Analysis of favored design frequency of high-frequency transformer with different power capacities

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***Abstract*-High-power high-frequency transformers will become important electrical components in future DC/DC converters of HVDC power transmission system. Flux density and working frequency are mainly the most two important parameters in transformer design process. According to the design method of transformers, the design size and weight of transformers will decrease significantly with the increase of the operating frequency. However, it does not mean that increasing the operating frequency of transformers can infinitely reduce the size of the transformer. Different working frequencies mean different transformer sizes, which are closely related to the costs of transformers. In the relatively low frequency level, the design size of transformers can reduce as the operating frequency increases, but when the frequency reaches a certain level, the design size of transformer cannot decrease anymore as the losses and temperature rises become so large that the transformer cannot work well enough, this frequency level can be called favored transformer design frequency. Under different working flux densities and capacities, this paper designs high-frequency transformers with different magnetic cores such as silicon steel laminations, amorphous alloy. After designing, it reveals that different core transformers have different favored transformer design frequencies, magnetic core with more outstanding loss characteristic and lower working flux density has a higher favored transformer design frequency.**

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This paper also explains why high-frequency transformers generally choose lower working flux density and high frequency transformer with a certain power capacity exists a corresponding minimum design size, this conclusion may be very useful and practical in future high-frequency transformer design of DC / DC converters.

***Index Terms*- high-frequency transformers; flux density; magnetic core; favored transformer design frequency**

I. INTRODUCTION

High voltage large capacity DC/DC converters and power electronic transformers are the key equipments in HVDC power transmission system and smart grid. By means of increasing the working frequency, the volume and weight of transformers can decrease[8]. The design method of high-frequency transformers is different from the normal 50Hz transformers, the target of designing high-frequency transformers is to minimize the volume of transformers, thus to enhance the power density of high-frequency transformers[3], but decreasing the volume of transformer can bring some challenging problems for the heat dissipation and insulation of transformers, which is a hot and difficult issue in this related areas currently[10].

The important target to design high-frequency transformers is to enhance the power density. In this paper, using the volume of normal 50Hz transformers as a reference, decreasing the designing size while enhancing the working frequency of high-frequency transformers until the transformers cannot meet the design requirements such as temperature rises and loss limit, the ultimate design frequency can be called the "favored design working frequency".

There is contradiction between the large capacity and high frequency in high-frequency transformers, which means the higher of the design frequency, the smaller size of the transformers and the smaller of the largest capacity of transformer will be. Under normal circumstances, the design capacity of high-frequency transformer is fixed, while the frequency can be changed in accordance with design requirements, so one of the design difficulties of designing high-frequency transformers is to find a proper working frequency that can minimize the volume of the transformer and meet the temperature rise limit at the same time, so that the power density of high-frequency transformer can be the highest, this so called "high frequency" is just the "favored design working frequency" mentioned above.

From the perspective of transformer design principle, the design volume is closely related to the design capacity, flux density and frequency[1], due to the fact that normal transformer is designed at the frequency of 50Hz, so there is no effect of frequency on the volume of the transformer design, but for high-frequency transformer, its power density and loss are strongly linked to design frequency. Lots of papers mainly focus on discussing how to design high-capacity large power density high-frequency transformers[7-9], however, the way to choose a proper working frequency is not a research content for the authors.

In this paper, by means of theoretically analyzing the volume of high-frequency transformers of different capacities and frequencies, the result shows that the minimum design volume indeed exists for high-frequency transformers at different design flux densities and capacities. At the same time, the relationship between favored design frequency and flux densities and capacities is worked out. In order to verify the accuracy of the theory analysis above, based on the design method of high-frequency transformers, after detailed design, the favored design frequencies are got at different capacities and flux densities, thus confirm the correctness of favored design frequencies for different magnetic cores with different core loss characteristics.

II. THEORY ANALYSIS OF FAVORED DESIGNED FREQUENCY

This paper mainly discusses the design volume of high-frequency transformers at different design flux densities and capacities, so it is necessary to express the equation of transformer volumes by using the design parameters. However, because transformer volume is not only related to the structure of magnetic cores and winding, but also the way of heat dissipation and insulation. So if the transformer volume is purely expressed by the actual three dimensional length, then the expression will be so complicated that it cannot be analyzed theoretically. Thus it's necessary to find another parameter to replace the transformer volume, if the shape of transformer magnetic cores and the fill factor of windings are unchanged, then the dimensional length of transformers can be replaced by the same parameter C, so the transformer volume can be expressed by C^3.

