Design of High Power Density Transformer
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Abstract. The traditional high-voltage high-frequency transformer has a drawback of low power density due to the rigorous requirements of high voltage insulation. This paper proposes a new configuration for the magnetic core based on planar EE cores. The parallel connection of planar cores was adopted as a unit, and several units were cascaded to form the high-voltage transformer. The electrical potential distribution of the proposed transformer is more uniform than a traditional transformer, and enables a decrease in the insulation distances. The mechanical configuration of a laboratory prototype is discussed, as well as the electrical, parasitic, and thermal behaviors.

Introduction
In this paper, the discussion is focused on the design of a high-voltage high-frequency power transformer in switched supply for an electrostatic precipitator application. There are several improvements in the switched supply compared with the conventional high voltage DC power supply (50 Hz or 60 Hz transformer is adopted). For example, high frequency switching operation will allow: (a) much more precise control over the operating parameters (such as output voltage level, current level, voltage rise times and response to variations in load demand), (b) a reduction in the size and weight of the high-voltage transformer and enhancing the power density of the transformer [1, 2].

However, the reduction in the size of the transformer is limited in high-voltage step up transformers (>30 kV). In order to obtain the required output high-voltage, it is necessary to employ a transformer with a large turns ratio and high insulation distances between primary and secondary windings, secondary windings and cores, and in the secondary itself [3]. And the requirements for high voltage insulation distances will become more and more rigorous with rated voltage of transformer rising. Commonly, the main insulation distance is proportional to the 1.5th power of rated withstand voltage of the transformer. Consequently, the method of reduction transformer’s size only by increasing the transformer’s rated frequency is limited in high-voltage transformer.

The other methods that may reduce in the size and weight of the high-voltage high-frequency transformer are as follows:

1) Adoption of high performance magnetic materials such as nanocrystalline core [4, 5];
2) Adoption of superconducting material [6];
3) Improvement of the transformer’s insulation structure [7, 8].

The method 1) is able to increase the flux density of core, and methods 2) will increase the current density of the windings of transformer, and 3) enhances insulation structure of the high-voltage transformer mainly. But those methods do not overcome the contradiction between transformer’s power density decreasing at high voltage and its increasing at high-frequency. In order to deal with the contradiction mentioned above, a new configuration for the transformer magnetic core was proposed based on planar EE cores. The parallel connection of planar cores magnetic circuit was adopted as a unit, and several units were cascaded to form the high-voltage transformer. Cascade transformers have already been used for high-voltage test systems [9] and multilevel PWM inverters applications [10]. In this paper, the cascade transformer has been used for high-frequency high-voltage applications. And it has the merits of cascade transformer and planar cores [11]. First, the output high-voltage is shared in the multistage voltage of transformer.
units, the main insulation distance may decrease with voltage decreasing. Second, the planar cores provide a relatively large surface area for the transfer of dissipated heat to the environment. Thus, the contradiction of high-frequency and high-voltage impact on power density of transformer is eased largely.

**Transformer Principle Proposed**

Fig. 1 illustrates the schematic circuit of the proposed transformer and power conversion circuit. It consists of high frequency transformer, full bridge inverter, voltage multiplier, and the electrostatic precipitator (ESP). The full-wave series multiplier is connected to the secondary side of the transformer. The full-wave series multiplier is AC to DC power conversion devices composed of the diodes ($D_5$, $D_6$, $D_7$ and $D_8$) and the capacitors ($C_5$, $C_6$ and $C_7$) that produce high DC voltage from a low voltage AC source. The output voltage of the voltage multiplier is $-2E_{pk}$, where $E_{pk}$ is the peak value of the transformer output voltage. The term $C_E$ and the non-linear resistor $R_E$ represent the equivalent load of the ESP.

\[
\Delta V \approx \frac{I_d}{4fC_6} 
\]

\[
\delta V \approx \frac{I_d}{2fC_6} 
\]

where $I_d$ is the average value of the output DC current, $f$ is the frequency of the inverter, and $C_6$ is the voltage multiplier capacitance, which also has a role as a filter.

Fig. 2 shows the schematic structure of the proposed transformer. It consists of two same “transformer branches” (branch 1 and branch 2). Each branch consists of three “transformer units” (unit 1, unit 2 and unit 3). Three transformer units are cascaded to form one transformer branch. Each transformer unit has an efficiency of 98%. Unit 1, unit 2 and unit 3 have 30.6 kW, 20.2 kW and 10 kW output power respectively. Thus, one transformer branch’s output power and efficiency can be calculated, they are 30 kW and 96% respectively. So, the overall cascade transformer has 60 kW output power and an efficiency of 96%.

The electric potential to earth of the three transformer unit cores are 5 kV, 15 kV, and 25 kV. The turn ratios of the three transformer units are equal (approximately equal to 20) with the same input.
voltage (510 V, 20 kHz). Thus, \( n_1 = n_3 \), where \( n_1 \) is the primary turns and \( n_3 \) is the cascaded winding turns which supplied energizing voltage for the next transformer unit.

