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Experiment and simulation for Induced current analysis in Outer single turn coil with pulsed electromagnetic Central solenoid air core coil

Mr. J. B. Solanki
Lecturer, B.& B. Institute of Technology,
Vallabhvidyanagar. Anand, Gujarat, INDIA
Email: jayraj_ee@yahoo.co.in

Abstract -This paper present idea about the knowledge of designing a pulsed electromagnetic central solenoid air core coil and get methodology of verifying induced current in the modified assembly. 2 T coil has been designed with a toroidal shaped single turn outer coil of 12 cm diameter for this experiment. A 1 KV 640 μsec pulse has been given to the designed 2 T coil because of which pulsed current was induced in the outer single turn coil. To verify such pulsed induced current analysis is a difficult task, theoretically which can be equally calculated by a FINITE ELEMENT ANALYSIS package, so a same modified assembly has been modeled and meshed in ANSYS 11.0 FEA package with same load data as given in the practical. Theoretical and practical results have been Validated.

keywords :- *Pulsed Electromagnetic coil, cenntral solenoid ,FEA, PFN, ANSYS & PSCAD Software.*

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I. INTRODUCTION

A solenoid is a coil wound into a tightly packed helix.The magnetic field inside an infinitely long solenoid is homogeneous and its strength does not depend on the distance from the axis, nor on the solenoid coil cross-sectional area[2]. the term refers specifically to a long, thin loop of wire, often wrapped around a metallic core, which produces a uniform magnetic in a volume of space when an electric current is passed through it. Design the central solenoid coil as pulsed electromagnetic coil and outer coil as single turn toroidal coil according to requirement 2T in outer single turn coil[1],[3].

A pulse forming network (PFN) is an electric circuit that accumulates electrical energy over a comparatively long time, then releases the stored energy in the form of a relatively square pulse of comparatively brief duration for various pulsed power applications[5]. In a PFN, energy storage components such as capacitors, inductors or transmission lines are charged by means of a high voltage power source, then rapidly discharged into a load via a high voltage switch, such as a spark gap or Thyrister triggering Circuits[7]. The pulse forming network serves the dual purpose of storing exactly the amount of energy required for a single pulse and of discharging this energy in to load in the form of specified shape. These are coil supplied by the PFN capacitor discharge using voltage multiplier[6]. For that coil design and make the 1 KV pulse forming network power supply and the 1 KV voltage multiplier for supplied to PFN and make triggering Circuit for trigger thyrister.

Design the coil for 2 T magnetic field at centre of the solenoid. Then one single turn coil with fixer keep out side the inner coil. Inner coil wound on one 35 cm long Perspex cylinder rod and outer coil wound on one 20 cm long hollow Perspex cylinder at the centre.

PFN capacitor discharge into the central solenoid inner coil and measure the induced current in outer single toroidal coil[8]. Also model and simulate this coil in ANSYS software. For this coil make model and do meshing with boundary. From experiment result take some input for the ANSYS simulation . At the centre of coil get the magnetic field almost same which is nearest to the theoretical.

II. DESIGN OF CENTRAL SOLENOID AIR CORE COIL

Wire is wound on 5.514 cm diameter Perspex material rod which is inner coil with total number of 335 turns . It has Layers. Single outer turn coil placed at 4 cm distance far from the inner solenoid coil.

a) *Dimension of coil*

Inner radius of coil a1 =2.757 cm

Outer radius of coil a2 = 4.069 cm

length of coil = 2b = l =31.5 cm

No of turn per = 335

Inductance of coil by this equation[1]

$$L = \frac{4}{5}\frac{n^2 * a^2}{\left(6 * a + 9 * l + 10 * (a_2 - a_1)\right)}$$

