Design of a Cascade Planar Transformer for Electrostatic Precipitator Use

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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. A prototype transformer has been designed and built with the following characteristics: 30 kV output voltage, 30 kW output power, and 20 kHz inverting frequency. The transformer was tested and found to have an efficiency of better than 96%. Compared with traditional high-voltage transformers, this transformer has good thermal behavior, good line insulation properties and a high power density.

Key-Words: - High Voltage, High Frequency, High Power Density, Planar Cores, Cascade Transformer, Insulation

1 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 are not overcome the contradiction between high-voltage decreasing the power density of the transformer and high-frequency increasing the power density of the transformer.

In order to deal with the contradiction mentioned above, a new configuration for the 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. This transformer has the merits of cascade transformer and planar cores [9]. First, the output high-voltage is shared in the multiple voltage levels 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.

2 Transformer Principle Proposed

The circuit schematic of the proposed transformer is given in Fig. 1. The transformer was driven from a voltage sourced H-bridge inverter. The switches T_1, T_2, T_3, and T_4 are IGBTs, where the pairs T_1 (T_3) and T_2 (T_4) operate at a symmetrical duty ratio. This operation requires a short and well-defined dead time between conduction intervals. A voltage multiplier rectifier was used on the secondary winding, so that the output dc voltage is twice the secondary winding output voltage. And the output is negative DC high voltage. The terms D_1, D_2, C_2, and C_3 are the capacitances of voltage multiplier and the diodes of voltage multiplier respectively.

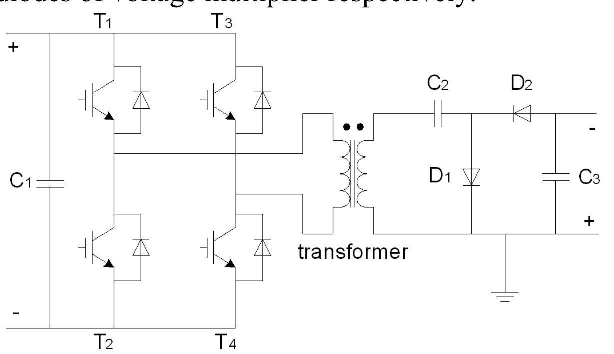


Fig. 1. The circuit schematic of the proposed transformer

In this circuit, there is no dc current that could create a transformer core saturation problem, and a higher transformer utilization factor than half-wave rectifier and full-wave rectifier versions is achieved [10]. The peak voltage ripple of the rectifier is calculated from:

$$\delta U \approx \frac{I_d}{2fC_3} \tag{1}$$

Where I_d is the average value of the output dc current, f is the frequency of the inverter, and C_3 is the voltage multiplier capacitance, which also has a role as a filter.

The schematic of the proposed transformer is shown in Fig. 2. The input voltage is 510 V, 20 kHz, which comes from three-phase rectifiers (380 V, 50 Hz) and the output voltage is 30 kV. This transformer is composed of three transformer units, which are cascaded to form an overall cascade transformer. The efficiency of the each transformer unit is 0.98, the output powers of the three transformer units are 10 kW, 20.2041 kW, and 30.6164 kW. Thus, the overall cascade transformer has an output power rating of 30 kW with an efficiency of 0.96.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). Thus, n_1=n_3, where n_1 is the primary turns and n_3 are the cascaded winding turns which supply energizing voltage for the next transformer unit.

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 (as shown in Fig. 3) 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.

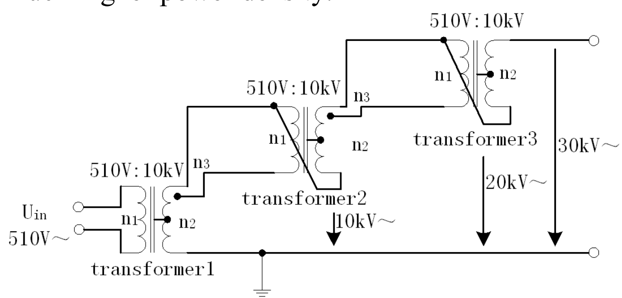


Fig. 2. The schematic of the proposed transformer

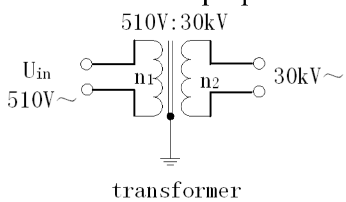


Fig. 3. The schematic of the conventional transformer

3 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, 30 kW output power, and 20 kHz inverting frequency. The cascade transformer design required consideration of the insulation, the magnetic material and the management of electrical, magnetic and thermal stresses.

