CHAPTER 2

ENERGY STORAGE DEVICES FOR PULSED POWER SUPPLY

2.1 INTRODUCTION

Technology has advanced to such high levels that we are on the verge of using electrical energy as the input to ultramodern war weapons. There is always a drive for using electrical energy in almost all sorts of applications for which the reason being its clean nature. Some of the ultra modern weapons which use electrical energy as their input are ETC’s and EML’s. The primary problem in using electrical energy as the driving source is the space occupied by the electrical power supply (Ian McNab 1997). Extensive work and research are being conducted all over the world for the minimization of the volume occupied by the power supply and to reduce its weight. These constraints have always been deadlocks in the design of high caliber EML or ETC even though researches have begun well before 1980.

In order to catalyze the convergence of the research in full caliber ETC’s and EML’s, different types of pulsed power supplies which produce pulsed output are to be studied. A detailed feasibility study is to be done on different available PFN’s. Each type of topology has its own advantages and disadvantages. So a logical compromise has to be made taking into account of the constraints which are posted by the desired energy requirement. The most feasible one is to be chosen by studying all the technicalities of the system.
2.2 ENERGY STORAGE DEVICES

The high energy storage devices classified into two types

1. Static energy storage devices
2. Rotating energy storage devices

The static energy storage devices are

(1) Battery
(2) Capacitor
(3) Inductor

The rotating energy devices are

(1) Magnetic Hydro Dynamic Generator (MHDG)
(2) Compulsator
(3) Flywheel Energy Storage System (FESS)

2.2.1 Battery

Battery is a device that converts chemical energy into electrical energy. Batteries have been used as electric energy storage devices for many years. In the recent days due to revival of interest in pulsed power supply design using a battery, great effort and investment has been put into the research and development of high performance chemical batteries. However, the battery performance has been far from meeting the requirements of the pulsed power application. Very limited amount of energy stored per unit weight is one of the major problems in the battery PPS.

In order to use the battery as energy storage device various techniques called PULSER program (Jack Lippert (1993), BUS program
(Pappas et al 1993) have been developed. These techniques were proved that the battery can be used as high energy storage device for rail gun applications. As the battery has the lower energy stored per unit weight now a day’s battery is used as intermediate energy storage device (Sitzman et al 2007).

2.2.2 Construction of Battery

Figure 2.1 shows the simple schematic diagram of battery construction. The basic components of a battery made up of electrodes with terminals to connect the external circuit. The electrodes material may be a rigid metallic grid impregnated into or coated onto a spiral rolled metallic foil which simply acts as a current collector.

![Construction of Battery](www.tpub.com)

The separator is used to keep the electrodes apart and prevent them from shorting. The separator may be a mechanical spacer, fiber glass cloth or a flexible plastic film made from nylon, polyethylene or polypropylene. The electrolyte which carries the charged ions between the electrodes and the case is to contain the active chemicals and hold the electrodes in place. For many years all electrolytes were in aqueous or gel form. Recently solid polymer
2.2.3 Battery Pulsed Power System

The block diagram of battery pulsed power system used in electromagnetic launcher is shown in Figure 2.2. The main components in the battery pulsed power supply are

1. Battery
2. Energy Storage Inductor (ESI)
3. Opening and Closing Switches.

In a battery pulsed power supply depending upon the requirements, batteries are divided into different groups, in each group the batteries are connected in series and in parallel. Each group in the battery pulsed power supply is electrically isolated until a connection is made at the breach of the rail gun. Each group of batteries is connected to load through energy storage inductor. The inductor is used to control the current that flows to the load.

Figure 2.2 Block diagram of battery Pulsed power supply system (Pokryvailo Kanter et al 2003)
The closing switch is connected to an explosive opening switch that controls the excess energy dissipation and finally interrupts system current at the end of an experiment. The opening switches commutate the current into a low inductance resistor that reduces battery bank current. At this level, the interrupt switches are opened and the system current is driven to zero. A successful discharge is largely based on the performance of opening and closing switching subsystem. Therefore, the opening and closing switch design specifies switches that have operated in pulsed power networks for many thousands of operations without major maintenance (Pappas 1993).