L = 1.335 mH ….. by calculation

L = 1.330 mH ……by measurement

Resistance of coil = 0.7 Ω

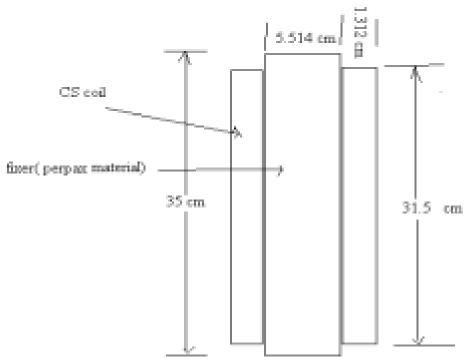

Fig.1. Inner Coil Dimension & fixer

Fig.2. Solenoid Coil

b) Magnetic field at the centre of central solenoid coil

A solenoid is a type of electromagnet when the purpose is to generate a controlled magnetic field. If the purpose of the solenoid is instead to impede changes in the electric current, a solenoid can be more specifically classified as an inductor rather than an electromagnet[2].

Magnetic field intensity at centre of central solenoid coil is given by the

$$H_0 = \frac{4\pi I'}{10} \frac{\beta}{\sqrt{(1+\beta^2)}}$$

Where , $\left(I' = \frac{NI}{2b} \right)$

$$\beta = b / a$$

Magnetic field intensity at centre Z axis

$$H_z = H_0 \frac{a^3}{(a^2 + z^2)^{3/2}}$$

Magnetic field at center Z axis

$$B_z = \frac{H_z}{1000}$$

III. PULSE FORMING NETWORK POWER SUPPLY

Voltage multiplier require for the Pulse forming network. To replace the DC source and use AC source economically a voltage multiplier circuit is used[3]. Each diode here has the voltage rating of 1200 V and 1 KA current rating. Capacitor used is of 20 µF and voltage rating of 1 KV. Input Voltage for Voltage multiplier is 230 AC 50 Hz With Isolation Transformer. By Using 2 stage Capacitor ,Its Convert The 1 KV .

A 2 stage pulse forming network (PFN) is used to give 1 KV, 640 µsec pulse to the designed coil. The circuit arrangement is shown in figure 3.

A. Pulse Forming Network parameters

<u>*Specification of PFN*</u>

- Capacitance C=20 uf
- Inductance L=1.28 mH
- NO. Of section n=3
- PFN impedance Z=8 Ohm
- Network voltage V_0 =1 KV

Expected pulse duration $T = 2n\sqrt{LC}$ *=640 us*

Load inductance = 1.33 mH

Peak pulse voltage = 1 KV
Capacitance used = 2 µF
Inductance used = 1.33 mH

Practical and simulation results are given below for load resistances of 10 ohms

B. Equation supporting PFN design

i. For resistive load

$$Z_0 = \left(\frac{L_p}{C} \right)^{0.5}$$

L_p = PFN inductance of a single stage
Z_o = load resistance

ii. For inductive load

$$Z_0 = \left(\frac{L_p + L_l}{C} \right)^{0.5}$$

Where,
L_p = PFN inductance of a single Stage.
Zo = load resistance
L_i = load inductance
C = PFN capacitance

iii. Time of pulse

$$T = 2n\sqrt{LC}$$

Where, n = No of stages in PFN

With these equations 1 KV and 100 μsec pulse forming network is designed.

C. *PSCAD Simulation of pulse forming network.*

A 2 stage Pulse forming network is designed and simulated in PSCAD. IN PSCAD DC source is used instead of Voltage multiplier The circuit arrangement is shown in figure 3.