3.1 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.

$$AP = \frac{P_t \cdot 10^4}{4 B_m f K_u J} \quad (2)$$

where AP is the area product (cm^4), P_t is the apparent power handling capability (W), 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.4 and Table 1. The area product AP_{EE} of a pair of EE is calculated from Fig. 4 and Table 1, AP_{EE}=50.27 cm^4. In this design, the parameters of equation (2) were calculated or selected as follows: P_t= 61.2412×10^3 W, B_m=0.3 T (ferrite), f=20×10^3 Hz, K_u=0.3 and J=300 A/cm^2. Hence, we obtained AP=283.5241 cm^4 from equation (2). 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.

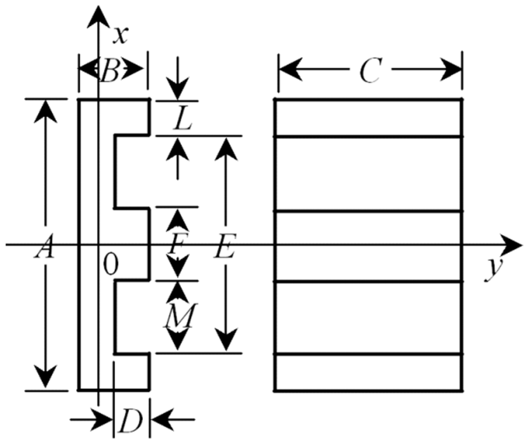


Fig. 4. Structure of the planar cores

Table 1: 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	*F*	*L*	*M*
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 [11]. The important parameters of transformer unit 1 are listed in Table 2. 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.2.

Table: 2 Parameters and copper losses of transformer unit 1 windings

winding	turn	wire	current density (A/mm^2)	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

3.2 Insulation Design

The design of the insulation is one of important issue in this research. In order to convenient for industry process, oil-paper insulation co-ordination is adopted as non-uniform insulation of the transformer. Oil is prior to use when it has to be great enough to prevent breakdown through the insulation. Since compared with insulating paper, the electric strength of oil is high (160kV/cm) and it's 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. The insulation data of one window of transformer unit 1 are listed in Table 3 and the structure of windings of transformer unit 1 is given in Fig. 5.

Table: 3 Data of insulation section for transformer unit1

core/insulation/windings (x axis direction)		electric potential to earth (V)	potential difference between conductors (V)	insulation distance (mm)	insulation material	x axis value (mm)
magnetic core		−5 000	—	—	isolation with tank	—
bobbin		−5 000	—	—	—	1
n_2	69-51	−5 000	1 376.8	1.25	thickness of bobbin	2
	50-32	−3 623.2	2 753.6	0.5	three-layer insulated wire	3
	31-13	−2 246.4	2 753.6	0.5	three-layer insulated wire	4
	12-1	−869.6	2 246.4	>0.5	three-layer insulated wire	5
n_1		±255	2 546.4 (1 169.6)	1.33 (0.33)	2 layers insulating paper (0.08 mm)	15
spacer and oil-duct		from 255 to −5000(absolute)	—	—	—	20
n_2	70-88	−6 376.8	6 676.8	5.33	2 layers insulating paper (0.08 mm)+pressboard+ three-layer insulated wire	21
	89-107	−7 753.6	2 753.6	0.5	three-layer insulated wire	22
	108-126	−9 130.4	2 753.6	0.5	three-layer insulated wire	23
	127-131	−9 492.7	1 739.1	>0.5	three-layer insulated wire	24
n_3	132	−9 565.6	1 812.0 (362.3)	1.33 (0.33)	2 layers insulating paper (0.08 mm)	25.04
	—	—	—	—	—	—
	138	−10 000	72.86	0.16	2 layers insulating paper (0.08 mm)	31.28
oil		from −10000 to −5 000(absolute)	—	—	—	36
magnetic core		−5 000	5 000	7.44	isolation with tank	—

