Field Enhancement Optimization of an Air-Cored Spiral Strip Pulse Transformer

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***Abstract*—The structure of a compact air-cored high-voltage spiral strip pulse transformer is relatively simple, but considerable attention is needed to prevent breakdown between transformer windings. Since thickness of the winding conductors in the spiral strip type is in the order of submillimeter, field enhancement at the edges of the winding conductor is very high. It is, therefore, important to find proper winding parameters to reduce the field enhancement and, thus, to make the system compact. An insulator structure, which has multilayered dielectric materials with different dielectric constants, has been considered and numerically simulated. The field enhancement factor has been defined and obtained as a function of the conductor edge shape, dielectric constants of the insulation layer, and the thickness of multilayered dielectric material. Optimum design parameters are obtained to reduce the field enhancement at the edge of the windings.**

***Index Terms*—Field enhancement, high voltage, numerical analysis, pulse transformer.**

I. Introduction

THE GAP between spiral strip winding conductors in an air-cored high-voltage pulse transformer must be very close to achieve high flux linkage between the primary and secondary windings, and also to make it compact. The main advantage of the air-cored spiral strip transformers is that the frequency limitations imposed on a transformer by its magnetic core are now removed and, hence, these transformers can be used at very high frequencies [1]. Thin copper foil has been widely used as the winding conductor for the spiral strip transformer. Since the copper foil is very thin, very large field enhancement occurs at the edges of the winding conductors.

Several techniques had been introduced to reduce the field enhancement at the edge of the windings. The first was to treat the winding conductor edges as round as possible. The second was to control the properties of insulation material around the winding conductors [2]. The third was to add a coaxial shield across the margins of the secondary windings [3]. The last technique was good in reducing the field enhancement at the edge of the windings, but had a detrimental effect on the magnetic coupling. However, no detail numerical simulation study results of the field enhancement optimization for the spiral strip pulse transformer have been reported. Recently, we carried out a detailed numerical simulation of the field enhancement for the spiral strip type pulse transformer, and the preliminary results were reported in [4]. Field enhancement factors for several different conductor edge shapes were calculated and presented. The results showed that an increase in the radius of rounded conductor edge significantly decreased the field enhancement at the edge of the spiral strip winding conductor.

In this paper, extended study results of the field enhancement at the winding edge by finite element method is presented and discussed to find an optimum design parameter of the spiral strip pulse transformer. In addition to the rounded conductor edge, thickness and dielectric constants of insulation multilayer have been used as control parameters in the calculation.

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TABLE I
SPECIFICATIONS OF THE HIGH VOLTAGE PULSE TRANSFORMER

	VALUE	UNIT
PRIMARY INDUCTANCE	170	nH
PRIMARY PULSE WIDTH	0.5 ~ 1	μs
PRIMARY (V/A)	50	kV
	1000	kA
SECONDARY (V/A)	500	kV
	100	kA
TURN RATIO	1 : 10	

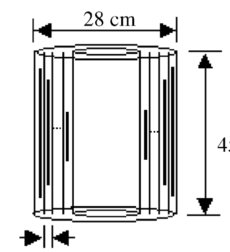

Fig. 1. Schematic drawing of the air cored high voltage spiral strip pulse transformer.

II. Numerical Calculation

The system for the calculation is an air cored spiral strip type pulse transformer constructed at Pohang Accelerator Laboratory (PAL) [5]. The detailed specification for the transformer is shown in Table I.

Fig. 1 shows the outline of the transformer. The gap between the spiral winding conductor layers is 0.09 cm. Total size of the system is 45 cm in length and 28 cm in diameter. Since the gap is much narrower than the total system size, the system can be simplified for the calculation, as shown in Fig. 2. Here, only

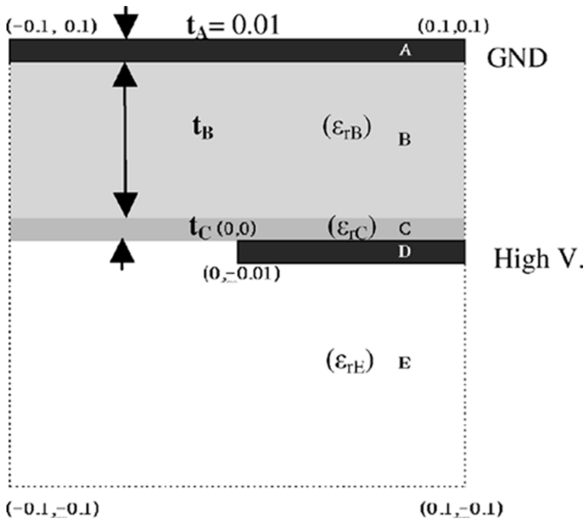

Fig. 2. System used in the calculation. Units are in centimeters.