Batteries typically have good energy densities, but low power densities. The first problem in battery design is battery voltage drop due to chemical activity and electrolyte concentration. World wide the research is on to reduce the voltage drop due to chemical reaction to improve the energy density of battery. To improve the power density of the battery various material are used to in battery design. The second problem is opening and closing switches. The switch is normally closed and permitting the power supply to charge the inductor, once the inductor fully charged the switch is opened and current starts to flows through the rail. When the projectile leaves the rail, the switches are closed once again, repermitting the power supply to charge the inductor. The opening switch carries high current and there is a high conduction loss that reduces the efficiency of the system. The switching devices should have low conduction losses and high di/dt and dv/dt ratings. Now the research is in progress to reduce the conduction losses and to improve the di/dt and dv/dt rating of switching devices. Table 2.1 gives the technical challenges involved in improving the battery pulsed power supply system.
Table 2.1 Technical Challenges involved in improving battery pulsed power system (Robert Guenther et al 2002)

<table>
<thead>
<tr>
<th>System/Component</th>
<th>Technical Challenge</th>
<th>R&amp; D priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>Validation of batteries in pulsed power system</td>
<td>Increase the power and energy density with nano material technology</td>
</tr>
<tr>
<td>Advanced battery concepts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrode/electrolyte interface</td>
<td>Voltage drop caused by limited chemical reactivity at the interface</td>
<td>Advanced electrolyte, electrode with higher surface reactivity</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Voltage drop caused by mass transfer over potential</td>
<td>Electrolyte with high concentration of reactant species and low ion transfer resistance</td>
</tr>
<tr>
<td>Opening and closing switch</td>
<td>Solid state device: reducing the switching losses, Improving di/dt and dv/dt of the switching devices. Spark gap: Reducing the erosion of electrode.</td>
<td>Solid state device: Increasing the resistivity by using GaAs and INP Switching losses; By developing integrated gate structure Spark gap: Using new material for electrode like graphite because no plasma is generated</td>
</tr>
</tbody>
</table>

2.3 MAGNETO HYDRO DYNAMIC GENERATOR (MHDG)

The working principle of MHD generator is that it converts the thermal energy into electric energy directly. The Figure 2.3 shows the vertical cut open view of the schematic configuration design of MHDG (Wang Ying 2004).
The MHDG generally consist of a combustion chamber, a generating channel and an exciting magnet. Combustion chamber is used to generate the conducting fluid and plasma. They are allowed to pass between two electrodes of the generating channel. The exciting magnet is used to create the magnetic field between the electrodes. Under the action of exciting magnetic field, the charged particles which is in plasma are experiencing to the Lorentz force and they reaches the positive and negative electrode respectively to form an electric potential difference. Due to this potential difference on the electric gun load, a big current is flowing through the load. Therefore MHDG has no rotating parts, and doesn’t need any middle energy storage and conversion component, which means it has a simple structure. The MHGD convert the thermal energy of chemical reaction into electric energy directly, so it has higher conversion efficiency (~ 30%) of chemical energy into electric energy and a small size (Wang Ying 2004).

2.3.1 Electric Circuit Model used in Pulsed Power Supply

The equivalent circuit of the MHDG in pulsed power system is shown as Figure 2.4. In which, G is the ideal MHDG, $V_o$ and $R_g$ is open circuit voltage and the internal resistance of the MHDG, $Z_L$ is the load of the rail gun that includes the variable resistance and inductance of the rail gun. As per the law of electromagnetic induction, an electric field $E$ is formed due to induced
electromotive force between the two electrodes, when a conductor (or conductive fluid) moves normal to the magnetic field $B$ with speed $v$ in a generating channel. There will be a current in the closed circuit, when the switch $S$ is closed and the load $Z_L$ of the rail gun is connected. To enhance the electric field and magnetic field, different methods such as Faraday and Hall type generator have been used. Esposito et al (1995) have reported that the Hall type MHD generator have better performances than those of the Faraday type generator.

![Figure 2.4 Electrical equivalent circuit of MHG for electric gun (Wang Ying 2004)](image)

**Figure 2.4  Electrical equivalent circuit of MHG for electric gun (Wang Ying 2004)**

Even though considerable research was undertaken from 1970’s on MHD devices, so far millisecond order PMHDG used by electric launchers has not been reported. The reason is that the pulsed current width of both long pulse and explosive short pulse PMHDG is easily generated, controlled and realized, but milli second order pulse current width for rail gun is not easy to do so. Donald et al (1986) have reported that to get higher power in MHDG, it needed high conductivity plasma and magnetic flux density. The first problem in MHDG is the current carrying capacity of plasma used in combustion chamber. Due to low conductivity of plasma, MHDG is limited to lower value of current pulse. Second problem is getting the millisecond pulsed output for rail gun. It depends on the shape of electrode and valve. This can be done by changing shape of the valve and spring elasticity. Third problem is obtaining
the high voltage between the two electrodes. It depends on the magnetic field existing between the electrodes. Research is going on in order to improve the above system and component in MHDG. Table 2.2 gives the technical challenges in improving the MHDG pulsed power supply system.

