Design of High Voltage Pulse Transformer for Solid State Pulse Generator for PIII applications, and Prototype Development

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Abstract:-

A pulse power modulator is a device which delivers a train of pulses to a pulsed load. Pulse power modulators are used for linear accelerators, radar applications, PIII applications, lasers etc. This paper is mainly related to PIII applications. Different types of topologies are existed in pulse power modulators for PIII application. Solid State Switching Pulse transformer Topology has been studied and implemented in this paper. This paper describes design and a proto type development of HV pulse transformer capable of delivering 50kV, 10A, pulse width of 10µsec and 400Hz repetition rate having a rise time less than 1 µsec.

1. INTRODUCTION

This paper gives detailed information about design of HV pulse transformer (which is of solid state type) used for PIII application. Plasma Immersed Ion Implantation (PIII) is a technique to change the surface composition of materials thereby improving the mechanical, chemical, electrical or optical properties of the base material. Pre-manufactured parts are immersed in a plasma and are pulsed with a high voltage source that accelerates the ion to the surface, where they become implanted, modifying the surface characteristics. Pulse Power Modulators are used for generating the required HV Pulses. Design of Solid State 50kV HV pulse generator is described below.

2. TOPOLOGY

The requirements on the generated pulses vary regarding for example rise/fall time, overshoot, back swing , pulse flatness and pulse energy are very high and can vary from application to application. Therefore pulsed power systems are built in different topologies. The performance of these modulators depends to a great extent on the pulse transformer performance. Nowadays a lot of development takes place in solid state technology. Therefore Solid State topology is preferred for this case. A lot of pulsed power systems use a pulse transformer to step up the voltage.

A. Pulse transformer topology:-

The basic circuit diagram is shown in the figure1.Need of high voltage switches are avoided by using step up pulse transformer. In the above description pulse transformer which is considered is of fractional turn type. To reduce the leakage inductance more number of primaries are used either a single switch is used or individual switch is used across each primary side. It provides a satisfactory rise time, so it would be convenient to keep the same transformer core and secondary structure and simply rewound the primary windings. Instead of fractional type if simple transformer construction is used according to the specifications, core is effectively not used and primary pulse current is more than several times of the load current, therefore for the same specifications fractional turn winding is preferred compared to simple construction due to some advantages. By using the transformer voltage is transferred to the load. When different voltages appear across the primary terminals individual switch is preferred compared to common switch.

The advantage of this topology is that the power switching is at comparably low voltage (1kV typically), and there is no need for seriesing of IGBTs. The only concern is to ensure equal current sharing between IGBTs, connected in parallel. IGBTs capable of handling up to 1700/3600A, 3300V/1200A are available, and can cater to most of the PIII applications.

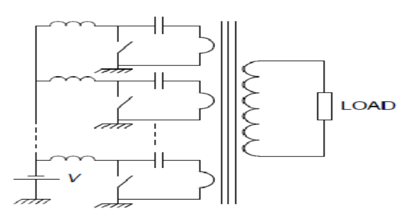

Fig1. Pulse Transformer Topology Scheme

3. SPECIFICATIONS

Output voltage: 50kV
Output Current: 10A
Pulse Repetition Rate: 400Hz
Pulse width: 10µsec
O/P Voltage Pulse Rise time :< 1µsec
Peak Power: 500kW
Average Power: 2000W
Input Voltage: 1kV
Input Current: 500A

4. DIFFERENT TYPES OF CORE MATERIALS

The magnetic material is the important material and plays major role in the implementation of pulse transformer. Core material which have higher flux densities, higher permeability and lower core losses make it possible to design the pulse transformer with low leakage inductance and distributed capacitance.

The common magnetic materials are silicon steel, Ferrite and Amorphous alloys. Locally available 11mil Silicon steel (CRGO) cores are not used for pulse power applications because of high eddy current losses.1mil or 2mil silicon steel cores are used for these applications. Silicon core have advantage of high B_s (1.5T) compared to ferrite cores. Ferrite cores have low core losses but having disadvantage of low B_s (0.4T) which lead to larger core volume of the pulse transformer. Amorphous cores have larger flux swing and low core losses. Amorphous magnetic cores allow smaller, lighter and more energy efficient designs in many high frequency applications. These cores offer superior design alternatives when used as a core material. Cobalt based 30KCP core studied and is used for experiments.

A. Core characterization of 30KCP:-

The chemical composition of the amorphous core material is Fe (63.95%), Co (30%), Cr (3%), B (3%) and C (0.05%) under the trade name of 30KCP.