![Figure 2. The schematic structure of the proposed transformer.](image)

And the current ratings of all units and all windings in one transformer branch are shown in Table 1.

| Transformer units | Current ratings of \( n_1 \) [A] | Current ratings of \( n_2 \) [A] | Current ratings of \( n_3 \) [A] |
|-------------------|-------------------------------|-------------------------------|-------------------------------|
| Transformer unit 1| 66.44                         | 1.08                          | 44.92                         |
| Transformer unit 2| 43.84                         | 1.08                          | 22.78                         |
| Transformer unit 3| 21.70                         | 1.08                          | ------                        |

By observing the potential difference of the secondary winding with respect to its core in Fig. 2, it is clear that the maximum potential difference is 5 kV. However, the corresponding potential difference of the conventional transformer with the same output voltage is 30 kV. Thus, the insulation distances of a cascaded transformer are much shorter than in a conventional transformer, and the cascaded transformer has a much higher power density.

**Transformer Design**

In this section a high-voltage high-frequency cascade transformer for an electrostatic precipitator power supply was designed with the following electrical specification: 510 V input voltage (quasi-square wave), 30 kV output voltage, 60 kW output power, and 20 kHz inverting frequency. Because the transformer branch 1 is same as branch 2 completely, the structure of transformer unit 1 is similar to unit 2 and 3. Thus, in following subsections, the design of unit 1 of the transformer branch 1 is an example to the design of the overall cascade transformer mainly. The cascade transformer design required consideration of the insulation, the magnetic material and the management of electrical, magnetic and thermal stresses.

**Magnetic Design**

The area product \( AP \) is the product of the winding window area and the cross-sectional area of the core, and it is a useful design parameter in selecting the core and the number of turns per volt [13].

144
\[
AP = \frac{P_t \cdot 10^4}{4B_m fK_u J}
\]  
(3)

where \(AP\) is the area product (cm\(^4\)), \(P_t\) is the apparent power handling capability (VA), \(B_m\) is the maximum core flux density (T), \(f\) is the operating frequency (Hz), \(K_u\) is the window utilization factor, and \(J\) is the wire current density (A/cm\(^2\)).

The planar ferrite EE type core ‘R 49938 EE’ from MAGNETICS Inc is selected for the cascade transformer. The material of ‘R 49938 EE’ is magnetic R-type material, which has low AC core losses and decreasing losses to temperature of 100˚C. The dimensions of the core are shown in Fig. 3 and Table 2. The area product \(AP_{EE}\) of a pair of EE is calculated from Fig. 3 and Table 2, \(AP_{EE}=50.27\) cm\(^4\). In each transformer branch design, the parameters of equation (3) were calculated or selected as follows: \(P_t=61.2\times10^3\) W, \(B_m=0.3\) T (ferrite), \(f=20\times10^3\) Hz, \(K_u=0.3\) and \(J=300\) A/cm\(^2\). Hence, we obtained \(AP=283.5\) cm\(^4\) from equation (3). Thus, transformer unit 1 needs 6 pairs of ‘R 49938 EE’ (and same as the transformer unit 2, and transformer unit 3 need 4 and 2 pairs of ‘R 49938 EE’ respectively).

![Figure 3. Structure of the planar cores.](image)

Table 2. Mechanical dimension of R 49938 EE [mm].

|   | A   | B       | C   | D   |
|---|-----|---------|-----|-----|
|   | 102±1.52 | 20.3±0.25 | 37.5±0.4 | 13.3±0.25 |
| E | 86±1 | 14±0.25 | 8   | 36  |

Once a core is chosen, the calculation of primary and secondary turns and wire size is readily accomplished. The selection of wire size also considers the existing skin and proximity effects in the current distribution in the copper wire. The important parameters of transformer unit 1 are listed in Table 3. The conductor of winding n1 is three layer copper foils in parallel and each foil with 20 mm width, 0.4 mm thick. The conductor of winding n2 is the ‘three-layer insulated round wire’ with 0.75mm diameter and it’s rated withstand voltage is 10kV. Two layer copper foils in parallel are composed of the conductor of winding 3 and the size of each foil is same as winding n1. Other specifications and design results of the transformer unit 1 windings is shown in Table 3.

**Insulation Design**

The design of the insulation is one of the important issues in this research. In order to convenience industry process, oil-paper insulation co-ordination is adopted as non-uniform insulation of the transformer. Oil is prior to use to prevent insulation breakdown when the electric field intensity is too high. Since compared with insulating paper, the electric strength of oil is high
(160kV/cm) and its dielectric constant is small (2.0-2.25). So the parasitic capacitance of the transformer may decrease when oil is adopted. Insulating paper is used to increase creepage distance and prevent creeping discharge.