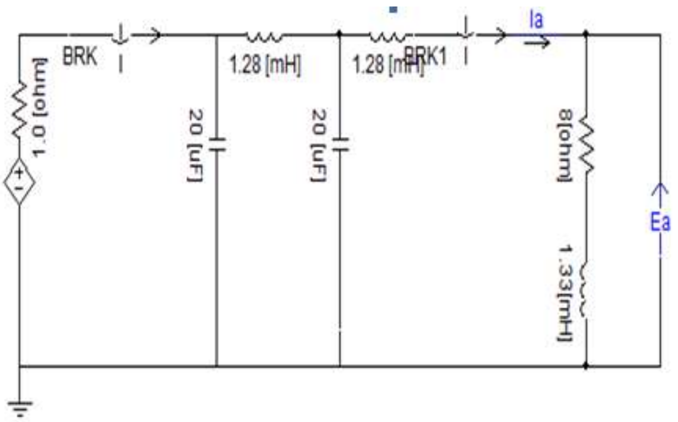

Fig.3 1KV pulse Discharge with PFN arrangement

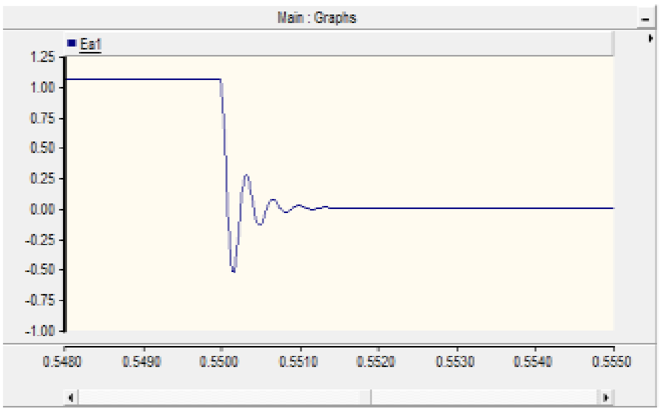

Fig 4. Solenoid Coil Voltage 1080 V

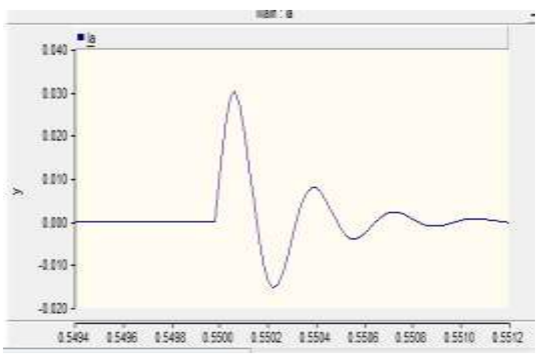

Fig.5. Current Waveform in 2T Inner Solenoid coil

Here from the graph it can be seen that 96 A is dumped in the coil to produce peak flux density of 2T at the peak current.

IV. DESIGN METHODOLOGY OF PFN POWER SUPPLY

1. ***Specify data load voltage, pulse duration, energy and No. of section***

    Load voltage VL =1000 V
    Pulse duration τ, us = 640 us
    No. of section n = 2
    Energy dumped to the load = WL = 2.287 kJ

2. ***Value of section Capacitance of PFN for required energy***

    Section Capacitance C = 2WL/V02
    Where, WL=Required energy dumped to the load
    V0=Network voltage