Table 2.2 Technical Challenges involved in improving MHD Generator in pulsed power system

<table>
<thead>
<tr>
<th>System/Component</th>
<th>Technical Challenge</th>
<th>R&amp; D priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma</td>
<td>To increase the current carrying capacity</td>
<td>Using new seed materials to increase the conductivity of plasma</td>
</tr>
<tr>
<td>Valve, combustion chamber</td>
<td>To get millisecond pulsed for EML application</td>
<td>Changing the shape of electrode, spring elasticity to regulate pulse shape</td>
</tr>
<tr>
<td>Exciting magnet</td>
<td>Improving the magnetic field between the electrode</td>
<td>Using super conductors</td>
</tr>
</tbody>
</table>

2.4 INDUCTOR

The inductor is a device which converts the magnetic energy into electrical energy. The inductor is consisting of conductor and around the conductor a coil is wounded. When the electric current passes though the conductor, it creates a magnetic field around conductor which results the inductance. The created magnetic flux is proportional to the current passing through the conductor. If the current flowing through the conductor changes, magnetic flux around the conductor changes which result in electromotive force that acts to oppose this changes in current. Hence, the inductance is defined as the ratio of amount of generated EMF to unit change in current.
\[ L = N \frac{d\phi}{dt} \text{ (H)} \]  

(2.1)

where \( N \) is the number of turns around a conductor.

\( \frac{d\phi}{dt} \) is the rate of change of flux linkages.

The number of turns, the size of each turns, and the material it is wrapped around all affect the inductance.

The amount of work is done to establish the current through inductor and therefore the magnetic field is stored as magnetic energy in inductor and given as

\[ U = \frac{1}{2} LI^2 \text{ Joules} \]  

(2.2)

where \( L \) is inductance of coil (H)

\( I \) is the current through the coil (amps)

2.4.1 Pulsed Power System using Inductor

Figure 2.5 shows the pulsed power system designed using inductor energy storage device for rail gun application.

![Figure 2.5 PPS using inductor (Sitzman 2007)](image)
The operation of this circuit is initiated by the closing of the opening switch, which causes the prime power source to develop a current in L1 and L2. SCR 2 closes, just before the current reaches desired firing level. The opening switch opens, once the current reaches at the firing level. Due to this, the current in L1 is reduces and the current in L2 increases to support the mutual flux. The voltage in the capacitor increases due to the leakage flux and along with the back electromotive force (e.m.f) from the rail gun. After some time delay, the SCR S1 closes, allowing the capacitor to discharge through L1 in reverse direction, and through the load in the forward direction. This causes the output current to increase a second time. After the voltage in C1 has decayed to zero, L1 continues to conduct, but through D2 rather than C1 (Sitzman 2007).

Pulsed inductors have been used for intermediate energy storage device in battery pulsed power system. A battery - inductor based pulsed power supply has several advantages over pulsed alternators and capacitor based pulse forming networks. Because an inductor system stores its energy in a magnetic field, it eliminates the moving parts which found in rotating machines. These features offer tremendous benefits in the design and operation of a fieldable pulsed power supply (Sitzmanet et al 2007).

The main problem of inductive energy storage pulsed power supply system is the time constant of the system. The time constant of the system is defined as the ratio of inductance to system resistance. For large rail gun system, the need to store tens of MJ of energy at a few MA current necessitate the inductor of inductance (L) of a few µH to achieve system resistances (R) that are less than tens of µΩ with copper conductor or other room temperature. So the characteristic decay time for currents is \( t = \frac{L}{R} < 0.1 \) s. This may be operationally unacceptable. This requires the inductor to discharge very quickly after it has been charged, otherwise substantial current
Another major technical challenge inherent to inductive pulsed power systems is the opening switch. An opening switch interrupts a high current flows through the inductor produces a high voltage that is in excess of the capabilities of present generation solid state switches. Akiyama et al (1992) reported that the mechanical switch or plasma switch can be used as an opening switch. They have made a comparison between the mechanical switches and plasma switches and have suggested that plasma switches has good reproducibility than mechanical switches. They have also suggested that the plasma switches has the ability to interrupts a high current rapidly, but they have short life time due to carbon as it decreases for each shot. Table 2.3 gives the technical challenges involved in improving the inductor pulsed power system.