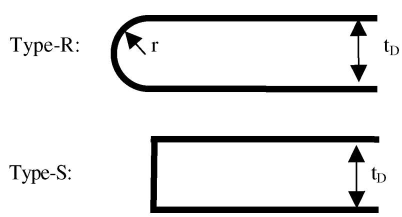

Fig. 3. Shapes of the spiral strip winding edge used in the simulation.

two adjacent layers of the spiral strip winding conductors are considered for simplicity.

This simplification may be valid when the field near the tip of spiral strip winding conductor layer D is considered. The applied potential in the simulation is 100 kV, which is two times higher than 50 kV of the actual transformer to give enough safety margins. The coordinate units used in the figure are in centimeter. The coordinate of center position in the figure is $(x, y) = (0, 0)$. The horizontal direction is used as x axis and the vertical direction is used as y axis. Here, A and D shown in the figure are the film spiral strip winding conductor layers that have 0.01 cm thickness. Layers B, C, and E are dielectric materials for insulation and have relative dielectric constants of ε_{rB}, ε_{rC}, and ε_{rE}, respectively. The thickness of the layers B and C are t_B and t_C, respectively.

The electric field calculation is based on the generalized Poisson equation [6]

$$\nabla \cdot (\varepsilon_r \nabla \phi) = -\frac{\rho}{\varepsilon_o}. \quad (1)$$

The field calculations for the simulation are carried out by using commercially available software "Tricomp 2D"[7]. The Dirichlet boundary conditions is used on the conductors and Neumann is used on the outer boundaries.

In the simulation, two types of spiral strip winding conductor edge for the layer D are considered, as shown in Fig. 3. They have same thickness $\boldsymbol{t}$ but have different edge shape. Type-R has a rounded edge with radius $\boldsymbol{r}$, and type-S has a square edge with sharp corners.

The control parameters used in the simulation are thickness of the dielectric layers ($\mathrm{t_B}$ and $\mathrm{t_C}$), dielectric constant value of the layers ($\varepsilon_{\mathrm{rB}}$, $\varepsilon_{\mathrm{rC}}$, and $\varepsilon_{\mathrm{rE}}$), and the rounded edge radius r.

III. Result and Analysis

Typical simulation results of electric field distributions for the type-R and type-S edges are shown in Figs. 4–7.

Here, the ε_{rB} was selected as 3, which is a typical relative dielectric constant value for the Mylar polyester film provided by DuPont. The ε_{rE} was 4.5, which is a typical relative dielectric constant value for transformer oil. The ε_{rC} was selected as 4 for the Figs. 4–6, and 3 for Fig. 7.

The t_B and $\mathrm{t_C}$ were 0.08 and 0.01 cm, respectively. The potential applied at the conductor layer D was 100 kV, while the conductor layer A was in ground potential. The rounded edge radius r was 0.005 cm.

The parameters ($\varepsilon_{rB} = 3$, $\varepsilon_{rE} = 4.5$, $\varepsilon_{rC} = 4$, $t_{\mathrm{B}} =$ 0.08 cm, $\mathrm{t_C} = 0.01$ cm, and applied potential $= 100$ kV) are used throughout the simulation done in this paper unless otherwise specified. In Figs. 4 and 5, contour electric field plots are shown for the spiral strip winding conductor layers of type-R and type-S. The contour lines indicate constant magnitude of electric field. The figure shows that the contour lines are very close each other near the tip of the winding conductor. This indicates that the electric field enhancement near the spiral strip winding conductor tip is very high. The layer C is located from $y = 0.0$ cm to $y = 0.01$ cm, and the layer B is located from $y = 0.01$ cm to $y = 0.09$ cm.Figs. 4 and 5 also show the discontinuous electric field at the interface of the layer B and C. Since the figures do not give detailed values of the field, the electric field was calculated from (0,0) to (0, 0.9) to find the electric field distribution between the winding conductors. Fig. 6 shows the electric field distribution. The figure clearly shows that the discontinuous electric field at the interface of the layers B and C. In the figure, the interface is located at $y = 0.01$ cm. The maximum electric field occurs near the winding edge which is locates at the (0,0) point. The maximum values shown in the figure are 1.83 $\times 10^8$ [V/m] for type-R case and 4.23 $\times 10^8$ [V/m] for type-S case. This indicates that the maximum electric field value of the type-S case is about 2.6 times greater than that of the type-R case. Fig. 7 shows the electric field distribution for the case of $\varepsilon_{rB} = \varepsilon_{rC} = 3$. This result is same as the result for one layer insulation because ε_{rB} and ε_{rC} are same. The maximum electric field values shown in the figure are 2.09 $\times 10^8$ [V/m] for type-R case and 4.45 $\times 10^8$ [V/m] for type-S case. The maximum electric field value of the type-S case is about 2.3 times greater than that of the type-R case.