The transformer design parameters are assumed to be S, f, B, which represent the capacity, frequency, and flux density respectively. In transformer design theory, the area product A_p is the standard to choose the size of magnetic cores[1], the bigger the value of A_p, the larger size of transformer will be, A_p is calculated by:

$$A_p = A_c \times A_w = \frac{S}{BfJK_f K_u} \propto C^4 \quad (1)$$

Where A_c and A_w represent the core cross sectional area and window area, K_f is the coefficient of waveform, which is 4.44 for sinusoidal and 4 for square waveform, K_u is the winding fill factor, which is usually 0.2-0.3 for Litz wire winding for high-frequency transformers.

In paper [11], when the way of heat dissipation is unchanged, the transformer losses will be inversely proportional to the dimension parameter C. Based on the Steinmetz equation, the unit volume magnetic core loss can be expressed by:

$$P_c = kf^{\alpha} B^{\beta} \propto \frac{1}{C} \quad (2)$$

In equation (2), for a specific magnetic core, the coefficients k, α, β are constant.

The unit volume loss of muti-strand Litz wire can be calculated by [4]:

$$P_w = \frac{(1+af^2)}{K_f \sigma} \cdot \frac{J^2}{2} \propto \frac{1}{C} \quad (3)$$

In equation (3), a is a parameter of transformer winding, $a \propto (w_w * d)^2$, w_w is the winding width, d is the wire diameter, σ is the electrical conductivity, J is the current density.

From (2) and (3), the relationship between B, J, f can be expressed by Eq. (4) and (5):

$$B \propto C^{\frac{-1}{\beta}} \cdot f^{\frac{-\alpha}{\beta}} \quad (4)$$

$$J \propto (1+af^2)^{\frac{-1}{2}} \cdot C^{\frac{-1}{2}} \quad (5)$$

Substitution (4) and (5) into (1) for given transformer capacity yields the equation about the dimension C and frequency f.

$$C^{\frac{7}{2}-\frac{1}{\beta}} \propto [\frac{S \cdot (1+af^2)^{\frac{1}{2}}}{f^{1-\frac{\alpha}{\beta}}}] \quad (6)$$

Almost for all the magnetic cores, the coefficients in the Eq. (2) have the nature: $3.5>\beta>\alpha>1$. For the reason that $V \propto C^3$, so the minimum value of C means the minimum size of the transformer. From Eq. (6), the dimension C reaches a minimum at a certain frequency f_{min}. So the f_{min} can be determined by differentiating Eq. (6):

$$f_{\min} = \sqrt{\frac{1}{a}(\frac{\beta}{\alpha}-1)} \quad (7)$$

The favored designed frequency is closely related to the core loss characteristic, winding structure, and the electrical characteristic of wire material from Eq. (7).

Two conclusions can be achieved from Eq. (7) about the favored designed frequency:

First: When the transformer capacity increases, the width of winding w_w and the wire diameter d will increase as well, so the value of a increases, which results in the decrease of f_{min}. So the transformer favored design frequency decreases as the transformer capacity increases.

Second: Under the condition that the level of voltage is unchanged, when the design flux density decreases, which means the number of turns of winding will be more. So in order to roll more turns of winding in the same window area, the diameter d must be smaller, then the value a will be smaller, which results in the increase of f_{min}. So the transformer favored design frequency increases as the design flux density decreases.

III. Specific Design of High-Frequency Transformer

The structure of high-frequency transformers usually choose the magnetic cores which are EE or UU type, because the value of A_p usually bigger for UU type cores, compared to EE type cores with the same volume, so UU type cores can place more turns of wires. As a result, UU type cores are preferred in large capacity high voltage high-frequency transformers, the basic structure of UU core and each dimension are shown in Fig.1.

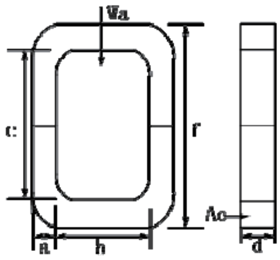

Fig.1 Basic structure of UU type core

In Fig.1, the transformer volume is V, the mean length of windings is MLT, the whole surface area for heat dissipation is A_t, the way to calculate these parameters is:

$$V = [2\cdot(b+c)+\pi\cdot a]\cdot a\cdot d \quad (8)$$

$$MLT = 2\times(a+d+b) \quad (9)$$

$$A_t = 8(ad+a^2+ab)+4(bd+bc+ac+cd+b^2) \quad (10)$$

Although in part I, the winding loss is calculated in equation (3), yet it is too complicated for actual design and computing, especially when the final winding structure is not determined. Here, another easy way to calculate the loss of winding is introduced, which is called "New England Technology":

$$G = \left(\frac{D_i\cdot\sqrt{f}}{10.44}\right)^4 \quad (11)$$

$$F_r = \frac{R_{ac}}{R_{dc}} = 1+2\cdot\left(\frac{N\cdot D_i}{D_o}\right)^2\cdot G \quad (12)$$

Where D_{i} means the diameter of Litz wire, D_0 is the final diameter of one turn of winding, N is the strands, F_{r} is the AC winding coefficient.

