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Use Of Diode As A Crowbar For Electromagnetic Launcher

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***Abstract*— High current high voltage switches are extensively used for power applications. Electromagnetic launcher (Railgun) requires switching large current in the proper sequence to ensure acceleration of projectiles to attain required velocities. These power applications require current of the order of Mega Ampere for 5-10 ms and hence need special purpose switches. The Spark Gap or Ignitron are conventionally used for power application as a crowbar switch. These switches operate at high voltage and high current capacity but have low reliability, robustness and lifespan. In this paper ignitron as a crowbar switch is replaced by diode switch. This reduced negative overshoot in the current.**

Keywords- Electromagnetic Launcher, Power Application, Crowbar Switch, Semiconductor Devices

I. Introduction

There has been an ongoing effort to increase both the lethality and range of guns both in conventional field artillery, naval guns and tank guns. Conventional powder guns used in these applications have almost reached the limit of their range capabilities with limitations imposed by physics than by technology. Thus it is seen that the conventional guns reach a peak velocity of around 1600 -1800 m/s. Adding more charge results in entering a regime of diminishing returns with the additional charge not giving a corresponding increase in velocity. Hence the electromagnetic gun also called the railgun is proposed if major performance improvements are to be achieved. The railgun does not depend on gases and their pressure to accelerate the projectile. It uses electromagnetic forces created by current flows to accelerate projectiles.

Normally high power application requires capacitor bank to store the electrical energy. The stored electrical energy is utilized to accelerate the projectile within few milliseconds. Electromagnetic launcher (Railgun) is one such application where short pulse is used to generate the required thrust to propel the artillery. For such short duration, we require magnitudes of the current of the order of hundreds of kA to accelerate the projectile. The capacitor discharges the stored energy of the order of kJ or MJ to generate the pulse in railgun. This requires switches used the railgun system to withstand high voltage and high Current. Traditionally the spark gaps, Thyratrons, Ignitrons, mechanically actuated switches, etc., were used for such applications. The mechanically actuated switches are having advantage over others due to its simplicity but found limitations in case of modular power supplies. As evident from previous discussion the switch used in the railgun has to discharge the stored energy from the capacitors and the response time should be minimal, and can handle very high di/dt. The selection of switches mainly based on the power rating and the technology used [1]. The conventional switches are having limitations to operate at these high voltage and high current capacity. Spark gap gives poor reliability and Ignitron is having drawback of short service life. Semiconductor devices like thyristor and diode are having advantages over Spark gaps and Ignitrons [2]. The thyristor are energy efficient and preferred due to negligible switching noise, high reliability and longevity. The crowbar diode has shown promising results in the literature and hence subsequently researchers started exploring the application of semiconductor devices as main switches.

Crowbar circuits are frequently employed in pulsed power systems in which a capacitor bank is discharged into a load. By forming a very low-impedance short circuit they provide a freewheel path for the load and prevent an excessive reverse voltage building up on the capacitor. By this action, we can greatly increase life of the energy storage capacitors and increase energy transfer efficiency from the capacitor to load. The application of crowbar circuits allows the generation of unipolar current pulses which some applications require. It also decrease the fluctuations in the pulse [3]. In this paper we propose how semiconductor switch replace conventionally used crowbar switch. In section III we will see ignitron as a crowbar switch. What are its limitations. Then in section V how diode can be used as a crowbar switch and how we can get better results using diode as a crowbar switch.

II. Railgun Tecnology

As shown in *Fig 1* it comprises a pair of parallel conducting rails along which a sliding armature is accelerated by the electromagnetic effect of current that flows down one rail into the armature and then back along the other rail. The rails are connected to a pulsed direct current power supply. In contrast to explosive or gas expansion propulsion the muzzle velocity is only depending to the aerodynamic properties of the projectile and the energy of the power supply. The force, which is acting on the armature, is the Lorentz force. It appears through the magnetic field of the rails.

A railgun consists of two parallel metal rails connected to an electrical power supply. When a conductive projectile is inserted between the rails, it completes the circuit. Electrons flow from the negative terminal of the power supply up the negative rail, across the projectile and down the positive rail and back to the power supply. This current makes the railgun behave as an electromagnet, creating a magnetic field inside the loop formed by the length of the rails up to the position of the armature. In accordance with the right hand rule, the magnetic field circulates around each conductor. Since the current is in the opposite direction along each rail, the net magnetic field between the rails B is directed at right angles to the plane formed by the central axes of the rails and the armature. In combination with the current I in the armature, this produces a Lorentz force which accelerates the projectile along the rails, away from the power supply. There are also Lorentz forces acting on the rails and attempting to push them apart, but since the rails are mounted firmly they cannot move. Maintaining the Integrity of the Specifications.