Field enhancement factor, F_E , has been defined to show percentage of the field enhancement with respect to average field between the gap as follows:

$$F_E = \frac{E_{\mathrm{m}}}{E_{\mathrm{a}}} \quad (2)$$

where E_m is the maximum electric field in the layer and E_a is average electric field between two winding conductor layers, which is the same as the electric field between two infinite parallel plate

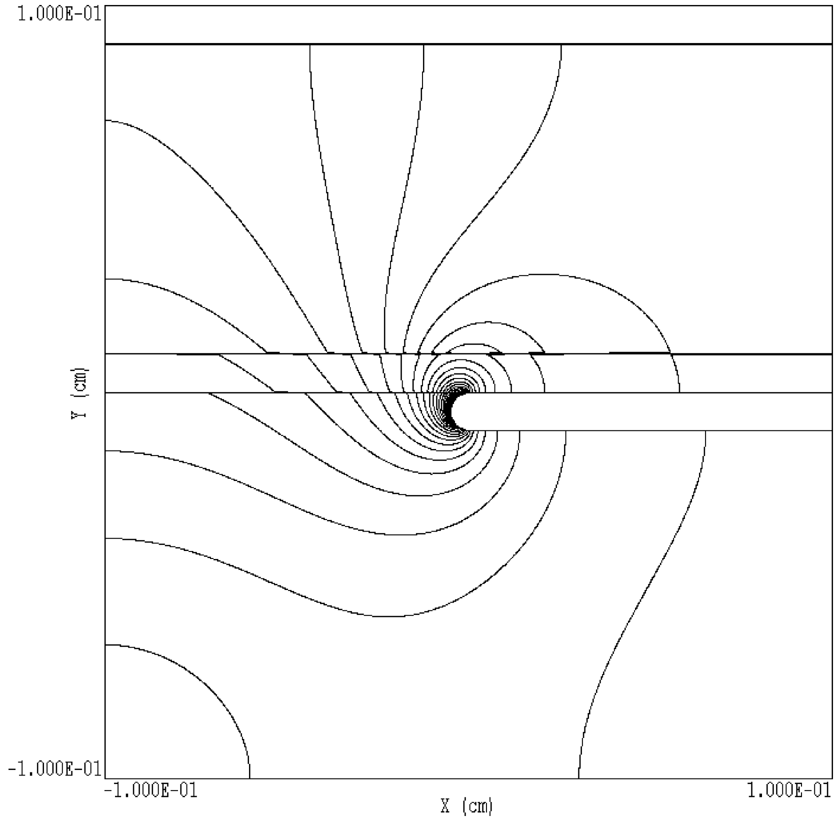

Fig. 4. Electric field distribution for the spiral strip winding edge type-R.

