Simulation and Studies of Pulse Transformer using 2D Finite Element Method

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Abstract : This paper presents simulation for the magnetic field patterns of a basket winding pulse transformer through the vector magnetic potential formulation. Visualization of solution of arising partial differential equation has been carried out using finite element technique. This modeling of magnetic field patterns leads to various other parameters of interest. The triangular mesh having 14643 nodes and 28924 elements derived using variational formulations based on minimizing energy for 2-D planar problems with first-order triangle elements are employed with precision close to 1 $\times 10^{-8}$.The estimated leakage inductance referred to secondary side is found to be 300 μH which is calculated via numerical integration method and in a limited shape and size of boundary.

Index Terms **- Pulse Transformer, Pulsed Power Supply, Finite Element Method (FEM), Vector Magnetic Potential.**

I. INTRODUCTION

The development of pulsed power supplies for various switching and industrial applications created a need for a relatively new type of transformer that transforms the energy in a pulse having a quasi-rectangular shape [2] and duration as low as1 μs .The most important use of pulse transformers has been the transformation of the energy in a pulse from a pulse generator to the impedance level of an RF oscillator or amplifier. The combination of high voltage source, pulse forming network (PFN), high voltage switch and pulse transformer (when required) is called a “power modulator” or “pulser”.

Historically, the pulse transformers have been employed to transfer or control energy by raising a voltage above a threshold or barrier level, invert the sign of voltage, effect " d-c isolation" between source and load, deliver the correct amount of power to a load of a given resistance by changing the voltage to the proper value, effect maximum transfer of energy (or power) from source to load by a transformation of energy to the proper impedance level.

Earlier [2, 6, 10, 11], numerous attempts have been done for modeling and design of high voltage pulse transformer. Due to availability of different analysis techniques and software packages, the modeling and simulation of the pulse transformer can be done with greater accuracy. In all earlier done works, there are many assumptions and approximations in modeling of magnetic field patterns inside and outside the core of pulse transformer like simple geometrical arrangement with rectangular core, approximated uniform idealized field, absence of core loss and nonlinearity of the core etc. In this paper, magnetic field patterns are developed with very less assumptions.

The flat top portion of the HV pulse output has the main component of total power output. As the pulse transformer is a major contributor to the waveform, the pulse transformer requires an accurate modeling and analysis.

Iron-based C-shaped amorphous alloy core material having combined property of low loss and high saturation flux density is used to provide high voltage and medium frequency. The core material also has low eddy current losses, low hysteresis losses, high saturation flux density (1.56T), high efficiency, low temperature rise, reduced weight and volume up to 50 %, operation at higher frequency at same flux level.

The signal handled by pulse transformer is usually a pulse (quasi-rectangular voltage pulse [2]) or a train of pulses and not a sinusoidal signal as in the case of a conventional power transformer. The transient response therefore plays an important role in defining the performance of the transformer. The Fig. 1 shows the wave shape of quasi-rectangular voltage pulse showing its related attributes.

