the cause of this phenomenon and avoid it well in the design, it is necessary to understand the distribution parameters of high-frequency high-voltage transformers and the effect of high-voltage rectifier circuits on circuit gain.

1. Overview

The design difficulties of high-frequency high-voltage DC power supply are mainly reflected in the design of high-frequency transformers. The leakage and distribution capacitor influence of high frequency ratio transformer becomes very obvious, which has a great influence on the design of circuit parameters. The distribution parameters of transformers are mainly leakage and distribution capacitors. Distribution capacitors are mainly inter-layer capacitors and inter-layer capacitors.

In this paper, the distribution parameters of transformers as part of the resonant parameters are used directly, and a wide range of design methods are proposed. This method also ensures that the DC gain of the high voltage power supply is in the appropriate range between 1 and 2, and has strong engineering application value. Finally, the effectiveness of this method is verified by simulation and experiment.

2. The introduction of basic methods

2.1. Get the distribution parameters

First of all, it is necessary to obtain the distribution parameters of high frequency transformers more accurately, the high-frequency transformer winding distribution parameter model that takes into account the distribution parameters is shown in Figure 1.

![Figure 1. High frequency transformer distribution parameter model](image-url)
Figure 1 shows that T is an ideal air core transformer with no distribution parameters. L1, L2 is the leakage of the original and side edges of the transformer, C1 is the equivalent distribution capacitor of the original edge winding; C2 is the equivalent distribution capacitor for the side winding, R1, R2 is the resistance of the transformer's original and sub-edge windings. The sub-edge current of a typical high-voltage transformer is very small relative to the original side, so R2, L2 is negligible. The number of turns of the original edge winding is relatively small relative to the side, and R1 is negligible. The simplified model of Figure 2 is obtained by folding the equivalent distribution capacitor of the side winding to the original edge.

\begin{equation}
C_2' = n^2 \times C_2 = n \times C_1
\end{equation}

The equivalent of a \( \pi \) type two-port network in figure 2 dotted wireframe is a T-type two-port network, as shown in Figure 3.

Also because the ideal air core transformer excitation electromagnetism is very large, excitation current is negligible, empty load time map 3 can be equivalent to Figure 4.

2.2. Get the equivalent model

For high-voltage DC power supply, in order to ensure the stability of the output voltage and reduce the ripple amplitude of the output voltage, the transformer output side uses a large capacitor as a filter. In general, there is \( n^2C_o >> C_p \), so the output voltage \( U_o \) remains the same in a stable state. Due to the presence of an output filter capacitor, the rectifier diode is only on when \( U_p > U_o/n \), and clamp \( U_p \) to \( U_o/n \) when the rectifier diode is on meanwhile shuts off when the current \( i_L \) crosses zero.
Steady-state analysis based on this nonlinear characteristic has been studied in many literatures, and the following are directly applied: [1,2,3,4]

The boost transformer, Rectifier Bridge, filter, and load are equivalent to R-C in-union networks, so that Figure 1 is equivalent to the circuit model shown in Figure 5.

Figure 5. High-frequency transformer model

In Figure 5, C1 is a series capacitor, L1 is primary plus secondary equivalent leakage, Lm is primary inductor, Cp is a secondary equivalent distribution capacitor, and Re and Ce are secondary output equivalent resistors and capacitors. If C2=Cp+Ce, Figure 5 can be further simplified to the model shown in Figure 6:

Figure 6. High-frequency transformer equivalent network model

Suppose the rectation angle of the diode is α:

\[ R_e = \frac{\lambda_1^2}{2n^2} R_o \]  
\[ C_e = \frac{2n^2}{\omega R_o \lambda_1^2} \tan[\theta] \]  
\[ \lambda_1 = \frac{1}{\pi} \sqrt{(1-\cos\alpha)^2 + \left(\frac{\sin\alpha + \alpha - \pi}{1 + \cos\alpha} - \sin\alpha\right)^2} \]  
\[ \theta = \arctan \frac{\sin\alpha + \alpha - \pi}{1 + \cos\alpha} - \arctan \frac{\cos 2\alpha - 1}{2\alpha - \sin 2\alpha} \]  
\[ Z_1 = j\omega L_1 + \frac{1}{j\omega C_1} \]  
\[ Z_2 = \frac{1}{j\omega L_2} + j\omega C_2 + \frac{1}{R_e} \]  
\[ M_1 = \frac{Z_2}{Z_1 + Z_2} \]  
\[ K_{DC} = \frac{1}{\lambda_1} |M_1| \frac{4}{\pi} \] 

2.3. The selection of circuit parameters is calculated

The parameter design in this paper is based on resonance, because the secondary high-voltage waveform spike is small when the circuit is resonant, and the working reliability is greatly increased for the secondary high-voltage rectifier diode. The design of resonance is defined as circuit resonance...
as a reference: that is, the virtual part of the equivalent network is zero, the equivalent circuit is represented as a pure resistance, at this time when the frequency of the input signal is the same as the inherent resonance frequency, the circuit resonance occurs. Therefore, after obtaining the expression of the equivalent model, it is convenient to solve the required parameters. L1 and C1 are determined by solving the two equations of KDC=1 and the imaginary part of the equivalent model is zero.