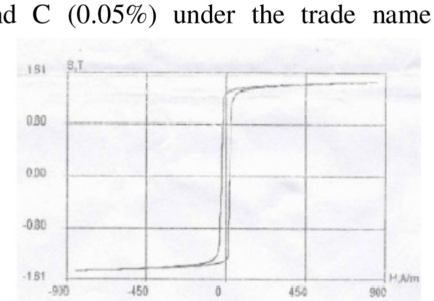

Fig 2.B-H loop of the core material

The core is made from 25µm thick tapes with SiO_2 insulation between layers and annealed in longitudinal field.

The magnetic characteristics provided by the manufacturer at 50Hz indicates that the core material has a flux swing around 3T ($-B_{max}$ to $+B_{max}$) and coercive field of 12A/m.The B-H loop of this core is shown in figure 2.Before using the core, it was cleaned with alcohol and then two layers of 2 mil semi-cured kapton tapes were wound on it to prevent incursion of outside dirt and any damage during handling the material.

5. NEED FOR CORE BIASING

For pulsed power applications pulse transformer is takes place major role. The basic circuit diagram is shown in the figure 3. Pulse transformer is a device which transfers unidirectional pulses from one level to another level. The repetitive unipolar pulse voltage leads to a unipolar flux swing in the core material. . It is well known that core gets saturated after the repeated applications of unidirectional pulses due to its retentivity.

Due to this the B-H curve of the core material always traverse the minor loop i.e. remains in the first quadrant. It never moves beyond zero to the negative magnetization region rather it comes back at the point of B_r on the B-H curve. Due to this the ΔB (incremental flux swing) available is just B_m-B_r.

By using the core resetting methodology ΔB (incremental flux swing) is double the value of the incremental flux swing without resetting, core material is optimally used and rise time is reduced compared to without resetting. Therefore core resetting is preferred for rise time reduction and optimal usage of the core material.

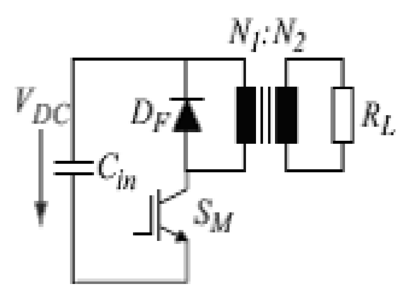

Fig3. Basic Circuit Diagram

A. D.C.Resetting:-

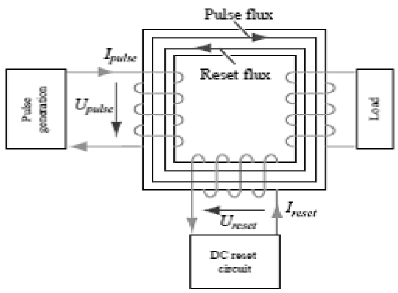

Fig4.Block diagram of circuit considering Reset winding

The most common method for core resetting in a pulse transformer is a D.C. resetting method. General block diagram is shown in the figure4. In D.C resetting D.C. current is used, this current can be supplied to the primary, secondary or tertiary. In order to keep the considerations in general tertiary winding is used. The current of the D.C. reset is flowing in a direction that generates a magnetic flux which is in opposite direction than the flux induced by the voltage pulse.

A large inductor is placed between the reset winding of the transformer and the power supply to protect the supply from high voltage pulses. The inductor is one of the largest components of the D.C. reset circuit.

The third winding is connected to the reset circuit which is represented by a series connection of the voltage source U_{reset} and the inductor L_{choke} with R_{choke}.

Depenidg on the core material the flux density in the core is B_{rem} and the starting point of the system in the B-H curve is A_1 shown in the figure5.

Assumin Upulse is zero , the current through the inductor and the magnetizing inductance is rising to Ireset as soon as the reset circuit is turned on.with the above equation the d.c. current Ireset leads to aconstant H-field and therefore to a constant flux density B_{reset} in the core .

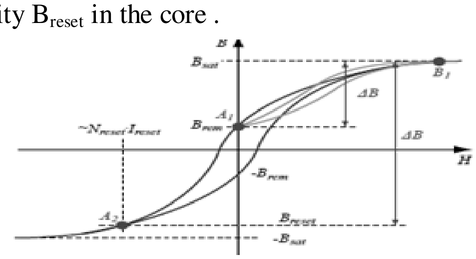

Fig5.B-H loop

During start up the operating point moves from A_1 to A_2 where H_{reset} and B_{reset} can be expressed as

$$H_{reset}= N_{reset}.I_{reset}/l_e \text{ and } B_{reset}=\mu_0.\mu_r H_{reset}$$

Assuming H_{reset} is fixed due to the hysterseis curve of the core material increasing the number of turns N_{reset} results in a smaller reset current I_{reset} and viceversa.As soon as the sytem reaches operating point A_2 an output pulse could be generated (section S_1). With the assumption of a rectangular voltage pulse faraday's law can be simplified as

$$U_{pulse} =N_{pri}.A_{core}.\Delta B/\Delta t \text{ with } \Delta t=T_1.$$

The voltage pulse results in a change of flux density ΔB which can be maximal $2B_{sat}$ (with $B_{sat}=B_{reset}$) for a system with D.C. reset circuit.a system without d.c. reset circuit is limited to $B_{sat}-B_{rem}$ i.e. from A_1 toB_1.By this reduction of the flux swing a core cross section twice as big as with reset must be used.