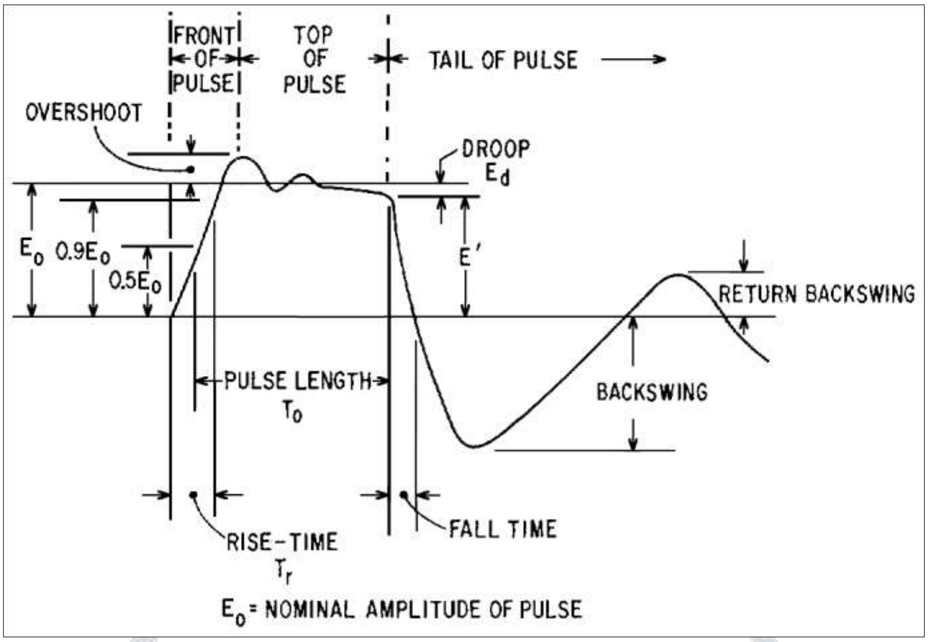

Fig. 1: Wave Shape of Quasi-Rectangular Voltage Pulse

The core and dielectric materials, magnetic circuits, cost, packaging technology and the associated electrical or electronic circuits are the contending elements among which a compromise is needed to have a good design.

II. Description and Design Methodology

Finite element technique [9, 13] is employed to visualize the patterns of vector magnetic potential $\vec{A}$ (in Wb/m), Magnetic flux density $|\vec{B}|$ (in T) andMagnetic field intensity $|\vec{H}|$ (in A/m) at various points in the specified region of interest of basket winding [6, 11] through the following algorithm :

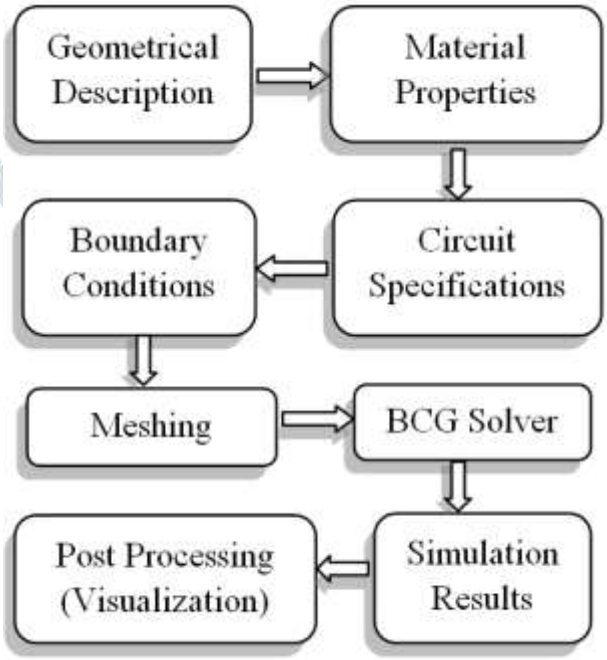

Fig. 2: Flow chart for estimation of field patterns

A. Electromagnetic (E.M.) Equations leading to required Partial Differential Equation (PDE)

The electromagnetics and field concepts used are as described :

$\vec{B}$ = Magnetic flux density (in T)

$\vec{A}$ = Vector magnetic potential (in Wb/m)
∇ = Vector differential operator
$\vec{H}$ = Magnetic field intensity (in A/m)
$\vec{J}$ = Conduction current density (in A/m^2)
μ_o= Permeability of free space (in H/m) = $4\pi\times10^{-7}$ H/m
μ_r= Relative permeability of material

$\nabla.\vec{B} = 0$ …(1)
(∵ Magnetic monopoles cannot exist, Maxwell's equation)

$\nabla.(\nabla \times \vec{A}) = 0$ …(2)
(∵ Vector Identity)

From (1) and (2),
$\vec{B} = \nabla \times \vec{A}$ …(3)

Applying Curl operator both side of (3), we get,
$\nabla \times \vec{B} = \nabla \times \nabla \times \vec{A} = \nabla(\nabla.\vec{A}) - \nabla^2\vec{A}$ ...(4)

For Static Magnetic Field
$\nabla.\vec{A} = 0$ …(5)

Therefore, (4) becomes
$\nabla \times \vec{B} = -\nabla^2\vec{A}$ …(6)

For Linear and Isotropic materials
$\vec{B} = \mu_r\mu_o\vec{H}$ …(7)
and
$\nabla \times \vec{H} = \vec{J}$ …(8)

Hence, (6) becomes
$\nabla^2\vec{A} = -\mu_r\mu_o\vec{J}$ …(9)
i.e.
Vector Laplacian of Vector Magnetic Potential= -μ_o μ_r(Conduction Current Density Vector)

The advantage of using the vector potential formulation is that all the conditions to be satisfied have been combined into a single equation. If $\vec{A}$ is found, $\vec{B}$ and $\vec{H}$ can then be deduced from $\vec{A}$. The equation (9) is an elliptic partial differential equation which arises in the study of many different types of engineering phenomenon.

