Classical modeling of High Voltage Pulse Transformer

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Abstract : This paper presents the brief review about the high voltage pulse transformer specifically utilized for the pulsed power supplies. A conventional classical block diagram for the lumped parameter model of the high voltage pulse transformer has been presented. Also the procedure to evaluate Inverse Transmission parameters is discussed.

***Index Terms*–Pulse Transformer, Pulse Power Technology, Lumped equivalent circuit, Inverse Transmission Parameters**

I. INTRODUCTION

Pulse modulators often employ high voltage pulse transformers. A magnetic coupled device designed for voltage pulse transmission between its input and output is called a pulse transformer. The waveform and quality of output voltage pulse for topologies based on pulse transformers, depends strongly on the performance of pulse transformer [1].The pulse transformer is a major contributor to the waveform. The major portion of total output power resides in the flat top portion of output high voltage rectangular pulse which is affected by the parasitic elements, leakage inductances and winding capacitance of the high voltage pulse transformer. Unlike the case of conventional power transformer in which supply is of sinusoidal nature, the high voltage pulse transformer works with voltage pulse of quasi rectangular nature [2]. The high power SMPS (Switched Mode Power Supply), control circuits working on low power etc. also have pulse transformers as their essential component.

In various modulators, it is required that the voltage pulse transformer should have low leakage inductance, high permeability core, low inter-winding capacitance etc. For the proper and desired operation of a pulse transformer it is necessary that no magnetic saturation occurs.

The high voltage pulse transformers' signal fidelity depends on the parasitic and non-ideal parameters of the transformer i.e. equivalent resistance, self-capacitance of each winding, inter-winding capacitance etc. Signal fidelity is the correct preservation of the relative amplitudes of the various parts of the signal at the output i.e.it denotes how accurately a copy reproduces its source.

Figure 1. Input – Output waveforms of ideal pulse transformer

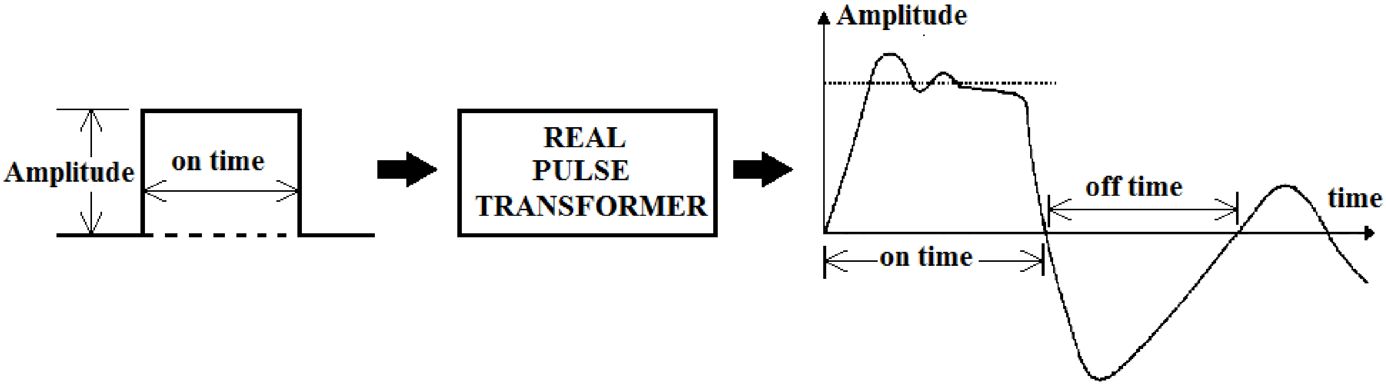

Figure 2. Input – Output waveforms of real pulse transformer

For analysis purpose, the high voltage pulse transformer is modeled as a lumped parameter equivalent circuit [1, 9]. Although, for a high voltage pulse transformer leakage inductances, winding capacitance and parasitic elements are modeled as lumped circuit elements, but these elements are actually distributed. In high voltage pulse transformers distributed capacitance between primary and secondary is always present which accounts for the flow of current without traversing the leakage inductance from source to load and for the stored capacitive energy. Low value of distributed capacitance, leakage inductance and high open-circuit inductance is desired for a good high voltage pulse transformer otherwise the output pulse would be a poorer copy of input pulse.