Table 3. Parameters and copper losses of transformer unit 1 windings.

| winding | turn | wire                      | current density [A/mm²] | length of winding [mm] | copper losses [W] |
|---------|------|---------------------------|-------------------------|------------------------|------------------|
| n1      | 7    | three-layer copper foil   | 2.768                   | 4254                   | 23               |
| n2      | 131  | three-layer insulated wire| 2.456                   | 93720                  | 9                |
| n3      | 7    | two-layer copper foil     | 2.808                   | 4710                   | 15               |

Thermal Analysis

The power handling ability of a ferrite transformer is limited by either the saturation of the core material or, more commonly, the temperature rise. Temperature rise is important for overall circuit reliability, and staying below a given temperature insures that wire insulation is valid. On the other hand, as core temperature rises, core losses can rise and the maximum saturation flux density decreases commonly. R-type material is adopted in our design transformer, which attempt to mitigate this problem by being tailored to have decreasing losses to temperature of 100°C. One of the two major factors effecting temperature rise is core loss, which is a function of the operating flux density [13].

\[
P_{\text{core}} = a f^c B_m^d \times 10^{-3}.
\]

where \(P_{\text{core}}\) is the loss density (W/cm³), \(a\), \(c\), and \(d\) is the factors (\(a = 0.074\), \(c = 1.43\), \(d = 2.85\) if R-type material is adopted, and \(f < 100\text{kHz}\)), \(f\) is the operating frequency (Hz), \(B_m\) is the maximum core flux density (kG, 10kG = 1T). And \(B_m\) is calculated by

\[
B_m = \frac{E}{4 A_{\text{c}} N_1 f \times 10^{-8}}.
\]

where \(E\) is the applied voltage of primary windings (V), \(A_{\text{c}}\) is the core area (cm²), \(N_1\) is the number of turns of primary windings, \(f\) is the operating frequency (Hz).

The \(B_m\) and \(P_{\text{core}}\) can be calculated according to the datum of Table.2 and Table.3, namely, \(B_m = 2.89\) kG, \(P_{\text{core}} = 110.58\) mW/cm³. With reference to Fig. 3, the total volume of the six pairs of ‘R49938 EE’ is approximately equal to 478.8 cm³. Thus, the total core losses are 53 W. Copper loss is the second major contributor to temperature rise. According to Table 3, the total copper loss of the windings is 47 W. Furthermore, the overall total losses are 100 W. For this situation, the power dissipation of transformer unit 1 is below 1% of the total output power.

The core shape also affects temperature and those that dissipate heat well are desirable. The planar cascade transformer is different from the conventional transformer in switching-mode power converters. The fluid encapsulation such as transformer oil was considered. Transformer oil is a good medium for heat transport. Under ideal natural convection conditions it has heat transfer coefficient of approximately 95 W.m⁻²K⁻¹; this is equivalent to forced air-cooling with a flow velocity of approximately 25 m/s [2]. On the other hand, Oil cooling has many merits as follows:

- It is favorable for improving the cooling, especially when multiple planar transformers are paralleled to form a higher power transformer (this type of transformer is easy to integrate, which will be shown later).
- It is favorable for enhancing the insulation of the planar transformer (the insulation strength of oil is 16 kV/mm).
- Compared with sulfur hexafluoride, transformer oil has little or no greenhouse effect.
Electrostatic Analysis

The logical and physical structure of the branch 1 of the overall planar cascade transformer is shown in Fig.4, where the planar cores compressed by two pairs of 3 mm thick epoxy compressing plate are composed of a power unit. The 3 mm pure oil clearance is reserved between the power units in the transformer active part assembly. According to electrostatic analysis, the electrical potential distribution in the direction of x1, x2, x3 plane (corresponding U₁, U₂ and U₃), and x4, x5, x6 plane (corresponding U₄, U₅ and U₆) can be drawn.

Figure 4. Logical and physical structure of the transformer branch.

It can be shown that the electrostatic field of the transformer branch is approximately uniformly distributed across the three transformer units. On the other hand, it can be seen that the electric field intensity is high between the magnetic core yoke and the windings, and between the different windings in the same transformer unit. And the electric field intensity between the different transformer units is also high. Consequently, the 1 mm epoxy resin bobbin and 3 mm oil clearance were placed between the yoke and windings, and the 3 mm epoxy compressing plate and 3 mm pure oil clearance is reserved between the different transformer units.

Component

One of the objectives in choosing the planar cascade configuration was the characteristic of component of the transformer unit. Namely the transformer unit may act as an independent power transform voltage unit. The transformer units are cascaded to form a higher voltage transformer, and a higher power transformer can be derived from the transformer units in parallel. However, there is a lower transformer utilization factor when over 3 stages of transformer units were cascaded. Hence, It should be a tradeoff among insulation distance, operating frequency, and stages of cascaded in practical transformer design.

Conclusion

This paper describes a novel transformer with magnetic cores based on planar EE cores and cascade transformer technology. The main features of the proposed transformer can be summarized as follows:

- The electrical potential distribution is more uniform than the conventional high-frequency transformer, and enables a considerably decrease in the insulation distances.
- The power density of the planar cascade transformer is high enough to 7.5 W/cm³.
- The transformer unit of the planar cascade transformer has the characteristic of component. It is flexible to output voltage extending and output power extending.
- Cooling is good and the efficiency is higher than 96%.

A prototype transformer with an output voltage of 30 kV, output power of 60 kW, inverting frequency of 20 kHz was built, and the design and analysis verified by the test results.
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