**Table 2.3 Technical Challenges involved in improving inductor based pulsed power system (Robert Guenther et al 2002)**

<table>
<thead>
<tr>
<th>System/Component</th>
<th>Technical Challenge</th>
<th>R&amp; D priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening switch and closing switch</td>
<td>Reducing the conduction losses and switching losses and improve the repetition rate and hold off voltage.</td>
<td>Spark gap: Using new material for electrode like graphite because no plasma is generated. Solid state device: Increasing the resistivity by using GaAs and INP.</td>
</tr>
<tr>
<td>Inductor</td>
<td>Minimizing of parasitic inductance inductor</td>
<td>By using new cooling liquid material, Shielding material of the inductor.</td>
</tr>
</tbody>
</table>
2.5 COMPULSATOR

The compulsator is a specialized alternator produces an alternating voltage which drives the current pulse through a current zero, achieving the desired pulse width. Therefore, the projectile leaves the gun without the need of crowbar switch at zero current. The magnetic energy stored in the discharge circuit is naturally recovered in a compulsator. The compulsator is the only pulsed power supply in which energy recovery is realistic without large mass and efficiency penalties (Spann 1991). The voltage is produced in the compulsator by the relative motion of a multi pole armature and field. Higher voltage can be generated by increasing a) the excitation field strength, b) the relative speed of the two components (i.e., the armature and the field), or c) by increasing the length of the armature. Material strength and dynamic issues generally limit the tip speed of the rotor (Sunil et al 1995). Figure 2.6 shows the cross sectional view of compulsator.

![Cross sectional view of compulsator](image)

**Figure 2.6 Cross sectional view of compulsator**

The shape of the current pulse changes with respect to type of electromagnetic launcher. By using compulsator the required wave shape is obtained by using proper compensation techniques. There are three
compensation techniques that are used to get a proper wave shape of current pulse and they are active, passive and selective passive compensation. In an active compensation technique a compensation winding which is stationary with respect to excitation field that is almost identical to the rotor winding, is placed in an air gap and connected in series with armature through the brushes and slip rings. As the rotor winding moves directly under the compensating winding, the result is that the full machine voltage is applied to the load without the compulsator impedance in the circuit and results in a narrow width current pulse of high peak power that is very sensitive to the load inductance and is not suitable for rail gun applications.

In passive compensation machine the active winding are replaced by low impedance, continuously conducting shields which are stationary with respect to excitation field of the machine and induces the voltage in a rotating armature conductor when the static exciting field diffuses through the shield. The compulsator impedance stays low, since the shield is continues and compensation is providing equally for the full rotation of armature, result is that the output waveform is a smooth sinusoidal shape with high peak currents. These machines have been used to power rail guns, but the rapid sinusoidal rise and fall of the current pulse is not the ideal pulse shape.

In selective passive compensation method the compensating currents are induced but the compensation is not provided equally for full rotation of the armature. This can be incorporated by using a discrete short circuited windings or non uniform winding. Either method allows the engineer to change the machine inductance characteristics based on the rotor position, thereby changing the output waveform. This method generates flat topped current pulse under short circuit (Sunil et al 1994). The other option to get desired wave form is using multi pole machines, it allow even greater flexibility in the control of the output current waveform. Pratap (1997) has reported the method of obtaining flexible wave shape by using different phase
system like single phase, two and multi phase compulsator. He has suggested that each system has its own advantage and disadvantages. Two of the drawbacks to using a single or multi phase machine are that they operate at high RPM to maximize energy storage and require AC-to-DC conversion for the self-excitation current and the output current to the load as shown in Figure 2.7. In this schematic diagram, the full-wave rectifier converts the three-phase AC output to DC that powers the field windings while another set of thyristors converts the output current to the gun (Kitzmiller 1997).