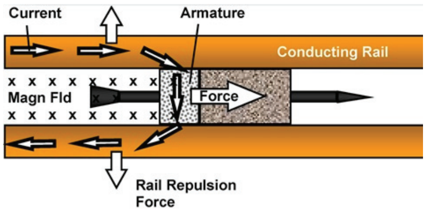

Fig. 1 Working principle of Railgun

The railgun has been for decades been languishing as a laboratory tool. However a review of the research efforts worldwide indicates that the technology is now maturing and moving from the laboratory to practical systems. A survey of existing literature on railgun indicates that there is a huge research effort ongoing in western countries, Japan and China in hypervelocity railguns. It is very likely that railguns will move from laboratory prototypes to weapon platforms.

III. Module Configuration

High power application requires capacitor bank to store the electrical energy. This capacitor bank is divided into modules. Each module will consist of high energy density capacitors a main switch which will switch the capacitor energy to the load and a crowbar assembly to prevent the voltage reversal. The number of capacitors per module will be four 50 kJ capacitors. The Capacitors of each module are physically connected through a common bus bar. The positive end of the bus bar coming out of the module will be connected to the anode of the Ignitron Switch. The bus bar is connected, via flexible coaxial cable to the gun breech at the other end. A single module configuration is shown in *Fig 2* where crowbarring is done using ignitrons.

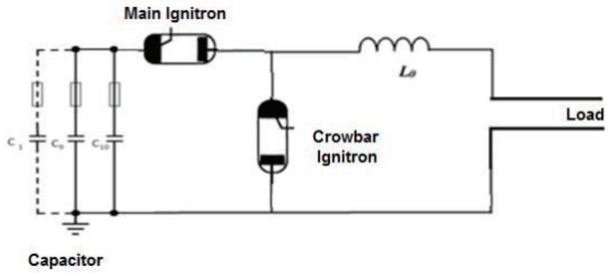

Fig. 2 Configuration of a single module with ignitrons

Each module will also have its independent switching systems in form of main and crowbar switches and independent pulse shaping inductor. The 200 kJ modules can be independently switched with its independent trigger system. The capacitor bank modules would be configured with ignitron based main and crowbar switches initially, Efforts will be made to replace the ignitron crowbar switches with semiconductor switches. Each module will have its own pulse shaping coil. Once the capacitors are charged up to firing voltage, the main switch is triggered and forced into forward conduction mode. Energy is then transferred from the capacitor to the railgun through the inductor. The crowbar diodes then go into forward conduction and the rest of the energy is then released into the railgun.

IV. Ignitron As A Crowbar

Based on the availability and simplicity, it was decided to go in for ignitron switches for the 3 MJ bank. Ignitron is basically a three terminal device with a graphite or stainless steel anode a mercury pool cathode, both contained in a vacuum enclosure and an ignitor pin. In the open or non-conducting state it operates on the left side of the Paschen minimum in the insulating mode. To close the switch, a current pulse is applied to an ignitor pin. The ignitor pin, which is in contact with the mercury pool but is not wetted, has a resistance of 10 to 100 Ω between its self and the mercury pool. The current pulse vaporizes a small amount of mercury which diffuses into the volume of the ignitron tube. If the voltage applied to the switch is great enough, the mercury vapour creates a conducting path from the anode to the cathode, and the switch closes.

In order to prevent reversal of voltage across the capacitors the capacitors are crowbarred when the capacitors have discharged completely or when the current is at its maximum. Here we are using Ignitron (BK496/ NL 496) as main switch with ratings as follows:

Crowbar Ignitron Ratings :

Peak anode Voltage	25kV
Peak Inverse Voltage	25kV
Peak Inverse Current	200 kA
Peak ampere-sec.per Pulse	400 Ampere second
Peak Repetition rate	1 pulse/second

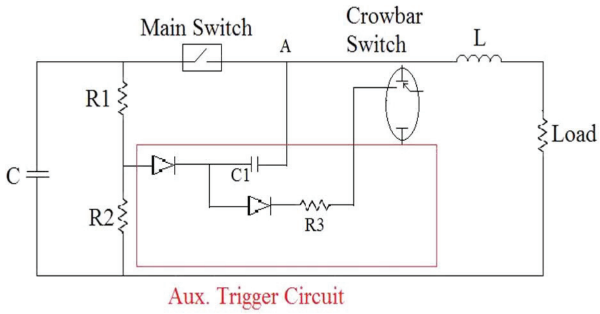

Fig.3 Crowbar switch with Aux. triggering circuit

In order to crowbar the circuit it is required to trigger the crowbar ignitron when the current has reached its peak. This can be done by detecting the peak using peak detection circuits or some digital logic and then generate a trigger pulse accordingly. But such a kind of peak detection is susceptible to noise and errors especially in this high magnetic field environment where noise can be induced easily in the current measurement.