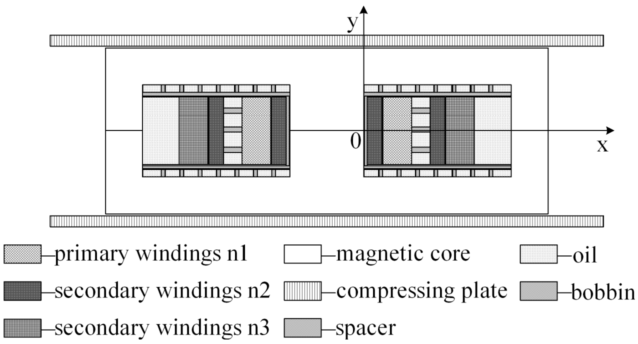


Fig. 5. Structure of windings of transformer unit 1

In Fig.5, the insulation of the x-axis direction is already shown in Table. 3. In the y-axis direction, the 3 mm oil clearance between bobbin and core yoke is reserved and the thickness of bobbin is 1 mm. As shown in Fig. 2, Fig.5 and Table.3, turn 1 and turn 69 of the n2 secondary windings are earthed and connected to the core respectively. The primary winding is 'sandwiched' between two groups of secondary windings. This type of winding arrangement has the lowest product of the parasitic inductance L_s and capacitance C_s, and the product of L_s and C_s determines the overall high frequency properties of the transformer [8][9].

3.3 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 ℃. One of the two major factors effecting temperature rise is core loss, which is a function of the operating flux density.

$$P_{core} = af^c B_m{}^d \tag{3}$$

Where P_{core} is the loss density (mW/cm^3), a, c, and d is the factors (a = 0.074, c = 1.43, d = 2.85 if R-type material is adopted, and f < 100kHz), f is the operating frequency (Hz), B_{m} is the maximum core flux density (kG, 10kG = 1T). So B_{m} is calculated by

$$B_m = \frac{E}{4A_c^{'} N_1 f \times 10^{-8}} \quad (4)$$

where E is the applied voltage of primary windings (V), $A^{'}_c$ is the core area (cm^2), N_1 is the number of turns of primary windings, f is the operating frequency (Hz).

The B_m and P_{core} can be calculated according the datum of Table.1 and Table.2, namely, B_m = 2.891 kG, P_{core} = 110.584 mW/cm^3. With reference to Fig. 4, the total volume of the six pairs of 'R 49938 EE' is approximation to 478.8 cm^3. Thus, the total core losses are 53 W. Copper loss is the second major contributor to temperature rise. According to Table. 2 the total copper losses of the windings was 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 with 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^{-2}K^{-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.

Besides the planar transformer's cores offer a large flat surface, the flexible oil circulation cooling system of windings is adopted as shown in Fig.6. Where Fig.6 (a) is the platform of the transformer unit 1, and Fig.6 (b) is the photograph of it. Note that there are two unit 1s in Fig.6 (b) photograph. The 6 mm spacing is reserved between each pair of planar cores. The 2 mm diameter of oil hole is adopted in the middle of spacing, which is convenience for oil circulation. So the method of conventional calculating the temperature rise with natural cooling is simply not applicable. Consequently a method described by John C. Fothergill [2] was used for the temperature rise calculations. A 25°C temperature rise was determined by these calculations.