3. ***Value of section inductance of PFN for required pulse duration***

Section inductance L= $\left(\frac{T}{n}\right)^2 * \frac{1}{c}$

4. ***Value of Z= Characteristics impedance of PFN***

$$Z = \sqrt{\frac{L}{C}}$$

5. ***Calculate value of load current***

$$I_L = V_0 \frac{1}{R_l + Z}$$

6. ***Calculate value of load voltage***

$$V_L = V_0 \frac{R_l}{R_l + Z}$$

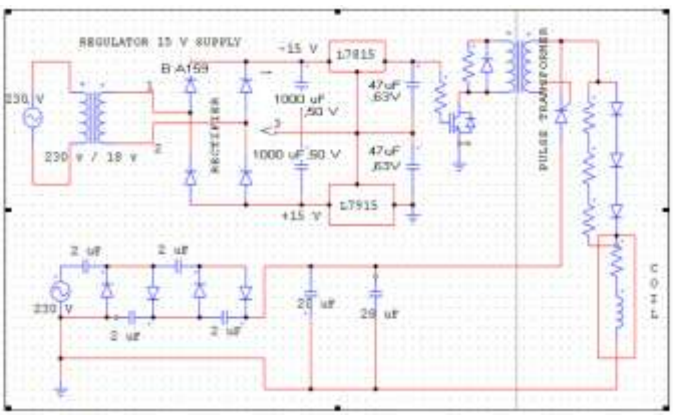

Fig.6. Circuit Diagram for 1.5 kv Pulsed Power supply

TABLE I. COMPARISION OF THEORATICAL, PRACTICAL AND SIMULATION RESULTS FOR LOAD RESISTANCE 10 OHMS AND LOAD INDUCTANCE 1.3

	Load resistance R_l(Ohms)	Pulse duration Ʈ(us)	Load current I_L (A)	Load voltage V_L (KV)
Theoretical	8	640	62.5	0.5
	10	-	55.55	0.55
Practical	10	550	65	0.8
Simulation	10	650	52	0.6

V. ANSYS SIMULATION OF INNER SOLENOID COIL WITH OUTER SHAPED SINGLE TURN COIL

A coil is modeled & meshed in ANSYS 11.0 software Package with copper rod at the centre. To have proof of concept a transient analysis is done applying same load as in practical.

Inner Coil dimensions are same as produced earlier and same for Outer toroidal shaped single turn coil also.

- Elements type: **Solid 93**
- No of elements: **51600**

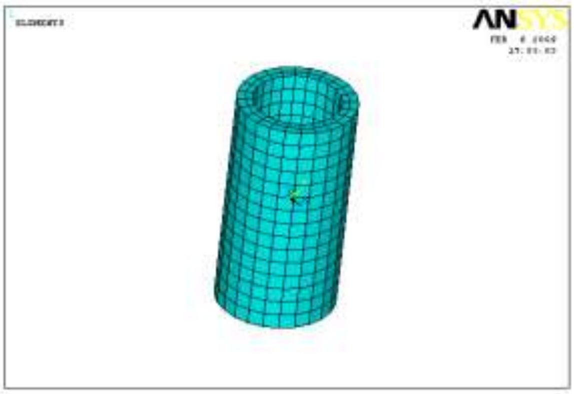

Fig.7. 3D meshing of central solenoid coil (2500 bricks)