It is desired that the voltage droop, rise time, and pulse distortion are as low as possible for a superior high voltage pulse transformer. Droop is the decline in amplitude of the output pulse voltage over the duration of pulse. Droop in output pulse is caused by the increase in magnetizing current during the time duration of the pulse. Core saturation is a function of voltage-time product. The high voltage pulse transformer's cost and size is roughly a linear function of voltage-time product. The high voltage pulse transformer must be "switched off" before the occurrence of its core saturation. In case of common alternating current transformer the magnetic flux changes between negative and positive values but in case of high voltage pulse transformer, the magnetic flux does not become negative, however it may become zero. Thus the high voltage pulse transformer is said to be operating in a unipolar mode. By using suitable configurations of winding to increase the coupling between the windings, parasitic elements such as capacitance of windings and leakage inductance could be minimized.

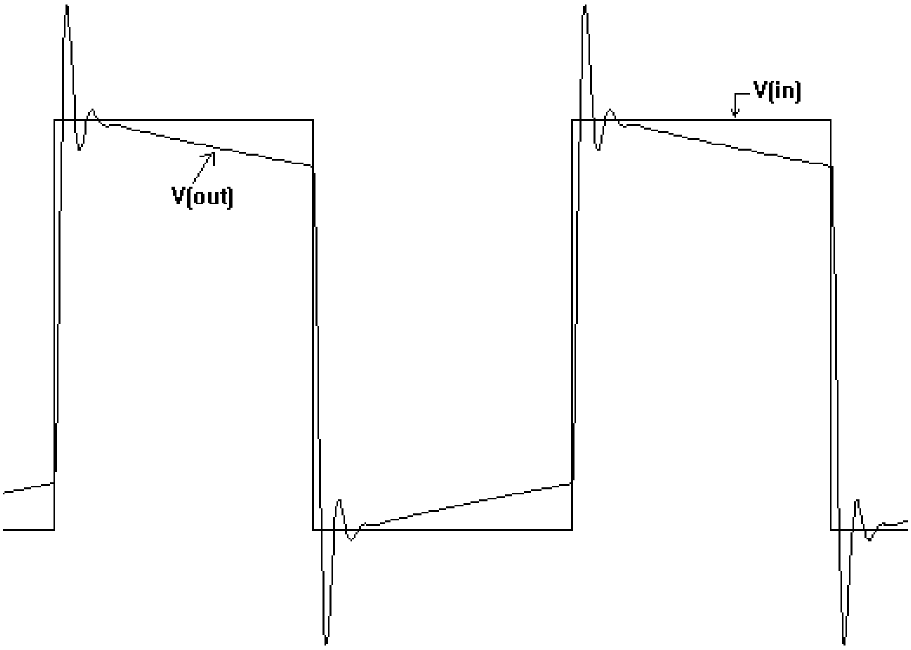

Figure 3. Pulse transformer with under damped response

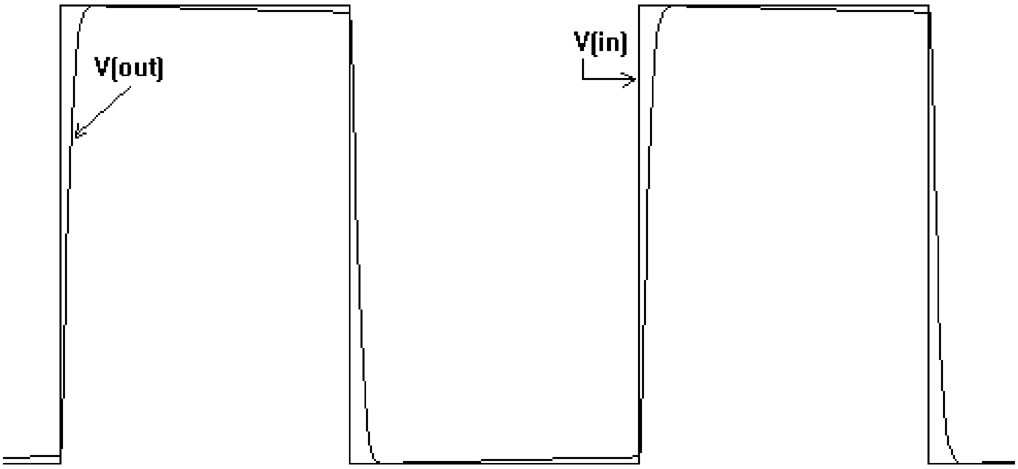

Figure 4. Pulse transformer with critical response

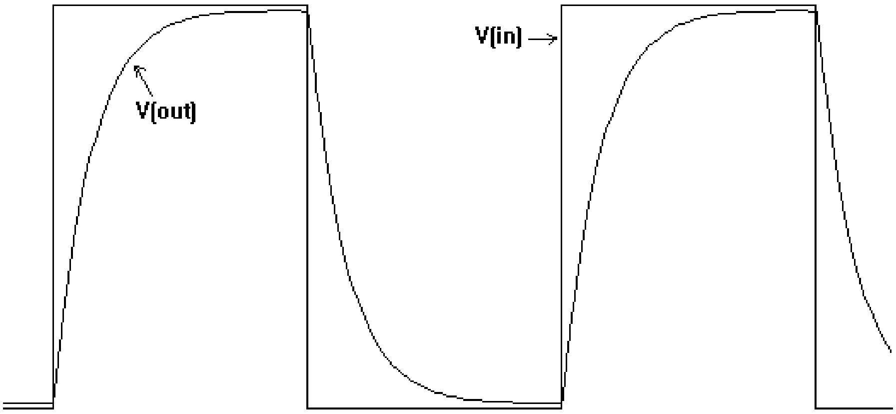

Figure 5. Pulse transformer with over damped response

The core materials used for high voltage pulse transformer are CRGO (Cold Rolled Grain Oriented) Silicon Steel, Amorphous cores, Nano-crystalline cores and Ferrite cores [1]. Usually there is a little silicon content in the Grain-oriented steel employed for electrical operations. The CRGO steel is made in such a way that in the rolling direction, the desired and best suited properties are developed by a strict control of the orientation of the crystal with respect to the sheet. CRGO is employed for the power and distribution transformers' cores. Amorphous core's material is a thin amorphous metal alloy ribbon produced by using rapid solidification process. A unique ferromagnetic property of amorphous cores is that it allows its ribbon to be magnetized and de-magnetized rapidly with lesser core losses at power frequencies