ISSN (Online) 2456 -1304

International Journal of Science, Engineering and Management (IJSEM)
Vol 4, Issue 11, November 2019

Saturating Inductor for High Voltage Switching

[1] Krishna Kumar Saini, [2] Praveen Kumar, [3] B–J Lee, [4] H. Rahaman

[1][2][4] B K Birla Institute of Engineering & Technology Pilani, India
[3] Pohang Accelerator Laboratory, Pohang, Gyeongbuk, South Korea
[1] krishna.saini@bkbiet.ac.in, [2] praveen.jangir@bkbiet.ac.in, [3] bjlee707@postech.ac.kr, [4] hasib.rahaman@gmail.com

Abstract— **Non-linear properties of magnetic cores constructed from ferromagnetic material or its alloy have found very attractive use in pulsed power systems such as radar, laser, high power microwaves and particle accelerators etc. A saturating inductor made from such magnetic material regulates the power flow in these pulsed power systems by modulation of line reactance. The line reactance in turn can be controlled electrically through appropriate switching current by altering the core material magnetization of the inductor. This paper presents the study on the characteristics of magnetic material, its designing criteria and application towards efficient pulsed power flow by means of repetitive switching at high voltage/ high current ratings.**

Index Terms—**Pulsed Power, Thyratron switch, Pseudospark switch, Saturable inductor**

I. INTRODUCTION

The power requirement in many electrically pulsed systems involves the delivery of large amount of energy in a very short time. Such pulsed power modulator systems have always quests for high peak power with high repetition rate and long time [1-5]. One of the limiting circuit components in these systems is the high voltage/ current switch. The choice of the switch is the thyratron switch based on low pressure hydrogen/ deuterium gas due to concurrent properties of high hold off voltage (> 10 kV), high peak current (> 1 kA), fast current rise time (> 10^{11} A/s), high current densities (~1 kA/cm^2) and long life time (>10^{10} shots). A single solid state switch cannot handle such high power or current rise time but may have comparable life time. However, an alternate to thyratron switch is the pseudospark switch that combines advantages of thyratrons and pressurized spark gaps to generate remarkably very high peak current (~ 10 - 100 kA).

The operation of these switches has a demerit due to dissipation loss as shown in Fig. 1 during commutation phase/ interval that limits the long term operation/ lifetime by means of anode heating, gas rarification and gas clean up. The dissipation loss, P_{diss} , is determined from

$$P_{diss} = \int V\, i\, dt$$

Where, V and i are the instantaneous switch voltage fall and current rise, respectively, during the interval dt. The commutation interval has significant anode dissipation due to falling anode voltage and rising current. It means the high energy electrons strike the anode surface to the vaporization point and dissipate as heat. A build up vaporization material within inner surface of the switch tube lowers the voltage hold off capability. In addition, average anode heating or reasonable anode life may limit the maximum repetitive switching to lower value.

One of the possible solutions of the above problem is the use of saturable inductor [5-7]. A delay in switching action is inherent in a saturable inductor thereby decreasing the dissipation loss in the commutation period. Therefore, theory of saturable inductor along with design criteria have been discussed for desired hold off voltage and switching delay in following sections.

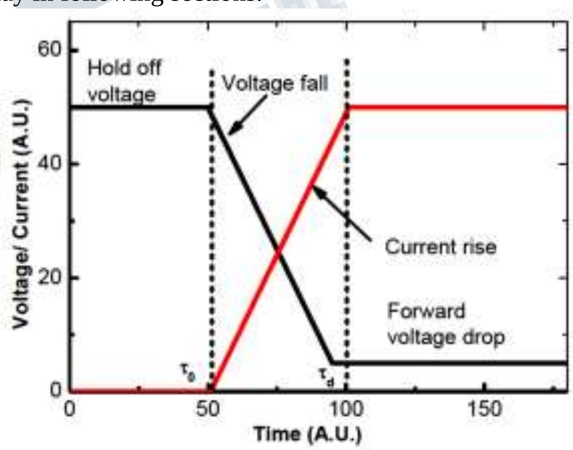

Fig. 1. Voltage and current graph of a typical switch. Commutation period: ($\tau_d - \tau_0$)

II. THEORY OF SATURABLE INDUCTOR

A saturable inductor employs ferromagnetic material core which saturates after a certain flux density. Voltage, V, across the inductor before the saturation is given by

$$V(t) = L\frac{di}{dt}$$

Or $$di = \frac{V(t)}{L}dt$$

The current, *di*, is then proportional to time, *dt*, as shown in Fig. 2, for which the inductance, *L*, is given by

$$L = \frac{IF\ \mu_0 \mu_r N^2\ A}{l} \qquad \text{(i)}$$

Where, μ_o and μ_r are the magnetic permeability of air and relative permeability of the core material, respectively. *N* is the number of coil turns, *l* is the magnetic length of the core and *IF* is inductance factor to include leakage flux and winding area to turn area.