![Figure 2.7 Electrical equivalent diagram of compulsator in Electromagnetic launcher](image)

The main problem in design of the compulsator is rotor coils as they are essentially built for 1) store energy inertial in the mass of the spinning rotor and 2) rapidly deliver large portions of this energy in the form of a pulse of electric current. The design of the rotor is a challenging exercise in optimization as one strives to meet a wide variety of design goals and constraints (Murphy et al. 1997). The rotor must have sufficient inertia to store a required amount of energy at a reasonable speed of rotation, while at the same time being as small and as light as possible. The rotor must accommodate electrical conductors and slip rings. Due to the nature of pulse
power generation, the rotor must withstand potentially large impulse forces and torques during discharge (Cook et al 1998).

The second problem is design of bearings as they must possess adequate load capacity to handle discharge transients, and must also allow the rotor to operate smoothly with sufficient life at high speed. Smoothness of operation is dictated by the precision of balance achieved by balancing the rotor on a commercial balancing machine or within its own housing, or by using both methods (Murphy et al 1997).

All rotating machines also have resonance speeds called critical speeds. These are speeds where vibration levels reach their maximum values due to the close proximity of natural modes vibration. An important aspect of compulsator design is minimizing the potential for high vibration when operating through (or on) a critical speed (Murphy et al 1997). Table 2.4 gives the technical challenges involved in improving the compulsator PPS system.

Table 2.4 Technical Challenges involved in compulsator pulsed power system

<table>
<thead>
<tr>
<th>System/Component</th>
<th>Technical Challenge</th>
<th>R&amp; D priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td>Design of rotor coil to withstand high transient field.</td>
<td>Developing new composite material of rotor.</td>
</tr>
<tr>
<td></td>
<td>Increasing rotor speed, hoop strength, strain</td>
<td>Improving compensating technique.</td>
</tr>
<tr>
<td>Switching system</td>
<td>Spark gap: Reducing the erosion of electrode</td>
<td>Spark gap: using new material for electrode like graphite because no plasma is generated.</td>
</tr>
<tr>
<td></td>
<td>Solid state device: Reducing the switching losses, improving ( \frac{di}{dt} ) and ( \frac{dv}{dt} )</td>
<td>Solid state device: increasing the resistivity by using GaAs and INP. Switching losses: By developing integrated gate structure.</td>
</tr>
</tbody>
</table>
2.6 FLYWHEEL ENERGY STORAGE DEVICE

Flywheels are kinetic energy storage devices, it store the energy in a rotating mass called rotor, with the amount of stored energy is dependent on the mass, inertia and rotational speed of the rotor. An accelerating torque causes a flywheel to speed up and store energy, while a decelerating torque causes a flywheel to slow down and regenerate energy (Swett 2004).

The main parts of the modern flywheel energy storage system are a power converter, a controller, a stator, bearings, and a rotor (Jamie Patterson et al 2004). The rotor includes the rotating part of the motor generator, and the rotating part of the bearings. The stator is also a part of the motor generator. Figure 2.8 shows this schematically:

![Schematic diagram of flywheel diagram](Jamie Patterson et al 2004)

2.6.1 Motor Generator

The rotor portion of the motor-generator consists of an array of permanent magnets lining the bore of the rotor. The magnets are oriented to produce a dipole field aligned across the bore of the rotor. The stator consists of turns of finely stranded wire where each strand is insulated (Litz wire). Litz
wire is used to minimize eddy current losses in the stator. In discharge operation the rotating dipole field of the permanent magnets intercepts the windings and induces a voltage in the windings. Conversely, when the machine is charging, the currents impressed on the stator windings create magnetic fields that exert forces on the magnet array in the bore of the rotor, causing it to spin up.

2.6.2  Rotor Bearing

The rotor bearing design is important to achieve low losses and to minimize maintenance. The bearing losses achieved are usually small, especially when compared with other losses when driving the flywheel. Most flywheels operate at high speed and use high specification bearings.

2.6.3  Composite Rotor

The rotor material is carbon fiber in an epoxy matrix. Prior to use in a flywheel system a number of rotors are produced and spin tested to destruction in order to substantiate the safety factor used in the design. Rotors have also been subjected to cycle testing and spin testing at elevated temperature. Table 2.5 gives the technical challenges involved in improving the FESS, pulsed power supply system.