maintaining the maximum relative permeability. These types of core have a non-crystalline structure and possess unique physical and magnetic properties that combine high permeability, strength and hardness with flexibility and toughness. A nano-crystalline (NC) material is a polycrystalline material with a crystallite size of only a few nanometers. A nano-crystalline alloy of a standard iron-boron-silicon alloy has smaller amounts of copper and niobium. The grain size of the powder reaches down. The material has very good performance at lower frequencies.Ferrites are ceramic compounds of the transition metals with oxygen, which are ferrimagnetic but nonconductive. Ferrites that are used in transformer or electromagnetic cores contain iron oxides combined with nickel, zinc, and/or manganese compounds. They have a low coercivity and are called "soft ferrites" to distinguish them from "hard ferrites", which have a high coercivity and are used to make ferrite magnets. The low coercivity means the material's magnetization can easily reverse direction without dissipating much energy (hysteresis losses), while the material's high resistivity prevents eddy currents in the core, another source of energy loss. Ferrite core is used for its properties of high magnetic permeability coupled with low electrical conductivity (which helps prevent eddy currents). Because of their comparatively low losses at high frequencies, they are extensively used in the cores of RF transformers and inductors in applications such as switched-mode power supplies.

Among the various topologies represented in the literatures, basket or cone winding type pulse transformer is most general one because in that by changing its windings angle, it can be modified to parallel winding type [7]. There are three types of pulse transformer considering its topology: parallel winding, cone winding and foil winding. It is also known that the cone winding has the best response compared to the other topologies as far as the rise time improvement is concerned [7].

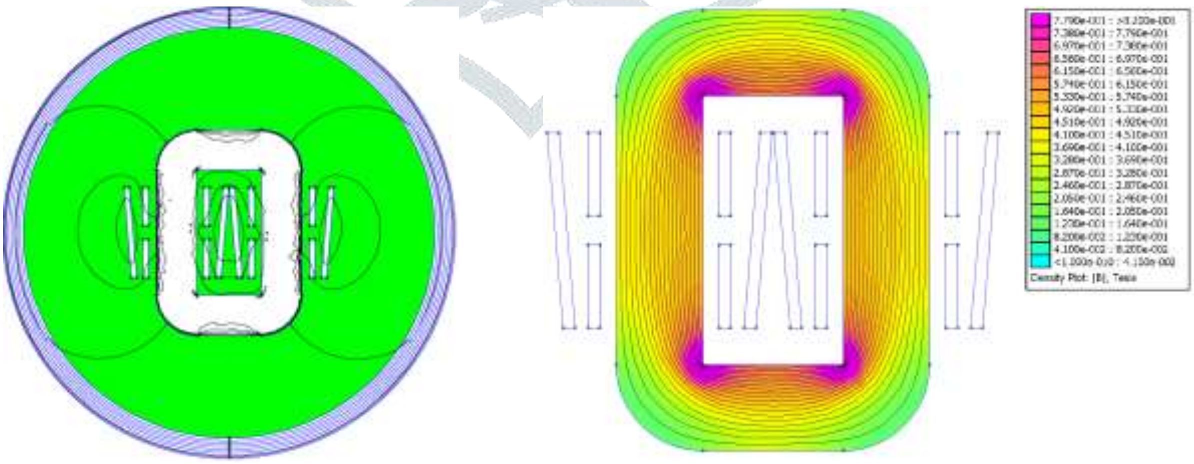

Figure 6.Magnetic field patterns for the cone winding pulse transformer

II. FOUNDATIONS

The meaning of symbols is as described :