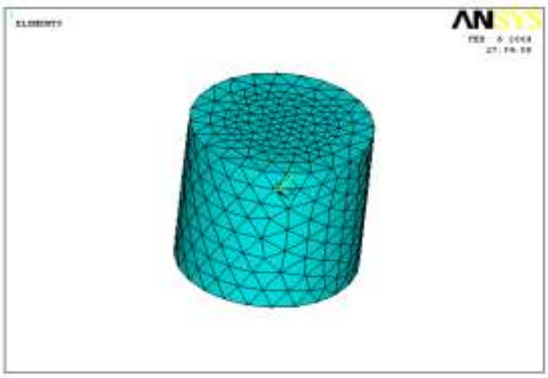

Fig.8 Meshing of boundary with central solenoid coil & outer coil

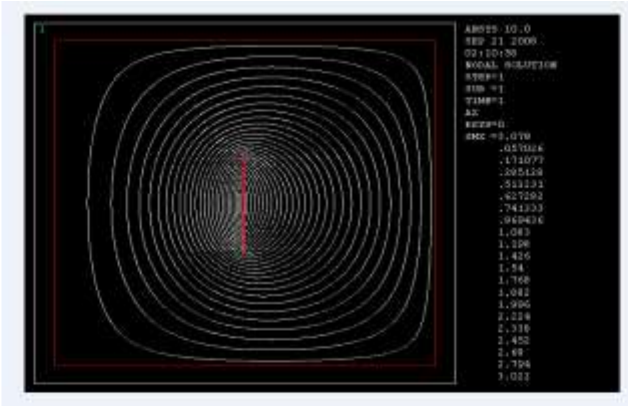

Fig.9. Flux line for inner coil

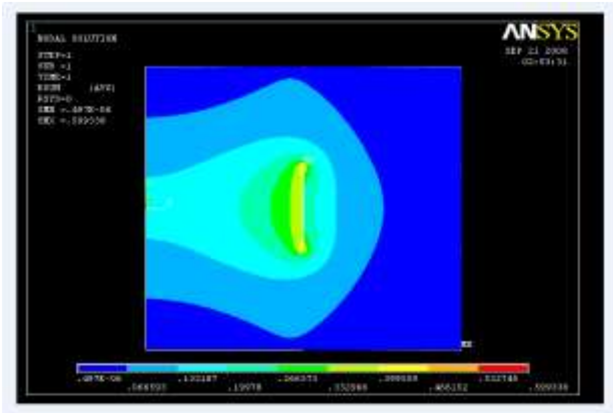

Fig.10. Magnetic field at center 2.18758 T

The model of coil is meshed with 2500 solid brick 51600 elements.

It is known that FEA analysis needs a particular air boundary limit to give out results. It was taken under consideration that while including air as an assembly the result was coming finer while increasing the air volume. Air volume has been optimized for a tolerable out put results.

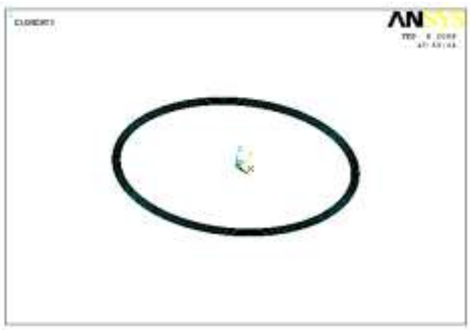

Fig.11. 3D meshing of Outer single turn coil (1000 bricks)

Shows the meshed modal of the Single turn coil kept at the outside of inner coil with 2500 solid 93 brick elements is shown in Figure 12.

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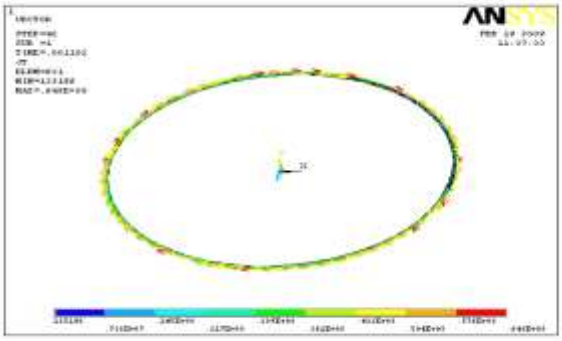

Fig.12. Maximum current induced in the toroidal shaped single turn coil (10.52A)

VI. Experimental Set Up

For Central solenoid coil experiment PFN power supply is required . By using function generator and thyrister triggering circuit in pulse forming network power supply give pulse to central solenoid coils. Voltage multiplier is used for develop high voltage 1000 V from 230 V. . According inductance value we have to design the capacitor for PFN supply.

Following the Experiment Set up :

Fig.13. Set up of Pulse forming power supply

Fig .14. central solenoid coil with single turn outer coil

A 1 KV 640 µsec 2 stage pulse forming network is used to give supply to the air cored coil with Outer single turn coil. Actually DC supply is required to have charging of capacitor but for economy consideration a voltage multiplier circuit is used with A.C. supply as shown in section 2 where design of the same is not shown. A Textronix Digital Signal Oscilloscope is used for measurement.