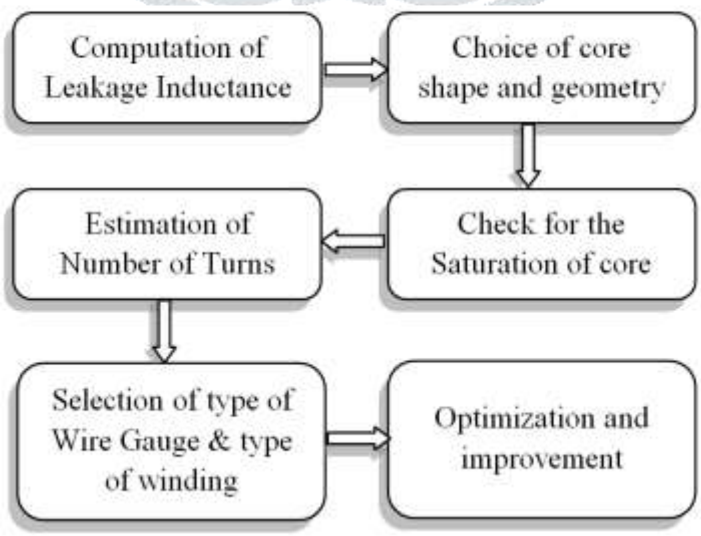

Fig. 3: Flow chart of traditional design procedure of pulse transformer

B. Finite Element Analysis

The Finite Element Method is a mathematical tool to numerically solve the partial differential equations (PDEs) especially whose exact closed form of solution is not possible. FEM are so popular and efficient because a large class of partial differential equations (PDEs) of engineering importance can be handled and those partial differential equations (PDEs) can be solved on almost any arbitrary shaped region.

Although the differential equations of interest appear relatively compact, it is typically very difficult to get closed-form solutions for all but the simplest geometries. This is where finite element analysis comes in. The idea of finite elements is to break the problem down into large number regions, each with a simple geometry (e.g. triangles).The advantage of breaking the domain down into a number of small elements is that the problem becomes transformed from a small but difficult to solve problem into a big but relatively easy to solve problem. Through the process of discretizaton, a linear algebra problem is formed with perhaps tens of thousands of unknowns. However, algorithms exist that allow the resulting linear algebra problem to be solved, usually in a short amount of time.

Finite Element Method addresses the limiting cases of Maxwell's equations. The magnetics problems addressed are those that can be considered as "low frequency problems," in which displacement currents can be ignored. Displacement currents are more prominent at higher frequencies and not considered in the simulation presented.

C. Magnetic Boundaries Constraints

Boundary conditions for magnetic problems basically are of five types viz. Dirichlet boundary condition, Neumann boundary condition, Robin boundary condition, Periodic boundary condition, Antiperiodic boundary condition.

The boundary method implemented in the simulation is a type of Improvised Asymptotic Boundary Condition (IBAC) called the open boundary method in which the magnetic field lines pass the boundary of the modeled region in the same way that they would as if the modeled object were truly in unbounded space.

D. Finite Element Method (F.E.M.) Simulation Results

The triangular mesh in this simulation is derived using variational formulations based on minimizing energy for 2-D planar problems with first-order triangle elements [3]. The simulation time has been reduced by a node renumbering scheme [4]. The complex symmetric version of biconjugate gradient (BCG) solver is used [5]. The results are as shown in Fig. 4, Fig. 5 and Fig. 6:

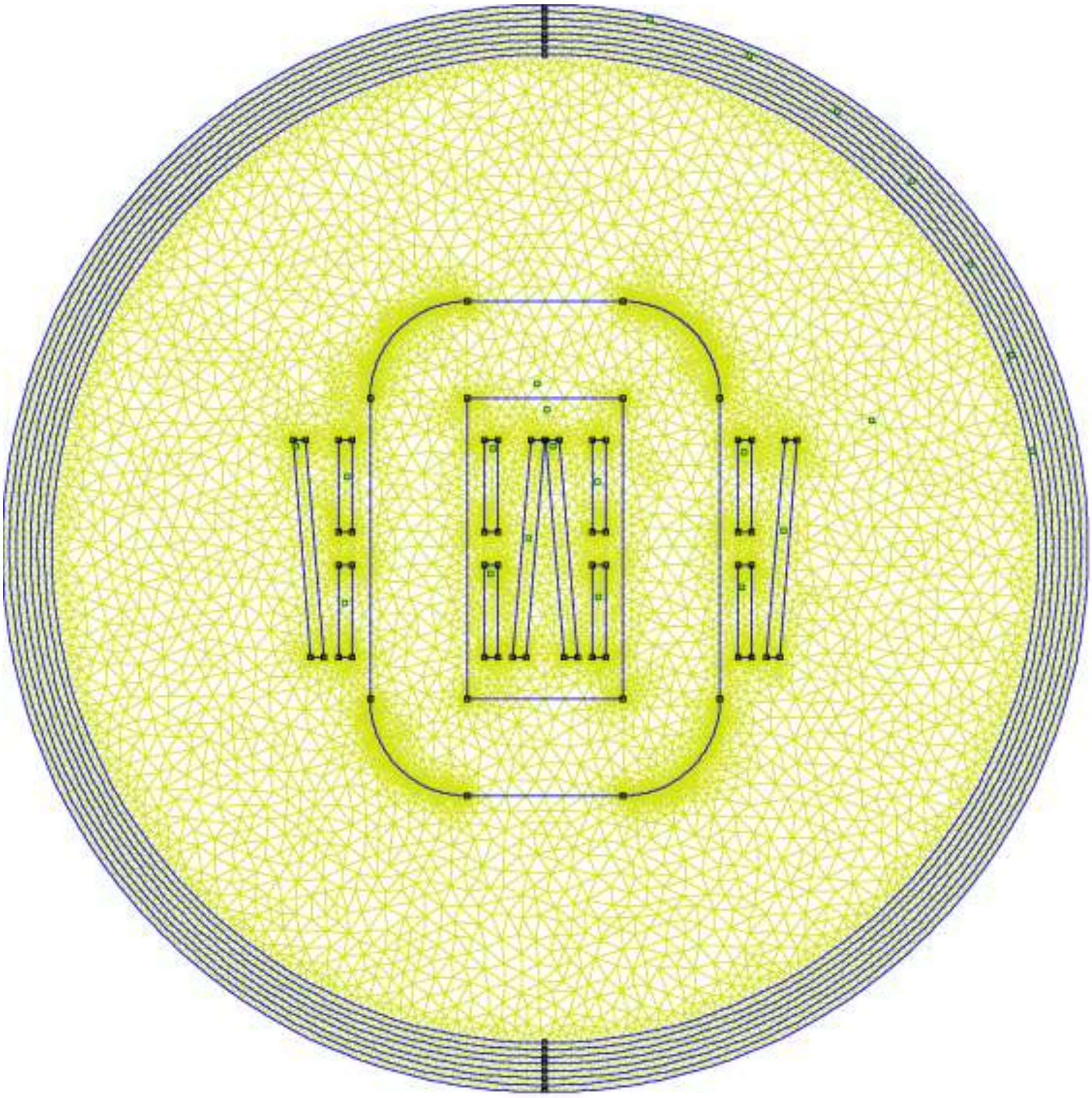

Fig. 4: Geometry and Meshing with 14,643 nodes

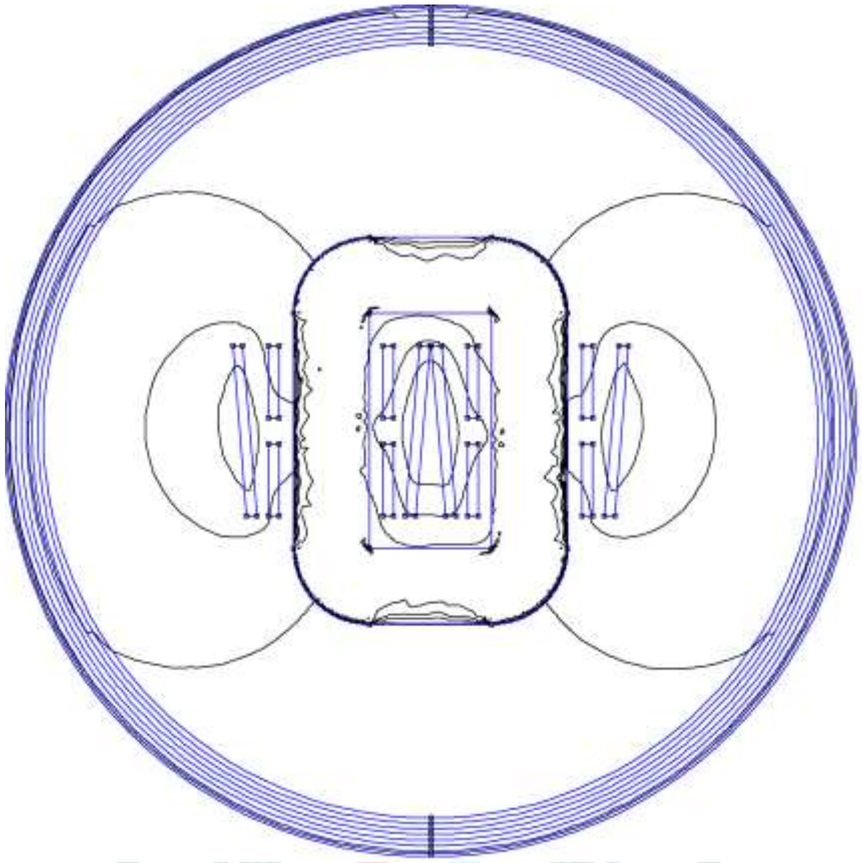

Fig. 5: Magnetic Field outside the C-shaped core

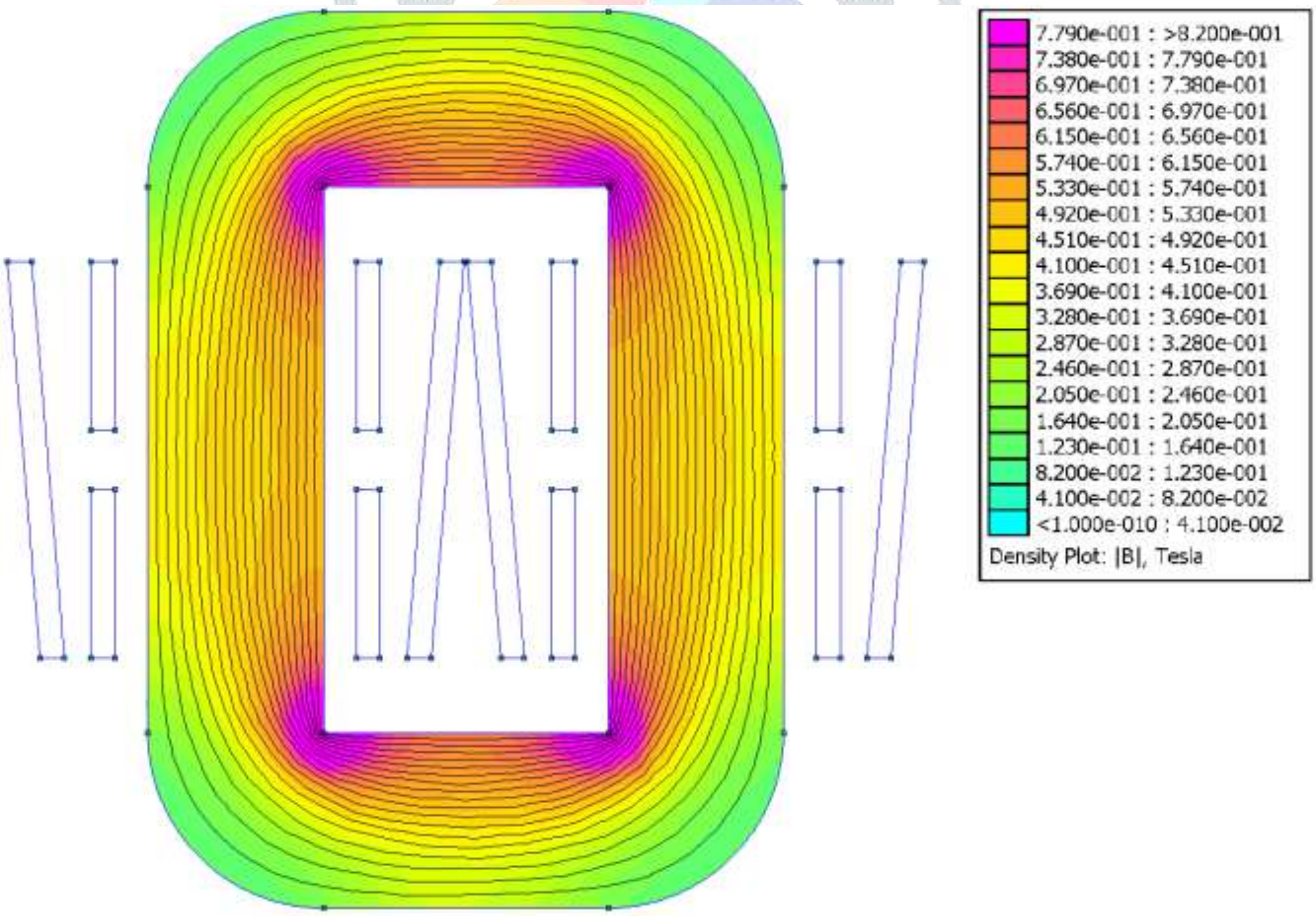

Fig. 6: Magnetic Field inside the C-shaped core

E. Transformer Details

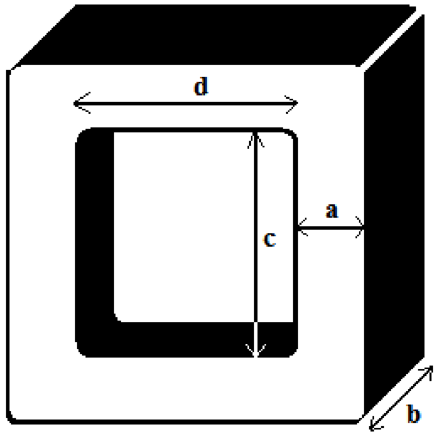

Fig. 7: Geometrical dimensions of pulsed transformer

a =	5.8738cm
b =	4.9213cm
c =	18.2563 cm
d =	9.5250 cm
Packing Fraction of Core Area (P.F.) =	0.8
Area of Cross-Section (A_c) =	a×b× P.F.= 0.0023 m^2
Maximum magnetic field in core (B_{max}) =	0.8 T
Secondary Output Voltage (E_s) =	25kV
On Time (t_p) =	10μs
Minimum Secondary Turns ($N_{s, min}$) =	$\frac{E_s \times t_p}{B_{max} \times A_c}$ =135.86
Secondary Turns actually taken (N_s) =	150