$\boldsymbol{R_{1a}}$ = Part of primary winding resistance (Ω)
$\boldsymbol{R_{1b}}$ = Part of primary winding resistance (Ω)
$\boldsymbol{L_c}$ = Primary side inductor accounting for the association of charging current with magnetic field (H)
$\boldsymbol{C_c}$ = Stray capacitance of primary winding to ground (F)
$\boldsymbol{R'_{2b}}$ = Part of secondary winding resistance referred to primary side (Ω)
$\boldsymbol{R'_{2a}}$ = Part of secondary winding resistance referred to primary side (Ω)
$\boldsymbol{L_1}$ = Leakage reactance of primary side (H)
$\boldsymbol{L'_2}$ = Leakage reactance of secondary side referred to primary side (H)
$\boldsymbol{L'_D}$ = Secondary side inductor accounting for the association of charging current with magnetic field referred to primary side (H)
$\boldsymbol{C'_D}$ = Stray capacitance of secondary winding to ground referred to primary side (F)
$\boldsymbol{C'_3}$ = Capacitance between primary and secondary referred to primary side (F)
$\boldsymbol{R_e}$ = Core loss resistance (Ω)
$\boldsymbol{L_e}$ = Magnetizing reactance of core (H)

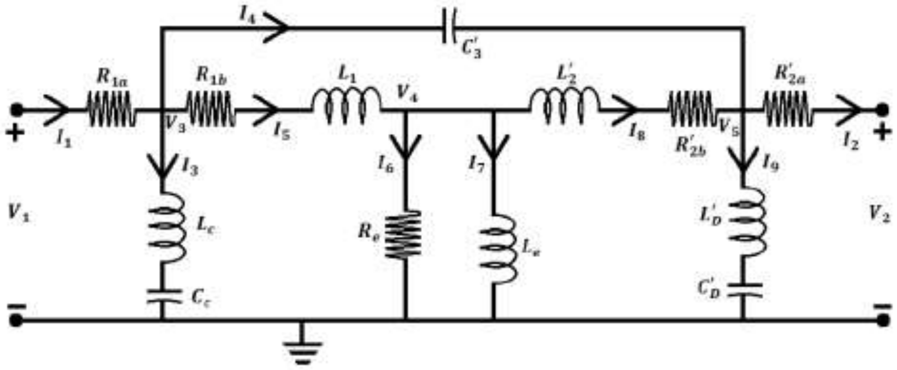

Figure 7.Lumped parameter equivalent circuit diagram of pulse transformer [1]

The governing equations leading to the development of multi input multi output (MIMO) conventional classical block diagram for the lumped parameter equivalent circuit of the high voltage pulse transformer are as described :

$$V_3 = V_1 - I_1 R_{1a} \qquad \text{eq. …(1)}$$

$$V_4 = V_3 - I_5 (R_{1b} + sL_1) \qquad \text{eq. …(2)}$$

$$V_5 = V_4 - I_8 (R'_{2b} + sL'_2) \qquad \text{eq. …(3)}$$

$$V_2 = V_5 - I_2 R'_{2a} \qquad \text{eq. …(4)}$$

$$I_3 = \frac{V_3}{sL_c + {}^{1}\!/_{sC_c}} \qquad \text{eq. …(5)}$$

$$I_6 = \frac{V_4}{R_e} \qquad \text{eq. …(6)}$$

$$I_7 = \frac{V_4}{sL_e} \qquad \text{eq. …(7)}$$

$$I_9 = \frac{V_5}{sL'_D + {}^{1}\!/_{sC'_D}} \qquad \text{eq. …(8)}$$

$$I_4 = \frac{V_3 - V_5}{{}^{1}\!/_{sC'_3}} \qquad \text{eq. …(9)}$$

$$I_5 = I_1 - I_3 - I_4 \qquad \text{eq. …(10)}$$

$$I_8 = I_5 - I_6 - I_7 \qquad \text{eq. …(11)}$$

$$I_2 = I_1 - I_4 - I_9 \qquad \text{eq. …(12)}$$

These equations are developed based on the operating performance of the high voltage pulse transformer. The corresponding classical block diagram for the lumped parameter equivalent circuit of the high voltage pulse transformer is as described :

