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Loss Calculation and Optimization Design of High Frequency Transformer

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Abstract: In this paper, the magnetization and loss properties are analyzed and compared of topical magnetic materials. The calculation methods are studied for the losses of the core and windings of the High Frequency Transformer (HFT). Based on the evaluation of the temperature increment, an optimization method is presented for the design of HFT. Finally, the losses of a test model of HFT is calculated and the results are compared with those tested.

Keywords: High Frequency Transformer, Magnetic Materials, Loss, Optimization

1. Introduction

In power electronic devices, such as DC/DC converter and solid state transformer, the operational frequencies of the transformers are chosen from several hundred Hz to several tens kHz in order to decrease their volumes and weights. This kind of transformers is called as High Frequency Transformer (HFT). The magnetization and loss mechanism of magnetic materials are related with the microscopic magnetization processes. In engineering application, the losses of soft magnetic material can usually be divided in three parts: eddy current loss, hysteresis loss and excess loss [1]. The Steinmetz formula is widely used to calculate the loss of magnetic core of transformer [2]. The losses of windings of high frequency transformer are related with the operation frequency, and the coefficient of alternative current resistance is used to reflect the skin effect and the proximity effect [3].

In this paper, the magnetization and loss properties are analyzed and compared of topical magnetic materials. The calculation methods of the losses of the core and windings of the HFT are analyzed. An optimization method is presented for the design of HFT. The losses of a test model of HFT is calculated and the results are compared with those tested.

2. Magnetization and Loss Properties of Topical Magnetic Materials

2.1. Silicon Steel Sheets

The superiorities of silicon steel sheets include: high saturation flux density, high stacking factor, high mechanical strength, good ductility, easy to cut, and low price, which let silicon steel sheets popularly used as the basic elements of lamination core of power transformer. But the eddy current and hysteresis losses of silicon steel sheets increase quickly with the increase of operation frequency, even if the sheets are ultrathin strips.

2.2. Amorphous Alloys

Amorphous alloys are also called as metallic glasses. When amorphous alloys are cooled from the liquid state and solidified as noncrystalline materials whose cooling rate is estimated to be in the range 10^5–10^6K/sec. The ribbons of amorphous alloys are usually a few millimeters wide, 25–35 nm thick, and meters to kilometers in length. The losses of amorphous alloys for unit volume are much lower than silicon steel sheets, especially in high frequencies. Therefore, amorphous alloys are usually chosen as the magnetic material for high frequency small capacity transformers and distribution power transformers. Maximum saturation magnetization is in the range 1.5–1.9 T, which is much larger than ferrites. Based on the design principle of transformer, rising the working flux density of the transformer core can decrease the turn number of the windings, and further the volume and weight of the high frequency transformer.

2.3. Nanocrystalline Alloys

A related class of nanocrystalline alloys is made by adding small amounts of Cu and Nb to an Fe–Si–B amorphous alloy. The most-studied composition is Fe74Si15B7Cu1Nb3. The Cu is believed to enhance nucleation of crystallites and the Nb to inhibit their growth. The saturation flux density of nanocrystalline alloys is high as amorphous alloys, and the high frequencies losses of nanocrystalline alloys for unit volume are lower than amorphous alloys. The price for unit mass of nanocrystalline alloys is so much higher than amorphous alloys that the material has not been applied in industry. In other hand, because the material is extremely brittle, it is difficult to manufacture magnetic core of nanocrystalline alloys with gaps.

2.4. Soft Ferrites

Ferrites have good properties of high frequencies losses. As a soft magnetic material, ferrites are widely used in small high frequency switching power supply, in which the operation frequency is from several kHz to several MHz. The saturation flux density of ferrites is lower as 0.2T so that the operation frequency chosen must be higher to make up the deficiency and lower the turn number of the windings of the transformer. Because ferrites are farinose, and unfavorable machining, the cores of ferrites are annular or closed UU shape without gaps.