Equation (i) shows the inductance dependence on the permeability of the core material. Fig. 3 represents the diagram of magnetic flux density, B, in a magnetic material due to applied magnetic field intensity or magnetizing force, H. B increases non-linearly with H up to B_{sat}, the saturation point, after which it does not increase any more. The permeability, μ (= dB/dH), of the core also increases in the beginning, reaches a maximum and then drops again with further increase of H [10]. At the saturation point, μ of the core is equal to unity, similar to that of air. In this way, the saturation of the core makes transition of the inductance to a much lower value, typically two to three orders of magnitude. It means the saturated inductor makes impedance transition, thereby increasing the current disproportionately in the circuit as shown in Fig. 2.

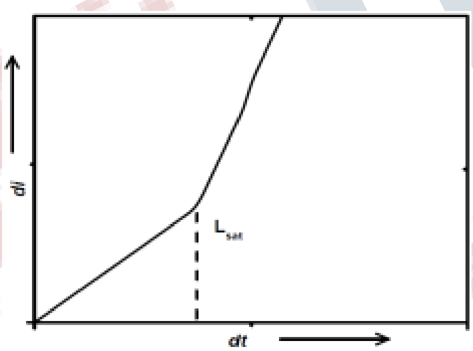

Fig. 2. Current behavior for unsaturated and saturated inductance

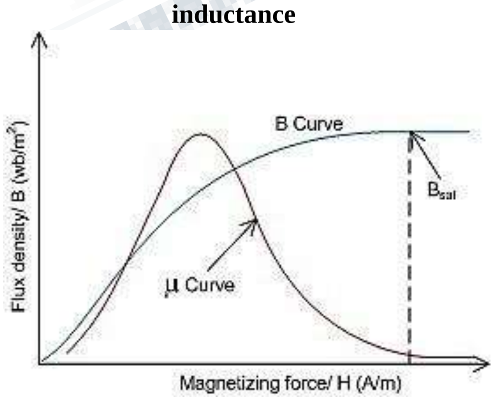

Fig. 3. Flux density and permeability curve against magnetizing force.

III. DESIGN CRITERIA

Magnetic materials are characterized according to various parameters determined by means of hysteresis loop as shown in Fig. 4. The hysteresis loop describes B-H curve to state the response of the material due to the external magnetic field intensity. Diamagnetic and paramagnetic materials are non-magnetic materials with a fixed slope whose permeability, μ, is about 1. Vacuum, air, copper and molybdenum are some examples. Ferromagnetic material has a non-linear B-H curve with permeability, μ, much greater than 1. Residual magnetism or retentivity, B_r, is the flux density left in the magnetic material in the absence of magnetizing force after it has been magnetized. Coercivity, H_c, is the magnetic field intensity required to demagnetize the material after it has been magnetized. Materials characterized with high B_r and H_r are hard magnetic materials. Permanent magnets such as AlNiCo and NdFeB fall in this category. The area enclosed by B-H curve is large and therefore, it has high hysteresis loss or core loss. Materials characterized with low B_r and H_r are soft magnetic materials. Iron, nickel, cobalt and their alloys fall in this category. The area enclosed by B-H curve is small and therefore, it has low hysteresis loss or core loss. These types of materials are preferred in transformers, motors and electromagnets etc. The soft magnetic materials are also preferred for saturating inductor. A large difference between B_r and B_s is preferred in order to use the material without reset condition. Reset condition means without using negative magnetic field intensity (reverse current) to reduce the magnetic flux to zero.

There are many manufacturers for high frequency ferrite cores in cylindrical toroid shape such as Ceramic Magnetics Inc., Metglas and TDK corporation etc [8-9]. Consider CMD5005 of Ceramic Magnetics Inc. made of Ni-Zn ferrite core (Fe_2O_3, NiO, ZnO) with surface area of 10 cm^2. Flux densities for B_r and B_s are 0.13 T and 0.33 T, respectively. The initial and maximum relative permeabilities are 2100 and 5500, respectively. Using ΔB of 0.2 T, N of single turn with 4 toroidal cores, and V of 20 kV in Eqn (ii), τ_d = 40 ns. In this manner, the rising current pulse is delayed by the use of saturable inductor as shown in Fig. 5, which in turn reduces the power dissipation during the commutation period.