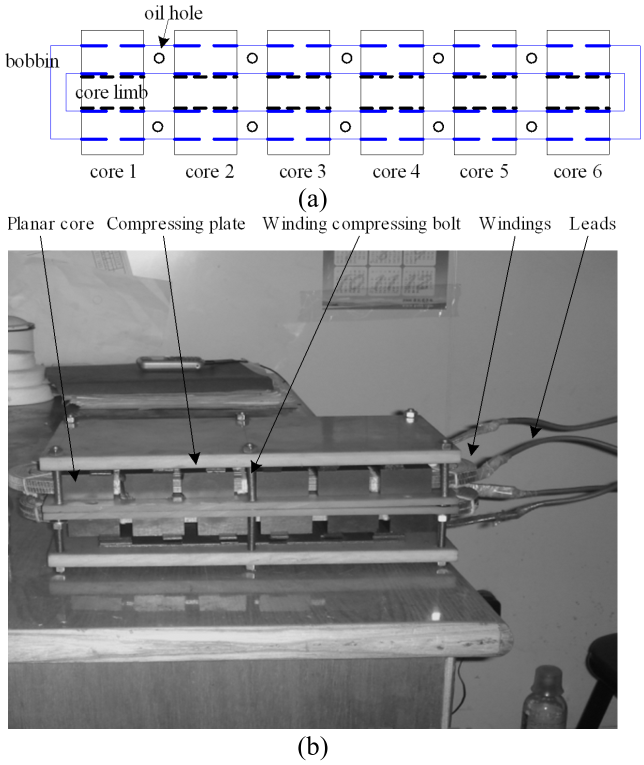


Fig. 6. (a) Platform of transformer unit 1 and (b) Photograph of the transformer unit 1

3.4 Electrostatic Analysis

The logical and physical structure of the overall planar cascade transformer is shown in Fig.7. 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 U_1, U_2 and U_3), and x4, x5, x6 plane (corresponding U_4, U_5 and U_6) can be drawn, as shown in Fig. 8. The curves in Fig.8 describe the maximum absolute values of the voltage of the windings in a work period, and the x-axial data is the size of the practical prototype transformer.

It can be shown that the electrostatic field of the overall transformer is approximately uniformly distributed across the three transformer units. On the other hand, it can be sawn 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. Other insulation data is shown in Fig. 5 and Table.3.

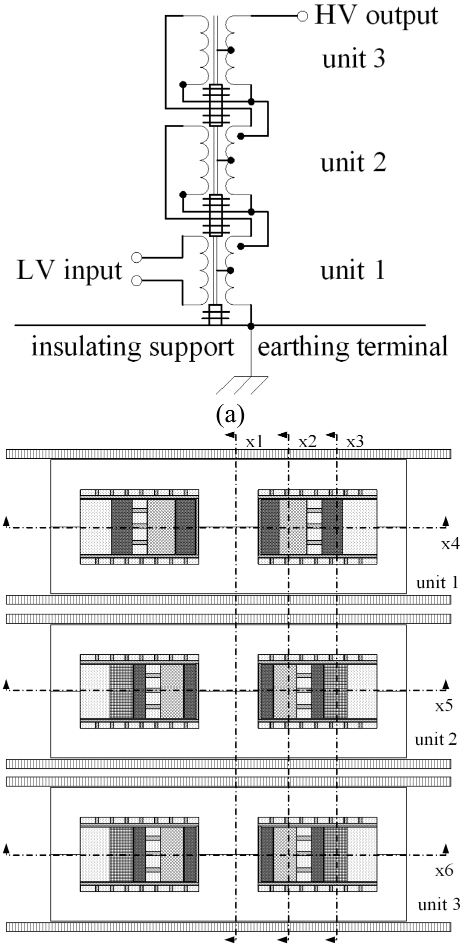
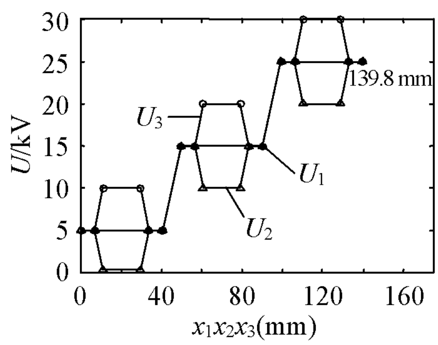
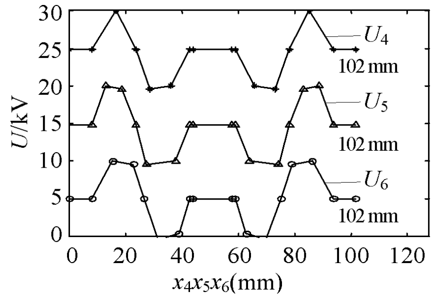