Instead we use a simpler methodology by using auxiliary anode of the ignitron. The scheme is shown in *Fig 3*. The crowbar ignitron is triggered at the same instant as the main switch and the conducting the auxiliary anode serves the purpose to keep the conducting channel live until the time that enough positive voltage comes across the main anode and cathode to turn it on. For this purpose a capacitor C1 is charged using the voltage divider with voltage input from the main bank C itself. Initially the point main switch is off before triggering So Point A is at ground potential. Using the divider the capacitor C1 is charge to some 900 V. As soon as the firing pulse is given to the main switch and the crowbar switch, point A is lifted up to the voltage of the capacitor bank (V). But the capacitor bank C is charged to 900V. This capacitor will thus start discharging through the auxiliary anode as soon as the firing pulse is given. The resistance R_3 is chosen such that the time constant R_3C_2 is more than the time taken by the main current to reach its peak. This will ensure that the conducting channel sustain until the point that the main anode attains a positive voltage sufficient enough to conduct.

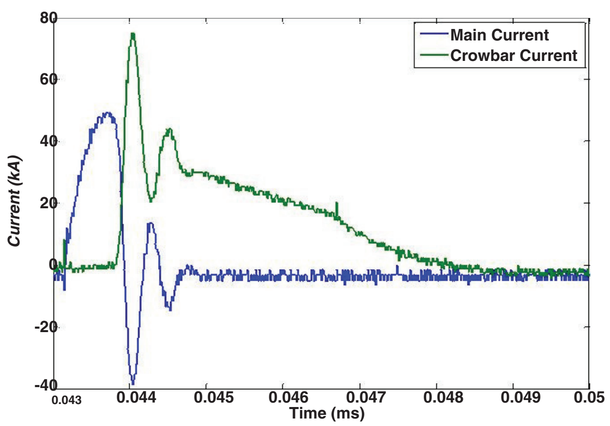

Fig.4 Test result of Ignitron as a crowbar switch

Fig.4 shows the test results of crowbar switch implemented using ignitron. The blue waveform denotes the load current and green waveform denotes the current through crowbar switch. It can be seen that until the load current is lower than a specific threshold voltage across crowbar switch, here 400 V, the switch is off and hence circuit performs normal operation. When the voltage exceeds threshold, the crowbar switch turns ON, thus protecting the load from overvoltage condition. In this condition, the current through ignitron based crowbar switch overshoots and charges the capacitor with reverse polarity. This appears to a disadvantage of ignitron circuit as the load current overshoots in negative direction to such a value. The crowbar ignitron also has to carry this additional current over and above the main module current. This puts additional stress on the main switch and the main switch cannot be used to its maximum current rating as the margin has to be kept for this overshoots.

Ignitron-type power-pulsed switches, often used for high-current handling, pose problems associated with mercury hazards, auxiliary cooling, shock limits and reliability in field deployments. Ignitrons, in particular, are bulky and fragile. It is also essential to mount ignitrons vertically and need some maintenance in form of local heating to prevent mercury condensation on walls and anode which will compromise its performance. Though their simplicity and low cost makes them suitable for laboratory applications but for on-field applications the diode based crowbar is used as it overcomes the above described limitations of ignitron circuit.

V. Diode As A Crowbar

The device under investigation is a rectifier diode developed by Westcode. Diode is having Vdrm= 4.8 kV (Repetitive peak reverse voltage) and Ifsm=25.4kA)Peak non-repetitive surge).

Fig.5 Westcode Diode W2899MC480

A. Design

Since the operating voltage is 8kV, two diodes have to be switched in series. To do this assembly, clamping of two diodes is done. Proper clamping is essential to the performance and lifetime of semiconductors. Insufficient clamping can cause incorrect operation of the device being used and premature failure of the device. Clamping force 25 kN is given. In *Fig. 6* such stack is shown of two serially switched diodes.

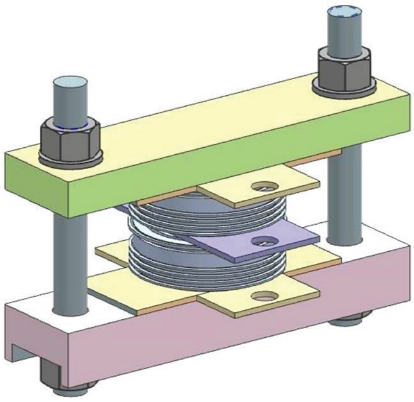

Fig.6 Diode Stack Assembly

We have to add shunt resistor across the diode to deliberately produce a mismatch in the DC voltage. First calculate leakage current across the each diode. Then using that value calculate the value of resistor which can be used.