2.5. Optimized Magnetic Material for High Frequency Transformer

The loss properties of silicon steel sheets, amorphous alloys, nanocrystalline alloys, and soft ferrites in 10 kHz and 50 kHz are shown in Fig.1. Loss properties and saturation flux densities of four magnetic core of silicon steel sheets, amorphous alloys, nanocrystalline alloys, and soft ferrites, are tested and listed in table 1. The saturation flux densities, losses for unit volume, machining properiesy and prices for unit mass are the main factors to choose magnetic material for high frequency transformers. From Fig.1 and table 1, it can be seen that the optimized magnetic materials are amorphous alloys or nanocrystalline alloys for high frequency transformer with several kHz operation frequency.

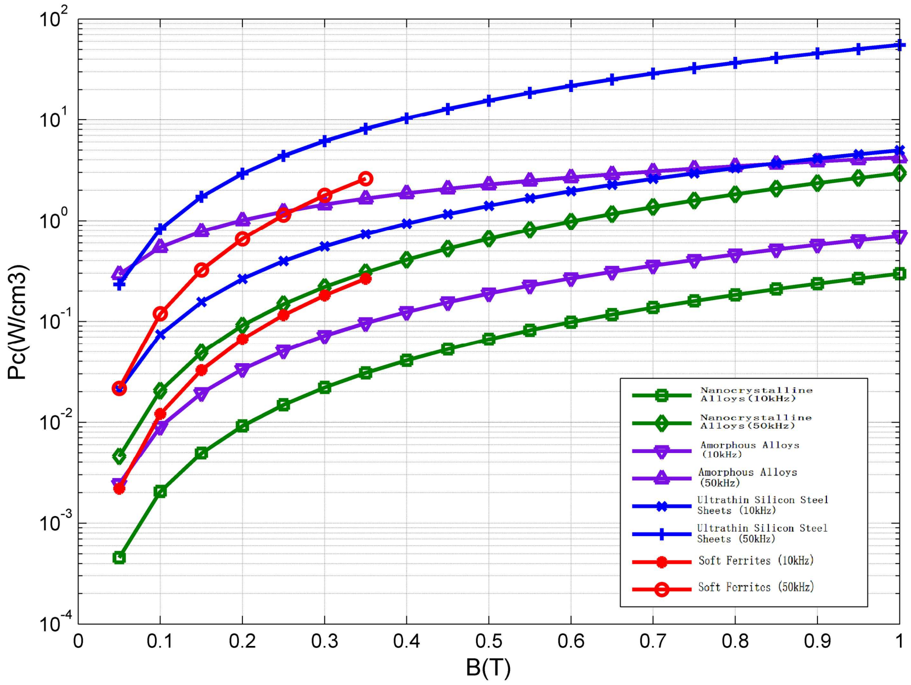

Figure 1. *Loss properties of ultrathin silicon steel sheets, amorphous alloys, nanocrystalline alloys, and soft ferrites.*

Table 1. *Loss properties and saturation flux densities of four magnetic cores.*

Magnetic material	**Saturation flux densities (T)**	**Loss properties ([W/cm3])**
Ferrites	0.35T	P_c=0.1334$B^{2.464}$[T]$f^{1.422}$[kHz]
amorphous alloys	1.2T	P_c=0.0536$B^{1.891}$[T]$f^{1.117}$[kHz]
nanocrystalline alloys	1.3T	P_c=0.0111 $B^{2.161}$[T]$f^{1.428}$[kHz]
ultrathin silicon steel sheets	1.5T	P_c=0.1593$B^{1.827}$[T]$f^{1.496}$[kHz]

3. Losses of High Frequency Transformer

3.1. Loss of Magnetic Core

Usually, losses of magnetic core can be divided in three parts: eddy current loss, hysteresis loss and excess loss. The losses of magnetic core per unit mass can be calculated by [1]:

$$P_c = C_h B_m^{\alpha} f + C_e B_m^2 f^2 + C_{ex} B_m^{1.5} f^{1.5} \tag{1}$$

where C_h, C_e, and C_{ex} are the coefficients of eddy current loss, hysteresis loss and excess loss, respectively. f is the operation frequency of high frequency transformer, and B_m is the maximum magnetic flux density of the core. α is an undetermined index, which is related with specified magnetic material. Another reduced core loss calculation formula is as follows [2]

$$P_c = C_w k B_m^{\alpha} f^{\beta} \tag{2}$$

where C_w is the coefficients related with the waveform of the magnetic flux density, 1 for sinusoidal wave, $\pi/4$ for square wave, and 2/3 for triangle wave. k, α and β are undetermined indexes related with specified magnetic material. (2) is also called Steinmetz formula.