Fig. 7. Logical and physical structure of transforme (a) logical structure and (b) physical structure



(a)



(b)

Fig. 8. Potential distribution of the transformer (a) x1, x2 and x3 and (b) x4, x5 and x6

3.5 Component

One of the objectives in choosing the planar cascade configuration was the characteristic of component of the transformer unit as shown in Fig. 9. 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 levels of transformer units cascaded. Hence, It should be a trade off among insulation distance, operating frequency, and levels of cascaded in practical transformer design.

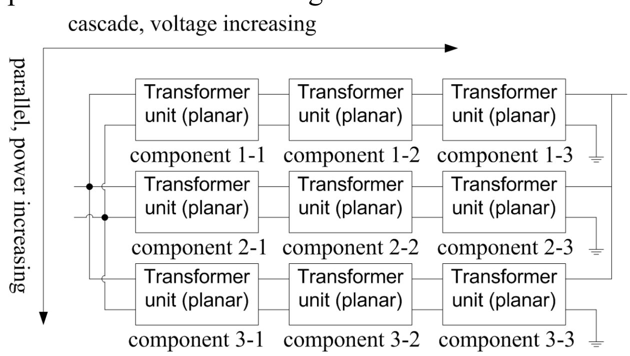


Fig. 9. The illustration of the component of the transformer unit

4 Leakage Inductance and Parasitic Capacitance Analysis

In order to simplify the analysis of the planar cascade transformer, the mutual capacitance and resistances of the n1, n2, and n3 windings (shown in Fig. 2) were neglected. Fig. 10 illustrates an equivalent electric circuit of the planar cascade transformer with all the n1 and n3 winding parameters referred to the n2 high voltage winding. These parameters are indicated by: L'_{p1}, L_{s1}, L'_{k1}, C'_{p1}, C_{s1}, and C'_{k1} which are the leakage inductances and self-capacitances of transformer unit 1's n1, n2, and n3 windings; L'_{p2}, L_{s2}, L'_{k2}, C'_{p2}, C_{s2}, and C'_{k2} which are the leakage inductances and self-capacitances of transformer unit 2's n1, n2, and n3 windings; and L'_{p3}, L_{s3}, C'_{p3}, and C_{s3} which are the leakage inductances and self-capacitances of transformer unit 3's n1 and n2 windings. Fig. 11 shows the simplified equivalent circuit of Fig. 10, where L_e and C_e are the lumped equivalent leakage inductance and parasitic capacitance [3] [13].

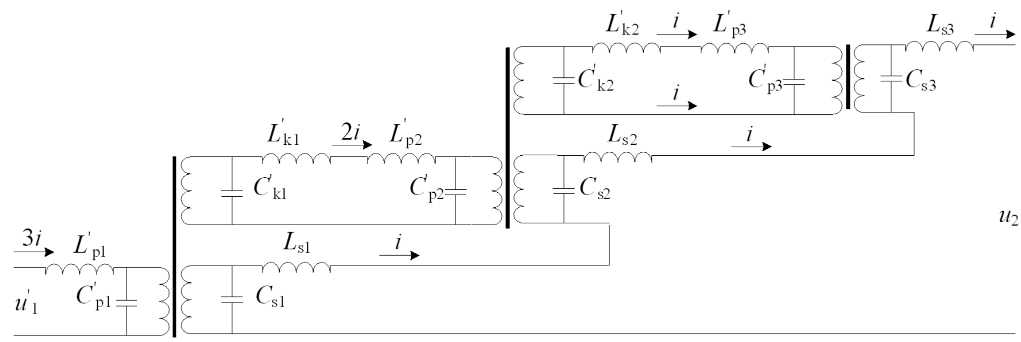


Fig. 10. The equivalent circuit of the planar cascade transformer

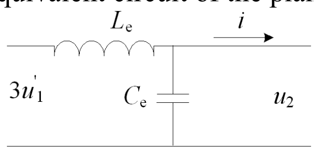


Fig. 11. The simplified equivalent circuit of the planar cascade transformer

According to Fig. 10 and Fig. 11, the follow expression can be obtained:

$$\frac{1}{2}L_e i^2 = \frac{1}{2}(L_{s1}+L_{s2}+L_{s3}+L'_{k2}+L'_{p3})i^2 + \frac{1}{2}L'_{p1}(3i)^2 + \frac{1}{2}(L'_{k1}+L'_{p2})\times(2i)^2 \tag{5}$$

We can show from formula (5):

$$L_e = L_{s1}+L_{s2}+L_{s3}+L'_{k2}+L'_{p3}+9L'_{p1} + 4(L'_{k1}+L'_{p2}) \tag{6}$$

If the influence of leakage inductances on C with voltage is neglected, the follow expression can be obtained:

$$\frac{1}{2}C_e u_2^2 \approx \frac{1}{2}(C_{s1}+C_{s2}+C_{s3})\times(\frac{u_2}{3})^2 + \frac{1}{2}C'_{p1}(\frac{u_2}{3})^2 + \frac{1}{2}(C'_{k1}+C'_{p2})\times(\frac{u_2}{3})^2 + \frac{1}{2}(C'_{k2}+C'_{p3})\times(\frac{u_2}{3})^2 \tag{7}$$

We can show from formula (7):

$$C_e \approx \frac{C_{s1}+C_{s2}+C_{s3}+C'_{p1}+C'_{k1}+C'_{p2}+C'_{k2}+C'_{p3}}{9} \tag{8}$$

From expression (6) and (8) we can see the total leakage inductances are increasing and the total parasitic capacitances are decreasing in the planar cascade transformer.

5 Prototyping and Testing Results

Following the design and analysis detailed above, a prototype of the planar cascade transformer with output voltage 30 kV, output power 30 kW, and work frequency 20 kHz, was developed. According to the method of experimental determination parasitic parameters of the transformer described by Hai Yan Lu [13], the lumped equivalent leakage inductance (L_e) and parasitic capacitance (C_e) were experimented, L_e = 0.22 mH and C_e = 0.31 μF.

5.1 Power Density Calculation

Considering the transformer design data as shown in Table 1, Table 3 and Fig. 8, the volume of the transformer is 2594 cm^3. Thus the power density of the planar cascade transformer is 11.565 W/cm^3.

For comparison purpose, a conventional high-frequency transformer (30kV) is also designed and prototyped. The design followed the procedure presented in [2]. The power density of the conventional high-frequency transformer is 0.98 W/cm^3. Clearly, the planar cascade transformer is considerably smaller than the conventional high-frequency transformer. Fig. 12 shows the contrast photograph of the conventional high-frequency transformer and the planar cascade transformer (transformer unit 1 is given only).

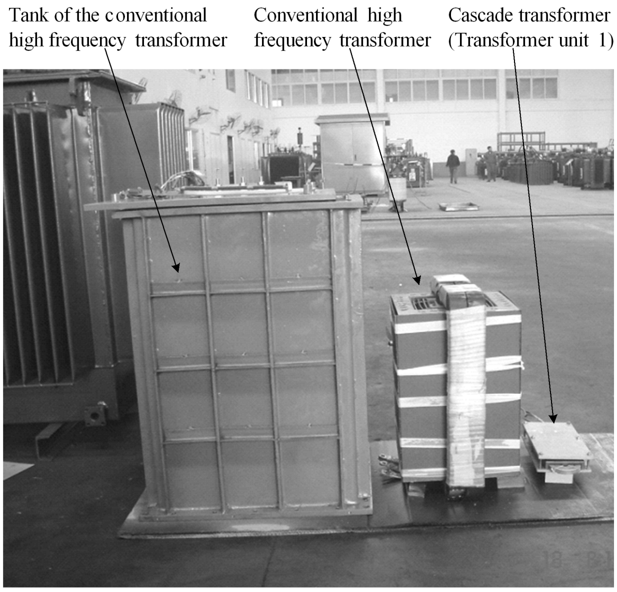


Fig. 12. Photograph of the planar cascade transformer contrasted with the conventional high-frequency transformer

5.2 Experiment

In this paper, the insulation, the current and voltage performance of the transformer is focused particularly.