Magnetic field in core corresponding to (N_s = 150) =	$\frac{E_s \times t_p}{N_s \times A_c}$ = 0.725 T [<0.8 T (acceptable)]
Primary Output Voltage (E_p) =	1 kV (given)
Transformation Ratio (a) =	25kV / 1 kV = 25
Primary Turns (N_p) =	$=\frac{N_s}{a}$ =6
Secondary Side Top offset =	2.5 cm
Secondary Side Bottom offset=	2.5 cm
No. of Parallel Paths in Secondary =	2
Secondary Side Current =	2 A
No. of Sections in Primary =	4
Primary Side Top offset =	2.5 cm
Primary Side Middle offset =	2 cm
Primary Side Bottom offset=	2.5 cm
Full Load on Secondary Side =	12.5kΩ (given)
Breakdown strength of air(V_b) =	30 kV/cm
Secondary winding top distance offset =	$\frac{E_s}{V_b}$× Safety Factor= $\frac{25}{30}$ × 2= 1.67 cm

(a, b, c, d: $(given)$; B_{max}, E_s, t_p: $(given)$; Secondary Side Top offset through Primary Side Bottom offset: $(given)$)

III. CONCLUSION

In this paper, an attempt has been made to carry out the simulation for the magnetic field patterns for the iron based C-shaped amorphous alloy core of a pulse transformer having basket windings through the vector magnetic potential formulation via finite element method. A more suitable solid state pulse modulator can be designed with the deeper understanding of the parameters of pulse transformer and its influence on the output waveform. The estimated leakage inductance referred to secondary side is found to be 300 μH which is calculated via numerical integration method and in a limited shape and size of boundary.

IV. Acknowledgment

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