Leakage current across each diode

Diode 1 : 50 µA

Diode 2 : 50 µA

Resistor Calculation

$$R = \frac{n\,V_D - V_S}{(n-1)\,I_b}$$

V_D - Maximum blocking voltage
V_S - DC Peak Voltage

Ib - Reverse leakage current
n - No of diodes

$$R = \frac{2(4800) - 8000}{(2-1)\,50\mu A}$$

So R = 32 MΩ

B. Strategy

As said earlier diode is having more advantages compare to ignitron. Here diode is used as a crowbar switch. *Fig.6* shows an equivalent circuit diagram of 25-kJ unit including capacitors. Ignitron as a main switch, 2 diodes in series as a crowbar switch, a pulse forming coil (L) and railgun as a load.

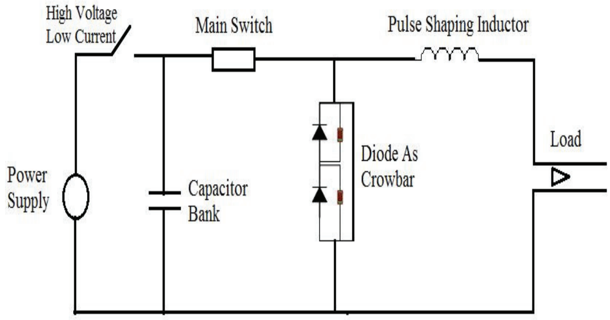

Fig.7 Layout of a switch assembly

C. Experiment Setup

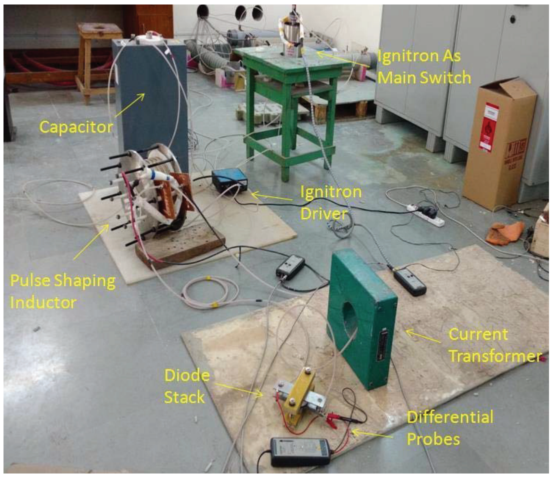

Fig.8 Experiment Setup

The experimental setup consist of a 25 kJ capacitor with a pulse shaping inductor, ignitron as main switch, ignitron driver and diode stack assembly as crowbar. Tested 1000:1 differential probes are used for voltage measurement where as Pearson 2093 Current transformer is used for current measurements.

D. Results

The graph in *fig.9* shows the waveforms recorded at various nodes of the diode based crowbar circuit shown in fig.7. The crowbar circuit gets ON as soon as the module current reaches its peak and bank voltage just starts becoming negative. The crowbar current (blue waveform) starts to increase whereas the main switch current (green waveform) reverses. Here, the main switch current does not overshoot to large negative value unlike in the ignitron based crowbar switch and thus reduces stress on the main switch which can now be used to its full rating.

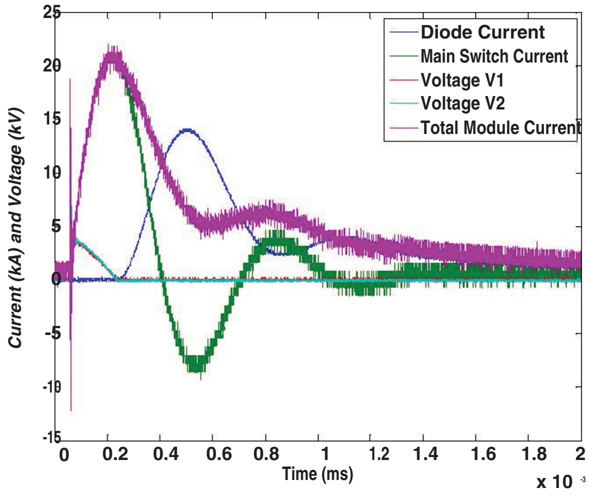

Fig.9 Test result of diode as crowbar switch

VI. Conclusion

The work presents the analysis of the crowbar circuits using ignitron and diode assembly. The ignitron based circuit has the disadvantages like high negative overshoot, requirement of high maintenance and lower reliability. The analysis of the diode based crowbar circuit implemented here shows that it has very low negative overshoot current and zero reverse voltage. Limitations of ignitron can be overcome by using diode. So we have proposed and replaced ignitron with diode as a crowbar switch.

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