6. DESIGN DETAILS

Due to its high flux swing and high permeability 30KCP core (torroidal shape) is used for experimental point of view. Tapered winding is preferred (constant gradient approximation) has been used so as to minimize the leakage inductance. According to the given dimensions of the Core and specifications of pulse transformer parameters are estimated.

A. For 30KCP:-

Core dimensions are

Inner diameter=220mm

Outer diameter=390mm

Height of the core=25mm

Considering stacking factor = 0.8

Effective cross sectional area=$17*10^{-4}$ m^2

Effective length of the magnetic circuit=0.958m

Then according to the specifications and core material data

We know

$$V = N.d\phi/dt \quad (1)$$

$$V=N.A_e.\Delta B/dt \quad (2)$$

$$N= (V*\Delta t)/ (\Delta B*A) \quad (3)$$

Number of turns on the primary side=3

Number of turns on the secondary side =150

We know

Magnetizing inductance (Lm) $=\mu_0.\mu_e.N^2.A/l_m$

Leakage inductance (L_L) = $\mu_0.N^2.\Delta.U/l_w$

Distributed capacitance (C_D) = $\epsilon_0.\epsilon_r.l_w.U/\Delta$

Where

μ_e = Effective Permeability

$\mu_o = 4\pi \times 10^{-7}$ (Permeability of free space)

l_e = effective length of the magnetic circuit

A_e = effective cross sectional area of the core

l_w = winding length

Δ= distance between layers

U= mean circumference of the core

ϵ_0= permeability of free space

ϵ_r = dielectric constant of the insulation

d= distance between layers

Depending on the number of turns, effective cross sectional area, effective magnetic length and output load parameters of the pulse transformer are calculated.

Primary inductance =256µH

Secondary inductance =0.64H

Leakage inductance =1.03mH

Distributed capacitance =41.5pF

Reset circuit calculations:-

We know $H_{reset} * l_e = N_{reset} * I_{reset}$

Assume H_{reset}=30A/m

Therefore $H_{reset} * l_e$=28.74 A turns.

If same number of primary turns considered in the reset winding then I_{reset}=6A

Due to unavailability of the bigger core proto type development was made using smaller core with dimensions of

Outer diameter=240mm

Inner diameter=160mm

Height of the core=25mm

The experiment was conducted for a output voltage of 30kV

Considering input voltage=860V

By using the equation 3

Number of turns on the primary side=3

Number of turns on the secondary side =170

Depending on the number of turns, effective cross sectional area, effective magnetic length and output load, parameters of the pulse transformer are calculated.

Primary inductance =200µH

Secondary inductance =0.642H

Leakage inductance =1.4uH

Distributed capacitance =30pF

Reset circuit calculations:-

We know $H_{reset} * l_e = N_{reset} * I_{reset}$

Assume H_{reset}=30A/m

Therefore $H_{reset} * l_e$=18.84 A turns.

According to the tests performed on the core for estimation of permeability it is concluded that reset current of 2A is optimum for pulse transformer operation.

Therefore number of turns required in the reset winding=7 turns.

7. PROTO TYPE DEVELOPMENT

For 30KCP:-

Based on the above confirmation data and estimations pulse transformer was designed. Teflon tape was used for holding the cores in place as well as to provide some amount of insulation required. Over these tape two layers of the Kaplon tape wound and it provides additional amount of insulation. Over this layer the primary winding is wound and is provided with enough insulation of required layers of kaplon tape over it as the insulation between primary and secondary. Based on the estimations the number of turns in the primary were made of foil type. A single uniform foil has a problem of increasing spacing in between the turns. This will introduce more leakage inductance into picture. Therefore rise time will increases. If the leakage inductance value is minimum then better will be the rise time. Therefore each turn consists of appropriately shaped copper strips. The strips are soldered to each other at the outer diameter of the torroid so that they are in series. The secondary is wound over the primary to reduce the leakage inductance. The secondary is wound on a prospex with tapered profile .A suitable turn's ratio is selected and the winding is done keeping right spacing each turn with utmost care. The fabrication is finished by applying required H.V. side insulation and obtaining proper leads. The polarities are marked keeping in mind the sense of direction of winding. The distance in between the primary and secondary is more at the high voltage side and less at the low voltage side.