3. The example design

Using the above design method, a DC high voltage power supply has been developed. The power supply requires an input of DC 360V and an output of 6kV/0.5A.

First of all, under the guidance of the design principle of minimizing the distribution capacitance, choose the way of multi-times rectify to reduce the number of secondary windings. Consider of the combined output current, in this case, in the form of a circuit with a second-order four-time voltage rectify. The circuit diagram shows figure 7:

![Figure 7. Rectified circuit diagram](image)

Here's the calculation process:

\[ f_s = 84kHz \; ; \; w = 1\% \; ; \; V_{out} = 6kV \; ; \; I_{out} = 0.5A \; ; \; n = 2 \; ; \]

\[ C_{by} = \frac{I_{out} \times n \times (n+1)}{2f_s \times V_{out} \times w} = 2.976 \times 10^{-7}F \]  \hspace{1cm} (10)

\[ V_{out} + \frac{I_{out}}{f_s \times C_{by}} \times \frac{(4 \times n^3 + 3 \times n^2 + 2 \times n)}{6} = 1.54 \times 10^3 V \]  \hspace{1cm} (11)

The output voltage drops:

\[ \frac{I_{out}}{f_s \times C_{by}} \times \frac{(4 \times n^3 + 3 \times n^2 + 2 \times n)}{6} = 160V \]  \hspace{1cm} (12)

\[ V_{out} = 6kV \; ; \; I_{out} = 0.5A \; ; \; n = 5 \; ; \; \omega = 2 \times \pi \times f_s = 5.278 \times 10^5 \times \frac{1}{s} \; ; \; L_2 = Lm \; ; C_w = 0.1 \times 10^{-6}F \]

\[ C_p = 100 \times 10^{-9}F \; ; \; R_0 = \frac{V_{out}}{I_{out}} = 1.2 \times 10^4\Omega \; ; \; Lm = 0.1mH \; ; \; Lr = 11\mu H \; ; \; C_1 = 150 \times 10^{-9}F \]

\[ \alpha = 2 \times a \tan \left( \sqrt{\frac{\pi \times n^2}{2 \times \omega \times C_p \times R_0}} \right) = 0.488 \]  \hspace{1cm} (13)

\[ \lambda = \frac{2}{\pi} \sqrt{(1 - \cos \alpha) + \left( \frac{\sin \alpha + \alpha - \pi}{1 + \cos \alpha} \right)^2} = 1.04 \]  \hspace{1cm} (14)

\[ \theta = a \tan \left[ \frac{1 + \cos \alpha}{1 - \cos \alpha} \right] - a \tan \left( \frac{\cos(2\alpha) - 1}{2\alpha - \sin(2\alpha)} \right) = -0.253 \]  \hspace{1cm} (15)
\[ C_1 = \frac{2 \times n^2}{\omega \times R_0 \times L_0^2} \times \tan(\theta) = 1.886 \times 10^{-9} \text{F} \]  
(16)

\[ C_2 = C_1 + C_p + C_w = 2.019 \times 10^{-7} \text{F} \]  
(17)

\[ L_1 = L_r + \frac{L_r \times L_m}{L_r + L_m} = 2.091 \times 10^{-5} \text{H} \]  
(18)

\[ Z_1 = j \times \omega \times L_1 + \frac{1}{j \times \omega \times C_i} = -1.595 \text{\Omega} \]  
(19)

\[ Z_2 = \frac{1}{j \times \omega \times L_2 + j \times \omega \times C_2 + \frac{1}{\text{Re}}} = 0.508 - 11.392i \text{\Omega} \]  
(20)

\[ M_1 = \frac{Z_2}{Z_1 + Z_2} = 0.877 + 4.797 \times 10^{-3}i \]  
(21)

So,

\[ |M_1| = 0.877 \]  
(22)

\[ KDC = \frac{1}{\lambda_1} \times |M_1| \times \frac{4}{\pi} = 1.074 \]  
(23)

The Saber simulation circuit diagram is shown in Figure 8:

![Figure 8. Simulation circuit diagram](image)

The primary use of full bridge series resonant circuit and the secondary uses a 2nd-order, four-time rectified circuit. The simulation input and output waveforms are shown in Figure 9:

![Figure 9. Simulates the input and output waveforms](image)

The experimental test transformer input waveform is shown in Figure 10:

![Figure 10. Input waveform](image)
Figure 10. Transformer input waveforms

As can be seen from the waveform in Figure 10, the circuit is working in a resonant state.

Figure 11. Thermal image of the switching transistor

According to the thermal image in Figure 11, it can be intuitively observed that the thermal distribution of the switch tube meets the expected requirements.

4. Conclusion

In this paper, a design method is proposed to consider the high voltage DC power resonance parameters of transformer distribution parameters; a simple model for easy engineering applications is established. The model is used to obtain the suitable circuit parameters by solving the equation, and using this method, a high-voltage DC power supply is developed. The effectiveness of the method is proved by the example design. This method not only facilitates the design of the resonant parameters of the high-voltage large DC power supply, but also solves the problem of the large change of the air load gain of the high-voltage power supply; especially for the high-voltage DC power supply design of pulse width modulation has a great reference value.

References

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