3.2. Losses of the Windings

The loss of winding of transformer can be calculated by:

$$P_w = k_r R_{DC} I_{rms}^2 \tag{3}$$

where R_{DC} is the direct current resistance of the winding, and I_{rms} is the root mean square current. k_r ($=R_{AC}/R_{DC}$) is the coefficient of alternative current resistance, which can be expressed as follows [3]:

$$\begin{aligned} k_r(X,m) = X[&\frac{\sinh(2X)+\sin(2X)}{\cosh(2X)-\cos(2X)} \\ &+\frac{2(m^2-1)}{3}\frac{\sinh(X)-\sin(X)}{\cosh(X)+\cos(X)}] \end{aligned} \tag{4}$$

where m is the number of layers of the winding, and $X = \frac{h_c}{0.071\sqrt{f}}$, in which h_c is the thickness of the conductor wires.

3.3. A Model of High Frequency Transformer

A model of high frequency transformer is made and shown in Fig.2, whose basic parameters are listed in table 2. The zero-load losses of the transformer for different frequencies are tested that can be used to represented the losses of core. The calculation formula of loss of core is obtained by means of the tested data, and it is as follows:

$$P_c = 0.00354 B_m^{1.75} f^{1.527} \tag{5}$$

Table 2. *Basic parameters of the model of high frequency transformer.*

Magnetic material	Saturation flux densities (T)	Voltages of windings (V)	Frequency (Hz)	Capacity (kVA)
0.3mm silicon steel sheets	0.7	560/160	400	1.5

The calculated and test losses of core are listed in table 3. The calculated and test losses of windings are listed in table 4. It can be seen from table 3-4 that the errors are small between the calculated and the tested losses of the core and windings.

Figure 2. *Model of high frequency transformer.*

Table 3. *Calculated and test losses of core.*

f (Hz)	Calculated *Pc* (W)	Tested *Pc* (W)	Error(%)
50	0.740	0.7	5.71
60	0.935	0.9	3.89
100	1.900	2.0	-5.00
200	5.304	5.5	-3.56
300	10.470	10.35	1.15

Table 4. *Calculated and test losses of windings.*

f (Hz)	Calculated *Pw* (W)	Tested *Pw* (W)	Error(%)
50	32.5	31.05	4.67
60	32.5	31.05	4.67
100	32.8	31.25	4.96
200	33.3	32.68	1.90
300	35.3	35.10	0.57
400	38.2	38.13	0.18

4. Optimization Design of High Frequency Transformer

One of the optimization design objects of high frequency transformer is to determine the optimum magnetic flux density B_{opt} corresponding to the minimum total loss P_t of the transformer and the determined operation frequency. Let the derivative of the total loss P_t to the magnetic flux density B equal to zero, that is,

$$\frac{dP_t}{dB} = \frac{dP_c}{dB} + \frac{dP_w}{dB} = 0 \tag{6}$$

We can obtained the optimum magnetic flux density B_{opt} as:

$$B_{opt}^{\beta+1} = [\boldsymbol{K}_1\boldsymbol{U}_{in} \cdot 10^4 \cdot \boldsymbol{MLT}\boldsymbol{\rho}_1\boldsymbol{I}_1^2 + \boldsymbol{K}_2\boldsymbol{U}_{out} \cdot 10^4 \cdot \boldsymbol{MLT} \cdot \boldsymbol{\rho}\boldsymbol{I}_2^2] / 4.44\boldsymbol{A}_c\boldsymbol{f}^{\alpha+1}\boldsymbol{k}\boldsymbol{\beta}\boldsymbol{V}_c \quad (7)$$

where k, α and β are the indexes related with specified magnetic material and the same as that in (2). U_{in} and U_{out} are the voltages of the primary winding and the secondary winding, respectively. I_1 and I_2 are the currents of the primary winding and the secondary winding, respectively. V_c and A_c are the volume and across area of the magnetic core, respectively. K_1 and K_2 are the coefficient of alternative current resistance of the primary winding and the secondary winding, respectively. MLT is the average turn length of the windings and ρ is the resistivity of conductor of of the windings.