5.2.1 Dielectric Test

Short duration power-frequency tests which supplied to high voltage winding – low voltage winding of each transformer unit is passed, where the voltage is 20 kV, the duration is 60 s. So the 30 kV rated voltage requirements of the overall cascade transformer is satisfied. Because the sum voltage of three transformer units is 48 kV by adding appropriate margins which may be non-uniform electrical potential distribution between the transformer units.

$$(30\times 3)\times 0.8 = 48 \text{ kV}$$

The photograph of the dielectric test is shown in Fig. 13, where the transformer is placed in tank with 25 # oil.

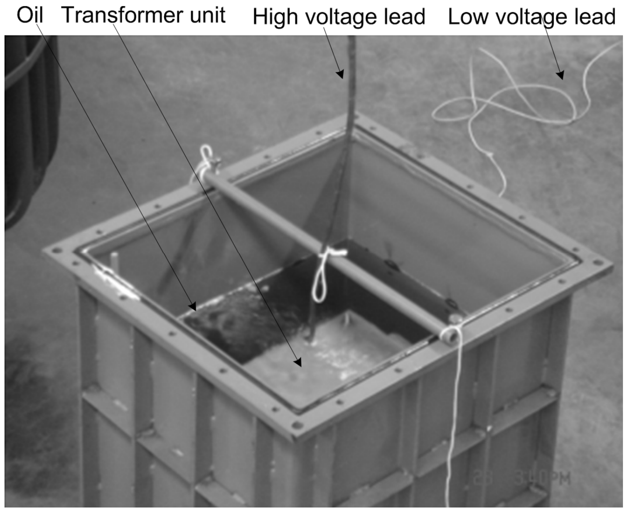


Fig. 13. Photograph of the dielectric test

5.2.2 Waveform Performance Test

In order to test the performance of the planar cascade transformer itself, the voltage multiplier rectifier is deleted. The experimental circuit is shown in Fig. 14.

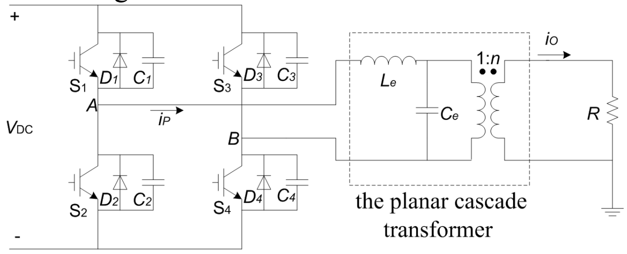
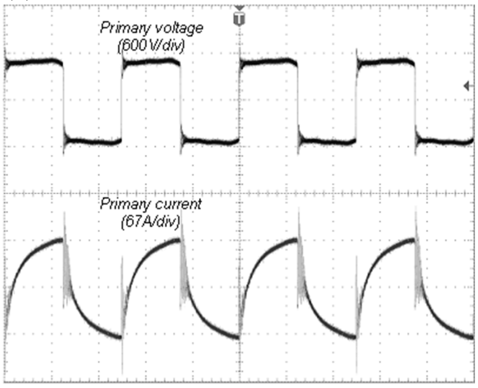