8.CIRCUIT OPERATION

The pulse transformer circuit experimental setup is shown in the above figure6. The pulse transformer prototype was operated in air. D.C. Voltage is converted into unidirectional pulses by using a switch. According to the given requirements IGBT is used as a switch. The IGBT used in this set up is Semikron make SKM 200GB 176D. The IGBT is rated to provide V_{CES} of1.7kV and I_C of 220A at T_C=25°C.The snubber connected across the IGBT ensures that the over-voltage across the IGBT during the switching OFF transient is within 1.2kV.Driver circuit is connected across the IGBT gate and emitter terminal for making the IGBT switch turn on condition.

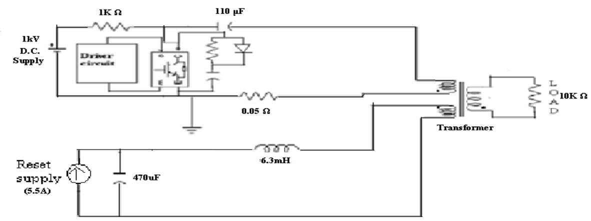

Fig 6.Operational circuit diagram

Capacitor (110μF) is charged by using a D.C. supply through a resistor (1kΩ). Resistor is connected to protect the circuit from high voltages. When IGBT switch is turn on capacitor is discharged and whatever the voltage appeared across the capacitor terminals is discharged and appeared across the pulse transformer input terminals. Experimental point of view at the output terminals (i.e. at secondary terminals) resistor is connected.

Tertiary winding is used for resetting the core. The Reset circuit consists of a Reset power supply (Constant Current Power Supply supplying 5.5A maximum) shunted by a High Value capacitor (470 μF) and a Blocking inductor (6.3mH). The inductor provides high impedance so that it doesn't introduce effect of tertiary voltage into primary during the operation. The capacitor limits the rise in the pulse voltage developed across the power supply, to a very low value.

The voltage across R_{SENSE} of 0.05 Ω is measured using a Tektronix makes 200MHz Bandwidth Oscilloscope.

A. Observations:-

A practical experiment is conducted on 30KCP core for 30kV output voltage. The pulse transformer prototype was operated in air. The IGBT was switched at a D.C. voltage of 860V. the pulse width was ~9.5μs.A pulse width of ~30kV was merasured across the load. The backswing of~1.6kV was measured.The two waveforms indicate exactly identical performance of the core at 15pps and 115pps operation. Pulse transformer primary current is measured across 0.05Ωshunt resistance.pulse transformer secondary voltage measured by 1000X probe across 10kΩ load. Experimental wave forms are shown in the figures 7 and 8.

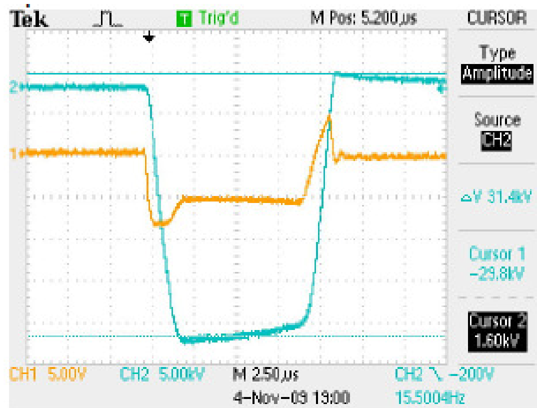

Fig7.outputwaveform$V_{D.C.}$ =861V, t=9.5μs. PRF=15pps, I_{reset} =2.85A

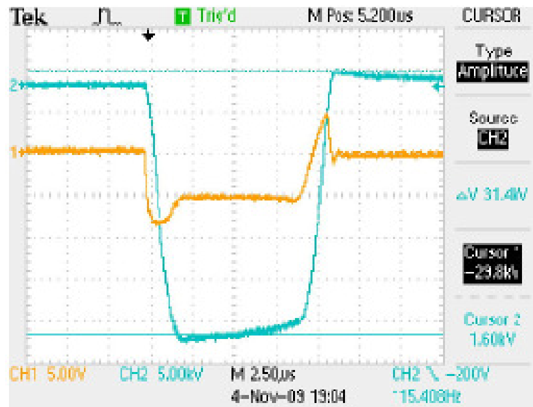

Fig8. All parameters are same as in the above fig except increased to115pps

9. CONCLUSION

A Solid State Pulse Power Modulator Using IGBT switches has been described. The usable flux swing for these cores is ~ 2.6T (-1.3T to +1.3T).The 1: 30 pulse transformer was tested at max 30kV, 9.5μs pulse width on 10kΩ load Resistance, for max 150 pps. . The pulse transformer response was over-damped and rise time measured was ~ 1μs. No variation in pulse shape was observed as a function of PRF. The prototype was in air, Hence sufficient spacing was introduced in the HV side.

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