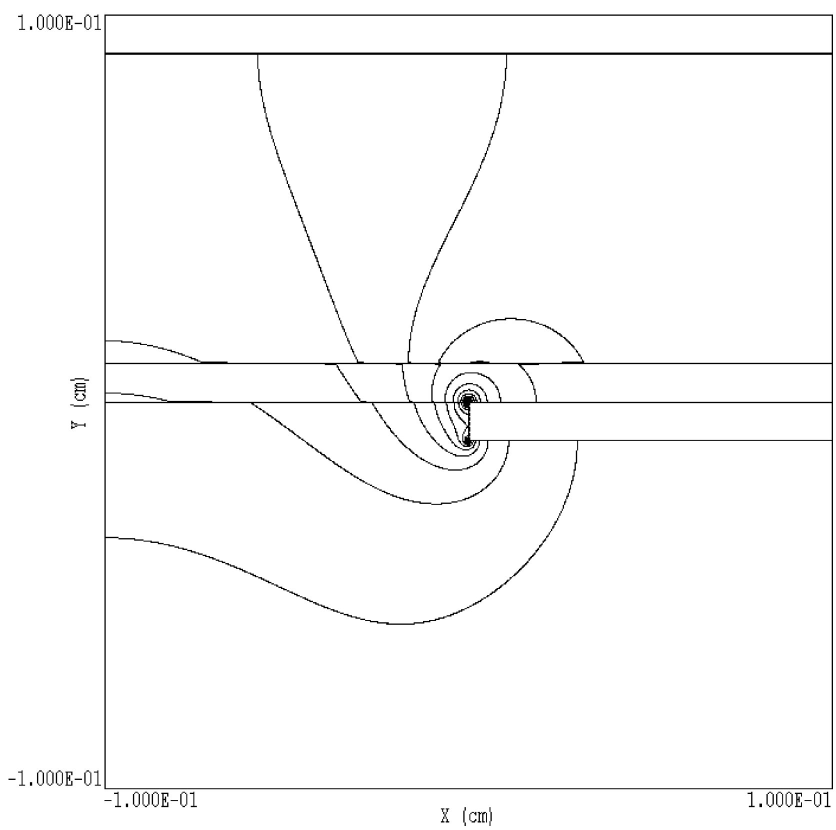

Fig. 5. Electric field distribution for the spiral strip winding edge type-S.

electrodes where the potential is set at same potential as the potentials between the layers A and D. This value indicates that there is field enhancement when the F_E value is greater than 1.

Fig. 8 shows the relation between circle radius of the winding conductor edge and the field enhancement. The control parameters used in the simulation is same as used in the Fig. 4 type-R

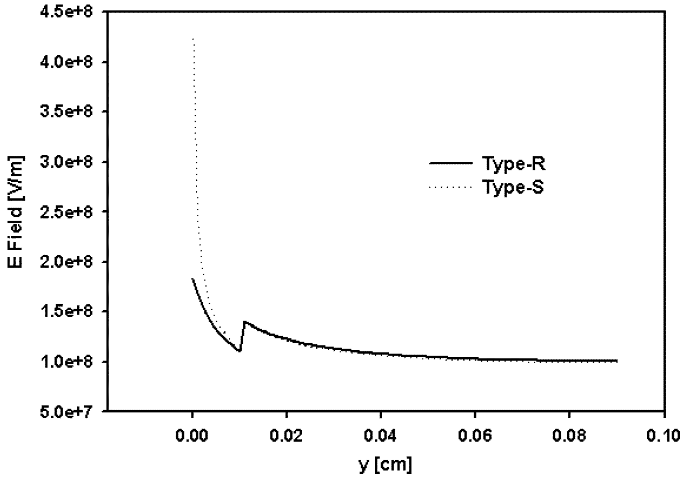

Fig. 6. Electric field distribution in the layers B and C as a function of distance y ($\varepsilon_{rB} = 3, \varepsilon_{rC} = 4$).

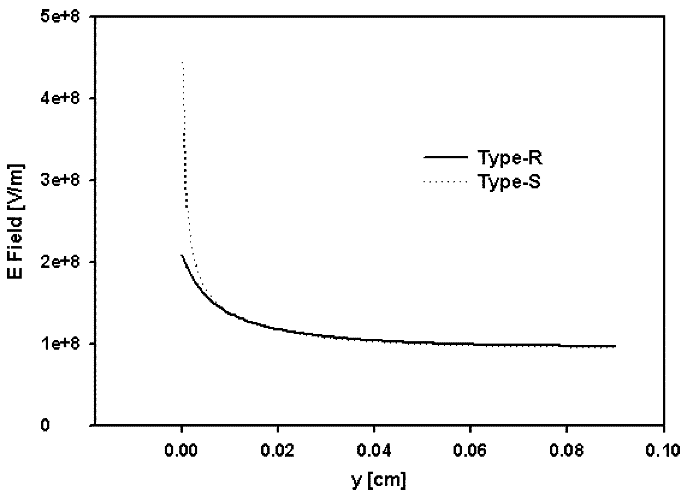

Fig. 7. Electric field distribution in the layers B and C as a function of distance y ($\varepsilon_{rB} = \varepsilon_{rC} = 3$).

case. A least square fit has been done to find the relation between radius r and F_E as follows:

$$F_E = 1.0 + 1.63e^{-120\,r}. \tag{3}$$

Here, the unit of r is in centimeters. The field enhancement factor decays exponentially and approaches 1 when the circle radius of the edge increases. Fig. 8 shows the field enhancement is about to saturate at $r = 0.03$. This indicates that a circle radius greater than 0.03 cm will be a good choice for the spiral strip type pulse transformer design.