The way to calculate the loss and temperature rise of natural heat dissipation transformer is:

$$P_c = V\cdot kf^{\alpha}B^{\beta} \quad (13)$$

$$P_w = F_1 I_1^2\frac{n_1\cdot\rho\cdot MLT}{N\cdot S_w} + F_2 I_2^2\frac{n_2\cdot\rho\cdot MLT}{N\cdot S_w} \quad (14)$$

$$\Delta T = 450\cdot\left(\frac{P_c+P_w}{A_t}\right)^{0.825} \quad (15)$$

Where I_1, I_2 is the current on each side, n_1, n_2 is the turns of winding, ρ is the electrical resistivity of winding, S_w is the area of Litz wire.

IV. CALCULATION OF FAVORED DESIGN FREQUENCY

One of the rough problems in designing high-frequency transformers lies in the consideration of how to insulate when the voltage level reaches high. Normal ways of insulation are designing oil immersed transformers or increasing the distance between windings, which will bring more difficulties for the calculating of transformer volume. In order to eliminate the influence of insulation on the transformer volume, in this part, the voltage level is set as 3.8kV/0.4kV, for the reason that the level of 3.8kV is not high, so in addition to the wire insulation itself, other insulation between winding and winding, wire and wire, winding and core will not add too much volume in the whole transformer. The magnetic cores are UU type as is shown in Fig.1.

Two type cores that have different loss characteristics are discussed, one is 0.3mm silicon steels, its core loss equation: P_c(W/cm^3)=0.285f(kHz)$^{1.527}B^{1.75}$, another is amorphous alloy, its loss equation is : P_c(W/cm^3)=0.06f(kHz)$^{1.51}B^{1.74}$, the temperature rise limit is 60℃.

For the silicon steel core mentioned above, after designing 10kVA silicon steel transformer, the design flux density is 0.7T, the results are shown in table I and II.

Table I Dimension of 10kVA silicon steel transformer

f	dimension(mm)			
	a	*b*	*c*	*d*
50Hz	85	200	400	170
100Hz	85	190	395	170
200Hz	85	180	390	165
300Hz	85	175	385	160
400Hz	85	170	380	155
500Hz	80	170	380	155
600Hz	80	170	380	155

Table II 10kVA silicon steel transformer volume and temperature rise

f(Hz)	*V*(cm^3)	ΔT(℃)
50	21199	30.0
100	20765	21.7
200	19734	25.4
300	18864	35.4
400	18011	47.6
500	16756	59.2
600	16756	73.3

From table I and II, when the capacity is 10kVA, from 50Hz to 500Hz, the volume decreases with the increase of design frequency, and the temperature rises increase as well. At the frequency of 600Hz, even maintain the same volume as 500Hz, the temperature rise still reaches above limit 60℃. So for 10kVA silicon steel transformer, the favored frequency is 500Hz.

For 10kVA amorphous alloy transformer, the flux is still 0.7T, the design results are shown below as table III and IV:

Table III Dimension of 10kVA amorphous alloy transformer

f	dimension(mm)			
	a	*b*	*c*	*d*
50Hz	95	110	170	110
100Hz	95	105	165	110
300Hz	95	95	155	105
500Hz	95	90	150	100
700Hz	90	90	145	95
900Hz	85	90	140	90
1000Hz	80	90	135	90
1500Hz	75	88	130	90

Table IV Volume and temperature rise of 10kVA amorphous alloy transformer in different frequencies

f(Hz)	*V*(cm^3)	ΔT(℃)
50	8970.7	54.2
100	8761.7	32.1
300	7964.5	20.0
500	7395.2	23.3
700	6435.9	29.1
900	5561.8	35.3
1000	5049.5	38.4
1500	4533.4	59.4

From table III and IV, at the same design capacity and frequency, amorphous alloy transformers have less losses and the volumes are much smaller. The favored design frequency for amorphous alloy transformer is 1.5kHz.

As is discussed in part I, the design flux density is also related to the favored designed frequency, so when the flux density comes to 0.7T, 0.5T, 0.3T and 0.1T, designing transformers again, the results are shown in table V and VI and Fig. 2 and 3.