For one kind of amorphous alloys, the calculation formula of the loss of magnetic core is: $P_c(\text{W/cm}^3)=0.0306B^{1.74}f(kHz)^{1.51}$. The optimization design results of a 10 kVA high frequency transformer are shown in table 5. For one kind of nanocrystalline alloys, the calculation formula of the loss of magnetic core is: $P_c(\text{W/cm}^3)=0.008B^{1.982}f(kHz)^{1.621}$. The optimization design results of a 10 kVA high frequency transformer are shown in table 6.

5. Conclusions

Based on the study of the paper, we obtained the following conclusions:

(1) For the large capacity high frequency, the optimization magnetic materials are amorphous alloys and nanocrystalline alloys which have better magnetization and loss properties.

(2) The Steinmetz formula can be used to calculate the loss of core, and the method of coefficient of alternative current resistance to the losses of windings of HFT.

Table 5. *Optimization design results of a 10 kVA amorphous alloys high frequency transformer.*

f(kHz)	Bop(T)	Vc(cm3)	S/Vc	Pc(W)	Pcu(W)	Pt(W)
10	0.2939	259.9911	39.84205	30.5711	53.5436	84.1146
20	0.1574	241.6788	41.37723	27.3037	47.7399	75.0436
30	0.1106	229.5788	43.55803	25.8983	45.3952	71.2935
40	0.0951	203.5538	49.12706	26.3105	46.1546	72.4651
50	0.077	192.6796	51.89963	27.059	44.5896	71.6486
80	0.0472	232.6637	42.98049	26.1927	45.7791	71.9718
100	0.0375	250.1911	39.96945	26.4792	46.2359	73.705

Table 6. *Optimization design results of a 10 kVA nanocrystalline alloys high frequency transformer.*

f(kHz)	Bop(T)	Vc(cm3)	S/Vc	Pc(W)	Pcu(W)	Pt(W)
10	0.5633	129	77.51938	13.8365	27.6104	41.4469
20	0.3217	113.9947	87.7233	12.3767	24.6451	37.0218
30	0.2349	105.8522	94.4713	11.8885	23.5591	35.4476
50	0.1486	104.5664	95.6330	10.8533	21.8397	32.693
80	0.1011	104.5664	95.6330	10.8344	21.4794	32.3138
100	0.0799	112.2372	89.0970	10.4679	20.9212	31.3891

References

[1] Boglietti A，Cavagnino A，Lazzari M，et al. Predicting iron losses in soft magnetic materials with arbitrary voltage supply: an engineering approach [J]. IEEE Trans. Magn., 39(2): pp.981-989, March 2003.

[2] Bertotti G. General properties of power losses in soft ferromagnetic materials[J]. IEEE Trans. Magn., 24(1): pp621-630, January, 1988.

[3] P.L. Dowell. Effect of eddy currents in transformer windings[J]. Proc. Inst. Elect. Eng., 113, pp1387-1394, 1996.

[4] I. D. Mayergoyz, G. Friedman, and C. Salling, “Comparison of the classical and generalized Preisach hysteresis models with experiments,” IEEE Trans. Magn., vol. 25, no. 5, pp. 3925–3927, Sep. 1989.

[5] E. Barbisio, F. Fiorillo, and C. Ragusa, “Predicting loss in magnetic steels under arbitrary induction waveform and with minor hysteresis loops,” IEEE Trans. Magn., vol. 40, no. 4, pp. 1810–1819, Jul. 2004.