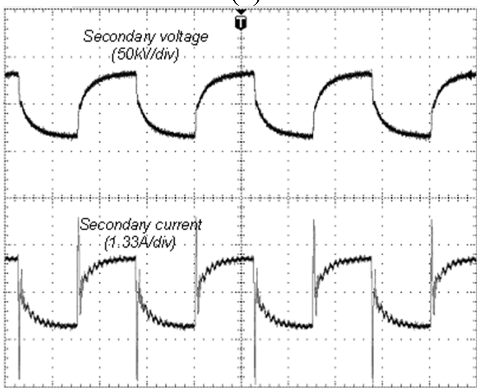
Fig. 14. The equivalent circuit of test

In the experimental circuit, the SKM 300GB125D switching devices from SEMITRANS are chosen as the switches S_1, S_2, S_3, and S_4. It's the maximum collector current I_{CP} and the rate current I_F of the anti-parallel diode is 210 A and 180 A respectively. The pairs S_1 (S_3) and S_2 (S_4) operate at a symmetrical duty ratio. This operation requires a short and well-defined dead time (3.41μ s) between conduction intervals. The terms D_1, D_2, D_3, and D_4 are the anti-paralleled diodes for the IGBTs. The terms C_1, C_2, C_3, and C_4 are the paralleled noninductive capacitances for the IGBTs, which are used to achieve zero-voltage switching (ZVS).

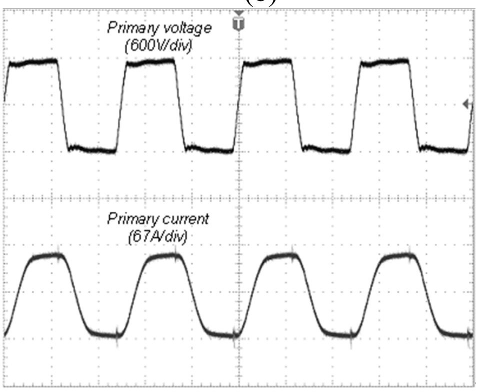
The test waveform of the planar cascade transformer is shown in Fig. 15. From the test waveform, we can see the total leakage inductive reactance is higher than the total parasitic capacitive reactance. Although the total leakage inductance is relatively high, it is favorable to limit the current when sparking occurs in the ESP power supply. Further, the designer can trade parasitic capacitance against leakage inductance in a predictable way by adding a capacitance in series with the primary side of the transformer. If the compensation measures are carried out, the resulting primary input voltage and current waveforms from the testing are as shown in Fig. 15 (c).



(a)



(b)



(c)

Fig. 15. (a) Primary input voltage and current waveform, (b) Secondary output voltage and current waveform and (c) Primary input voltage and current waveform under compensation

From the primary input voltage current waveform and secondary output voltage current waveform, the 96.7% efficiency of the planar cascade transformer can be derived.

The photograph of the voltage and current waveform performance test is shown in Fig. 16, where the resistance is wire load resistors (30 kΩ, 30 kW).

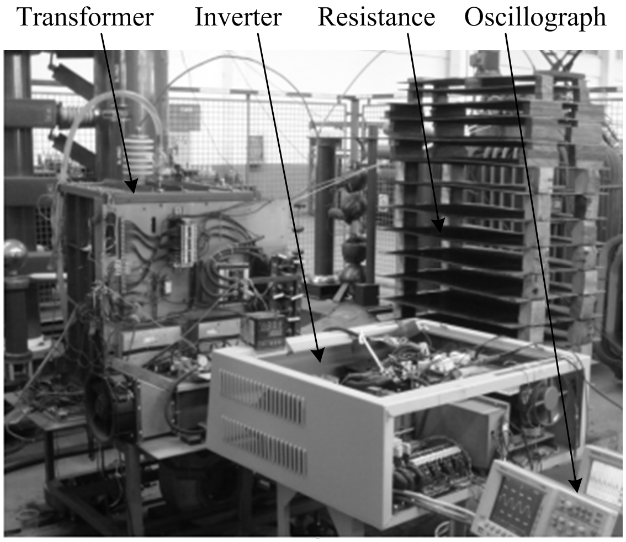


Fig. 16. Photograph of the waveform performance test

6 Conclusion

This paper describes a novel transformer with magnetic cores based on planar EE cores and cascaded 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 11.565 W/cm^3.
- 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 30 kW, inverting frequency of 20 kHz was built, and the design and analysis verified by the test results.

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