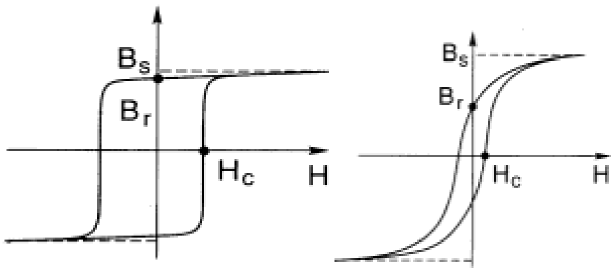

Fig. 4. Hysteresis loop for (a) Hard magnetic materials, and (b) Soft magnetic materials.

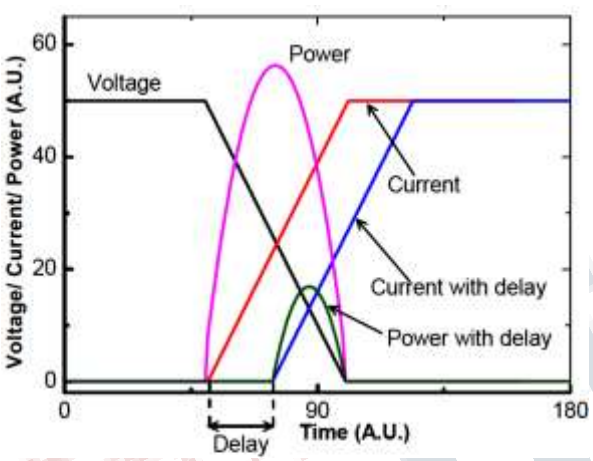

Fig. 5. Delay in current rise time with saturable inductor.

IV. CONCLUSION

The ferromagnetic material based saturable inductors have great potentials for switching devices in pulsed power applications. The high permeability provides high inductance or reactance of the inductor causing the switching delay time. The inductor upon saturation, characterized by low permeability and subsequently low inductance, is accompanied by fast energy transfer to the load. The design and magnetic material constraints imposes appropriate delay in current rise time of the switch. This delay will reduce the dissipation loss during commutation at least by an order of magnitude. At high repetition rate, the power dissipated at the switch is strongly reduced which in turn may able to increase the life time of the switch.

REFERENCES

1. G.D. Wait and M.J. Barnes, "Thyratron Lifetimes, a Brief Review", 2nd Modulator Klystron Workshop for Future Linear Collider, SLAC, Standford University, Oct 9-11, 1995
2. Xupeng Chen, Jeffrey de Lamare, "Life Review and Development of Thyratron in Linac Coherent Light Source", SLAC-PUB-17262, 2018, Web.
3. K. Frank, B-J Lee, I. Petzenhauser, & H. Rahaman, "Does gas-filled switches still have a future?", IEEE Int. Pulsed Power Conference, pp. 432-437, 17-22 June, 2007.
4. V. Pathania, D.K. Pal, B.L. Meena, N. Kumar, U.N. Pal, R. Prakash, and H. Rahaman, "Switching Behavior of a Double Gap Pseudospark Discharge", IEEE Trans. Dielectr. Electr. Insul., Vol. 22, No. 6, pp. 3299-3304, Dec 2015.
5. L. Ducimetiere, D.C. Fiander, "Commutation Losses of a Multigap High Voltage Thyratron", IEEE Conference of Power Modulator Symposium, San Diego, pp. 3162-3164, 26-28 June, 1990.
6. S. E. Ball, T. R. Burkes, "Saturable Inductors as High Power Switches", IEEE Pulsed Power Conference, pp. 269-272, 1-3 June, 1981.
7. Weidong Ding, Saikang Shen, Jiaqi Yan, Yanan Wang, and Bo Wang, "Discharge Characteristics of a Pseudopsak Switch in Series With a Saturable Inductor", IEEE Trans. Plasma Sci., Vol. 47, No. 10, pp. 4572-4578, Oct 2019.
8. M. A Goldman and J. E. Tuozzolo, "Observation of Induced Electrical Conductivity of Kicker Magnet Ferrites, After Vacuum Firing", Booster Technical Note no. 183, 1990.
9. Magneticsgroup.com/material/nickel-zinc-ferrite/
10. B. D. Cullity and C. D. Graham, "Introduction to Magnetic Materials", A John Wiley & Sons, Inc., IEEE Press, 2nd edition, 2009