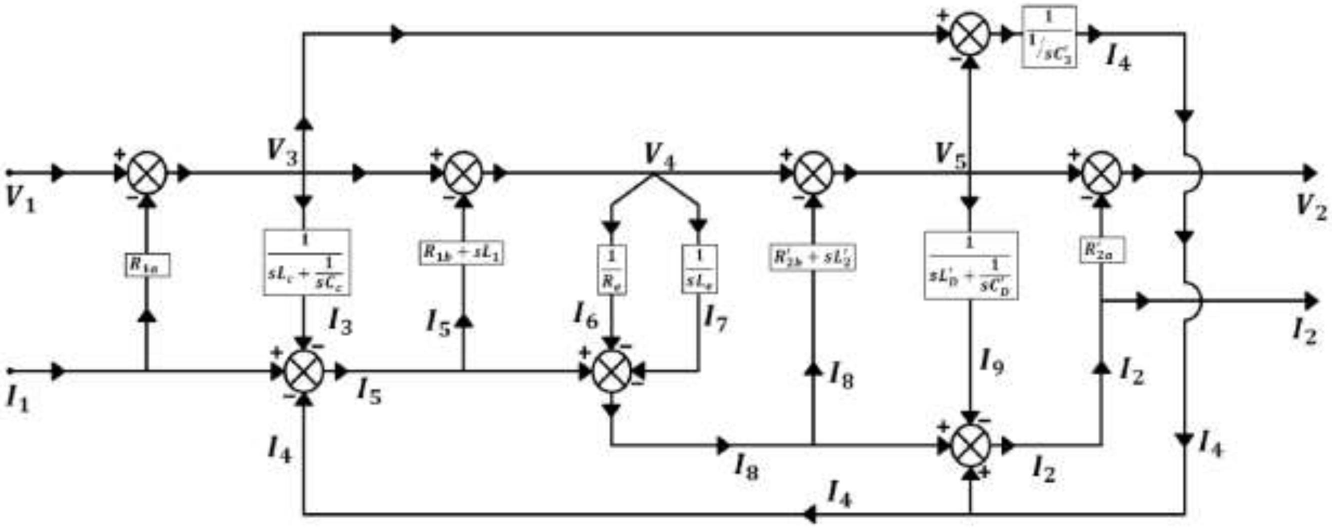

Figure 8.Classical control system block diagram of the lumped equivalent circuit of the high voltage pulse transformer

III. OCTAVE CODES FOR THE SIMPLIFICATIONS

For convenience, prime notation has been dropped.

After the suitable initialization of variables namely R1a, R1b, R2a, R2b, L2, Lc, L1, Re, Le, Cd, C3, Cc and Ld, the following code is implemented in octave :

```
s=tf('s');
```

```
G1=R1a;
G2=((Lc*Cc*s^2)+1)/(Cc*s);
G3=L1*s+R2a;
G4=(Le*s+Re)/(Le*Re*s);
G5=L2*s+R2b;
G6=((Ld*Cd*s^2)+1)/(Cd*s);
G7=R2a;
G8=1/(C3*s);
Ga=G3+G4+(G3*G4/G5);
Gb=G4+G5+(G4*G5/G3);
Gc=G3+G5+(G3*G5/G4);

Gd=Gc*G8/(Gc+G8);
Ge=Gb*G6/(Gb+G6);
Gf=G2*Ga/(G2+Ga);

Gg=(Gf*Gd)/(Gd+Ge+Gf);
Gh=(Gd*Ge)/(Gd+Ge+Gf);
Gi=(Gf*Ge)/(Gd+Ge+Gf);

Gj=G1+Gg;
Gk=Gh+G7;

A1=1+(Gk/Gi)
B1=Gi-((Gi+Gk)*(1+(Gj/Gi)))
C1=-1/Gi

D1=1+(Gj/Gi)
V2_by_V1=(A1*D1-B1*C1)/D1
```

Here, the quantities A1, B1, C1 and D1 are basically the s- domain inverse transmission parameters corresponding to the equations :

```
V2 = A1 V1 + B1 I1
I2 = C1 V1 + D1 I1
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and the quantity V2_by_V1 is denoting the open circuit voltage gain. Furthermore, various other quantities of interest say input impedance, output impedance and responses corresponding to various inputs may be evaluated

IV. CONCLUSION

In this paper, an attempt has been made to present a brief review about the high voltage pulse transformer. A conventional classical block diagram for the lumped parameter model of the high voltage pulse transformer has also been presented and the procedure to evaluate inverse transmission parameters is described.

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