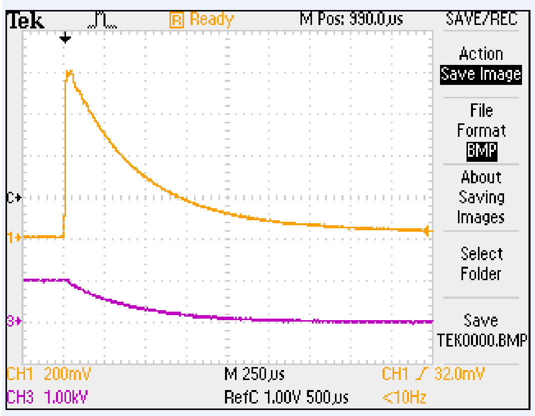

Fig.15. 1 KV and 96 A current dumped in Central solenoid coil

VII. Results

For taking practical results a TEKTRONICS Digital oscilloscope is used. Practical results are neatly matching with the simulation results from FEM analysis.

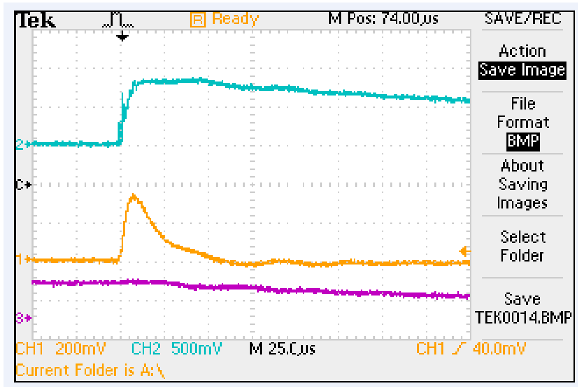

Fig.16.. DSO results showing induced current

For measuring current use 2 Different the DC current Transducer like Series AAC- 947-500A and 218-100A.For Voltage Measurement TEXTRONIX 1000 X HIGH VOLTAGE Probe used .

In DSO Result,

Chanel –1 shows the Induced current in Outer single turn coil, 3.52 A,

Ch-2 Shows the Current in Inner central solenoid Coil

Ch-3- Voltage Across the PFN

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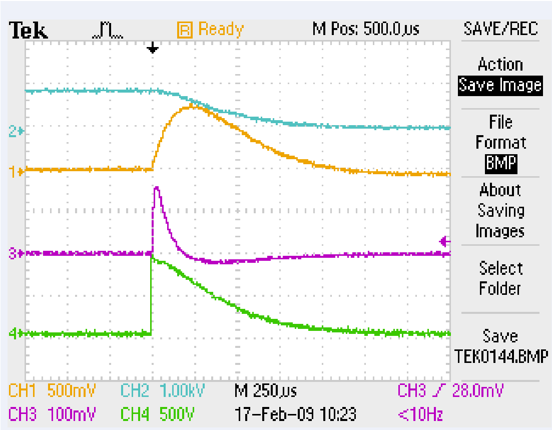

Fig. 17 Practical result for specification of 2 stage pfn for load inductance of 1.33 mH, pulse duration of 640 us with 10 Ohms load resistance

Waveform in figure 10 is produced for comparing the voltage induced in the coil to calculate induced current as well as induced voltage in the same assembly in FEA package.

TABLE II. RESULTS

	Theoretical result	Practical Result	PSCAD result	Ansys result
Inner coil current	96 A	96.45A	94.56 A	96.45A
Outer coil current	-	3.52 A	-	10.52 A
Mgnetic field at center	2.009 T	-	-	2.1875 T

The calculated induced current in *the graph is 3.52A in practical and 10.52* A in FEA package. The two obtained currents are matching in tolerable limits[1].

VIII. CONCLUSION

It can be concluded that the falling time is dependent on load inductance as well as PFN inductance. As inductance increases falling time will increase, so at higher value of load inductance or PFN inductance exact square pulse might not be obtained. Experiment and Ansys result in Table 2 is mismatching some where which is because of the inductance value mismatch as well as value of discrete load data entry in ANSYS and not perfect set up of Experiment. PFN is used to obtain a complete one waveform which can be modified for consistently multiple pulses for modified strategy. Optimized result has been obtained with increasing the air volume by using central solenoid air core for practical as well as FEA analysis.

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