A numerical calculation has been carried out by varying control parameters, such as the dielectric constant values of the layers C and E, as shown in Figs. 9 and 10. The figures indicate that the field enhancement at the spiral strip winding conductor layer is decreased by increasing the dielectric constant values of the layers C and E. It saturates at about $\varepsilon_{rC} = 5$ for the edge type-R. This means that the relative dielectric constant value of about 5 or greater is desirable for the pulse transformer insulation material when the type-R spiral strip winding conductor is used.

Figs. 11 and 12 show that the field enhancement at the edge of conductor layer D as a function of the thickness of layer C. The

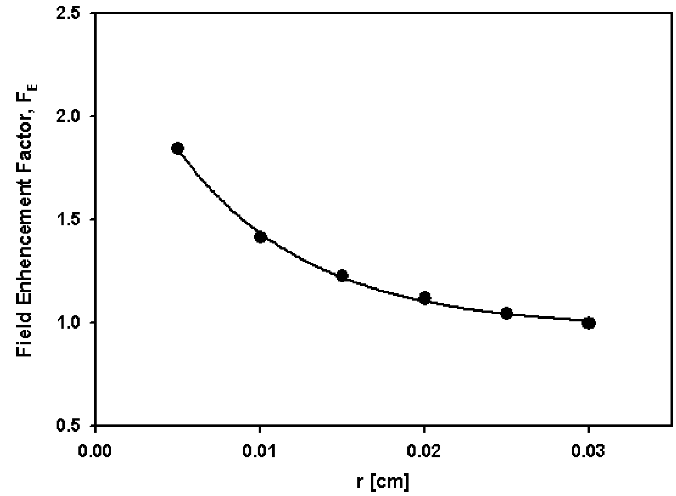

Fig. 8. Field enhancement factor as a function of r for the type-R case.

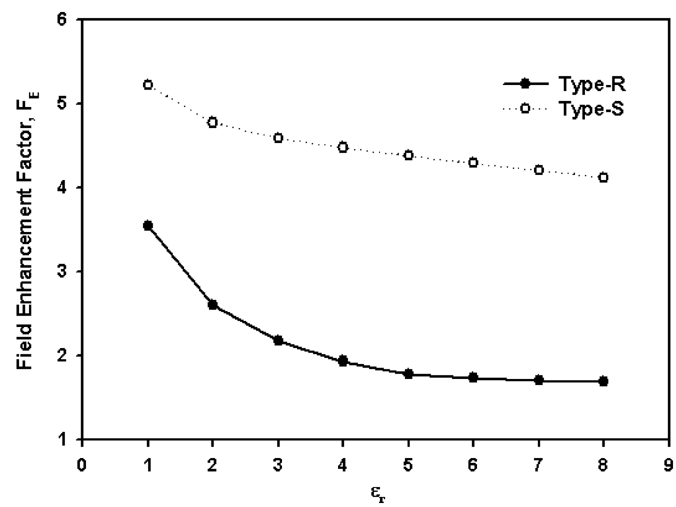

Fig. 9. Field enhancement factor as a function of ε_{rC}.

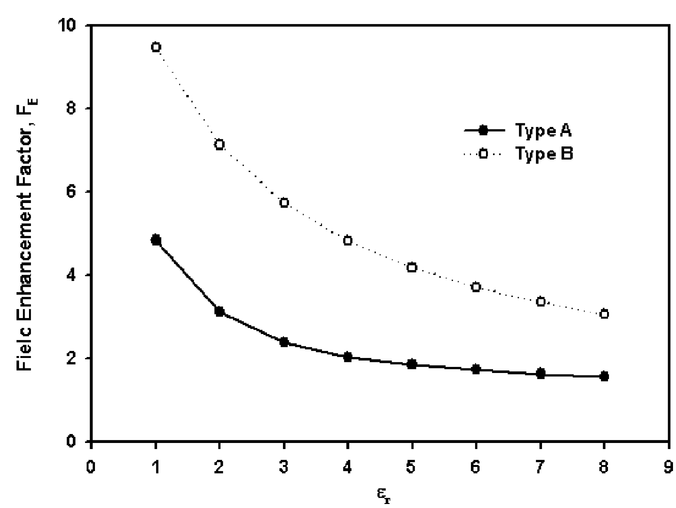

Fig. 10. Field enhancement factor as a function of ε_{rE}.