Table V Favored design frequency(kHz) for silicon steel transformer

S / B	10 kVA	50 kVA	100 kVA	200 kVA	300 kVA	400 kVA	500 kVA
0.1T	7.48	1.8	1.65	1.42	1.25	1.13	1.10
0.3T	1.35	0.58	0.50	0.41	0.39	0.37	0.36
0.5T	0.760	0.31	0.280	0.230	0.223	0.213	0.21
0.7T	0.500	0.220	0.18	0.158	0.148	0.140	0.133

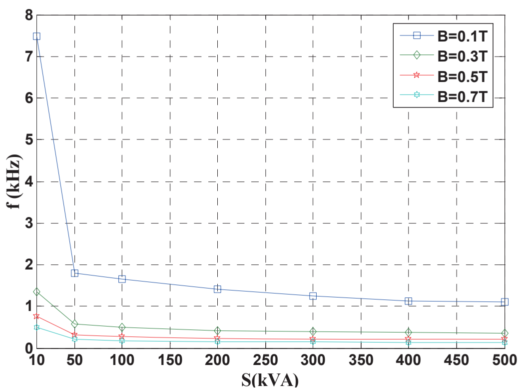

Fig.2 Favored design frequency for silicon steel transformer with different capacities and flux densities

Table VI Favored design frequency(kHz) for amorphous alloy transformer

S / B	10 kVA	50 kVA	100 kVA	200 kVA	300 kVA	400 kVA	500 kVA
0.1T	13.8	6.6	6.5	4.6	4.0	3.6	3.35
0.3T	4.20	2.50	2.45	1.85	1.56	1.42	1.32
0.5T	2.30	1.80	1.75	1.2	1.00	0.92	0.84
0.7T	1.50	1.30	1.20	1.10	0.97	0.90	0.82

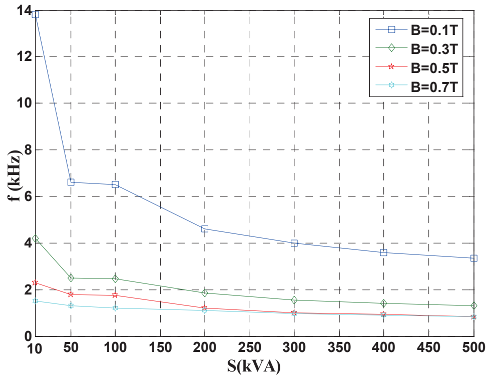

Fig.3 Favored design frequency for amorphous alloy transformer with different capacities and flux densities

From the design results above, the conclusion about favored design frequency is verified, and also the favored frequency reaches a steady value when the capacity is large enough. For an example, when the silicon steel transformer's capacity is 300kVA or larger, the values of favored design frequencies all reach stable with different flux densities. Another conclusion which is not mentioned in part I is that the favored design frequency for amorphous alloy transformer is much higher than silicon steel transformer.

Because the amorphous alloy cores are cheap and easily built, and their high-frequency losses are relatively lower. So currently, lots of high-frequency transformers are designed with amorphous alloy cores, different models of amorphous alloy cores have different loss characteristics, if choosing cores with lower losses, the favored designed frequency will be higher, but the cost will higher as well.

Because the working frequency of medium and high frequency transformers is defined as 400Hz or higher, if designing transformers with the silicon steel cores discussed in this paper, the proper design capacity should be 200kVA or smaller, the flux density is 0.3T or lower. Even if meeting these requirements, the losses are so high that the efficiency will be low.

In table VI, the highest favored frequency for 10kVA amorphous alloy transformers is 13.8kHz, but it does not mean that when enhancing the design frequency, the amorphous alloy transformer's power density will be much lower. On the one hand, the volume for amorphous alloy transformer has been small enough, compared to silicon steel transformer, so when it is necessary to increase the volume a little to satisfy the frequency which is higher than the favored frequency, the power density will be still large enough. On the other hand, the transformers discussed in this paper are all dry, which means that the temperature rise limit is low, when the natural heat dissipation is replaced by forced air cooling, the favored working frequency will be higher. Third, when using amorphous alloy cores with lower losses, the favored frequency can increase as well.

V. Conclusion

In this paper, by means of theory analysis, the relationship between the favored working frequency and transformer capacity, flux density is worked out, namely, the favored working frequency will increase with lower capacity and flux density. Meanwhile, the basic design method of high-frequency is also shown. In the end, by calculating the specific favored working frequencies for transformers with different capacities and flux densities, it verifies the accuracy of the conclusion mentioned in theory analysis.

Although most of the work in this paper appears at the level of theory and the conclusions are not verified by experimental tests, this paper will also be meaningful for the future design of high voltage high capacity high-frequency transformers, especially when it comes to think out the proper working high frequency for transformer to minimize its volume.

VI. References

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