field enhancement factor in layer C decreases when the thickness of layer C is reduced. On the other hand, the field enhancement factor in layer B increases when the thickness of layer C is reduced. This indicates that there exists an optimum thickness

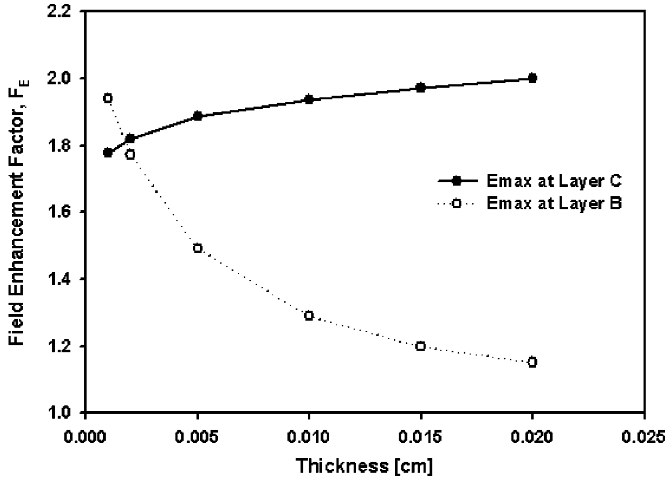

Fig. 11. Field enhancement factor for the edge type R as a function of thickness of the insulation layer C.

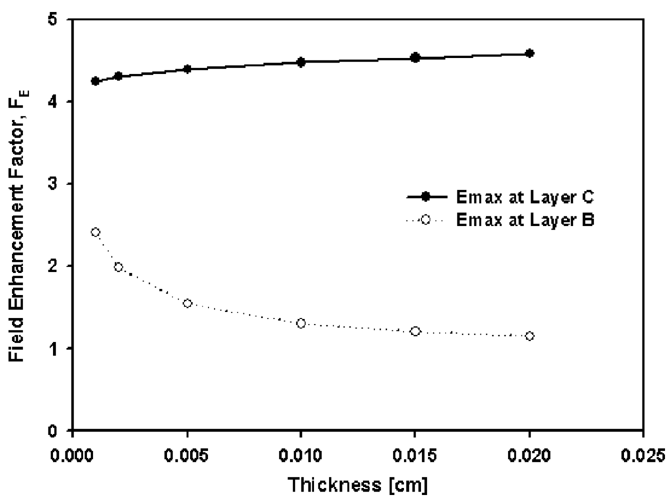

Fig. 12. Field enhancement factor for the edge type S as a function of thickness of the insulation layer C.

value of layer C. The F_E curves in Fig. 11 cross at the position about 0.002 cm. This indicates that the maximum electric field value in the layer B for the spiral strip winding conductor edge type A case is greater than the value in the layer C when the thickness of layer C is less than 0.002 cm. Hence, the optimum thickness value for the layer C is 0.002 cm when the electrical breakdown strength of layer B and C is equal. In Fig. 12, the F_E curves does not crossover each other. This means that optimum thickness value for the layer C is less than 0.002 cm.

IV. Conclusion

The electric field of an air cored high-voltage pulse transformer has been numerically calculated and analyzed. The field enhancement factor has been defined and calculated as a function of the circle radius of the edge, dielectric constant value of the insulation layer around the spiral strip winding conductor layer, and thickness of the insulation layer. The conductor edge shape is important to reduce the field enhancement, and the circle radius of greater than 0.03 cm is a good choice for the spiral strip type transformer design when the thickness of the conductor strip is 0.01 cm. The field enhancement can be further reduced by increasing dielectric constant around the spiral strip winding conductor layer. The relative dielectric constant value of about 5 or greater is desirable for the pulse transformer insulation material when the circle edge shape is used. An optimum thickness value for the layer C insulation material has been obtained as 0.002 cm when the circle edge conductor layer is used.

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