Table 2.5 Technical Challenges involved in flywheel pulsed power system

<table>
<thead>
<tr>
<th>System/Component</th>
<th>Technical Challenge</th>
<th>R&amp; D priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor of the Flywheel</td>
<td>Increasing energy density of the rotor</td>
<td>Using high resistivity and conductivity composite material of rotor.</td>
</tr>
<tr>
<td>Rim</td>
<td>Managing the radial spin stress</td>
<td>Developing new approaching method to design a rim.</td>
</tr>
</tbody>
</table>
2.7 CAPACITOR

The capacitor is a device that converts the electrostatic energy into electrical energy. It consist of two conductor in between a dielectric medium is placed. The energy stored in the dielectric is given as

\[ U = \int_0^E E \, dp = \varepsilon_0 \int_0^E \varepsilon(E) \, dE \]  \hspace{1cm} (2.3)

where \( U \) is the stored energy in Joules, \( \varepsilon_0 \) is the permittivity of free space \((8.854 \times 10^{-12} \text{ F/m})\), \( E \) is the electric field applied to the dielectric in V/m, \( dP \) is the change in polarization induced in the dielectric by the applied field and \( \varepsilon(E) \) is the electric field dependent permittivity \( k(E) = (E/\varepsilon_0) \). For most dielectrics the permittivity and dielectric constant are not field dependent, therefore, the stored energy reduces to

\[ U = \frac{1}{2} \varepsilon_0 E^2 \]  \hspace{1cm} (2.4)

Or for a capacitor the overall energy stored is given as

\[ U = \frac{1}{2} CV^2 \]  \hspace{1cm} (2.5)

Therefore, as seen by equation (2.4) and equation (2.5), more energy can be stored in a dielectric with a high permittivity (high \( k \)), in capacitor with a high capacitance (high \( C \)) and in a dielectric or capacitor that has a high breakdown strength allowing the application of high \( E \) or \( V \) (Wesley Hackenberger 2006).

Figure 2.9 shows the capacitor based pulsed power supply used in rail gun applications.
When the switch S is closed in the capacitor based pulsed power supply, the capacitor will begin to discharge into the system and transfer its energy into the inductor. At the point when the capacitor is completely discharged, the inductor will be fully charged and current will be at its peak. From this point the current will exponentially decay until the projectile exits the barrel resulting in an open circuit (Dwight warnock 2003).

Figure 2.9 Capacitor based pulsed power supply

Capacitors are available today in five basic technologies and are used across a broad spectrum of applications. The currently commercially available technologies are listed below (Walter et al 1998):

1) Ceramic;
2) Electrolytic;
3) Polymeric film;
4) Paper and mica film (mica and paper).

Cletus Kaiser (1998) and Walter et al (1998) have addressed characteristics of the above capacitors and they have given some guidance in their applications.
The peak power densities of the capacitor are generally quite high in comparison to other devices, including batteries and rotating machinery. Average power densities can also be very high in applications where capacitors are repeatedly charged and discharged. Efficiency can be very high, in excess of 99 percent (Ennis et al 1990). The main limitation to improving these systems either by delivering more energy or by reducing their size, particularly on mobile platforms, is the capacity and size of the energy storage capacitors. In order to increase the energy density in a capacitor various methods such as double layer capacitor Metalized electrode and TPL polymer have been developed (Ling Dai et al (2005), Guido Picci (2000), Kirk et al (2005). Stefan et al (1992) has given four different approaches such as diamond-like carbon films, chemically vapor deposited diamonds films, ULTEMB polyetherimide films, and computer-modeled modified polyetherimide film to develop materials for high energy density and high voltage (10kV) capacitors. Table 2.6 gives the technical challenges involved using in capacitor based pulsed power supply.

<table>
<thead>
<tr>
<th>Component/System</th>
<th>Technical Challenges</th>
<th>R&amp;D Priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer film capacitors</td>
<td>Films with improved dielectric properties</td>
<td>New polymer films with increased dielectric constant and dielectric withstand similar to biaxially oriented polypropylene</td>
</tr>
<tr>
<td>Ceramic capacitors</td>
<td>Improved operating electric field</td>
<td>Research to improve high energy density, high temperature ceramic dielectrics</td>
</tr>
<tr>
<td>Double layer capacitors</td>
<td>Lack of understanding of aging and degradation processes at high temperature</td>
<td>Investigate role of impurities in the carbon electrodes and interactions among the electrodes, electrolyte, and separator</td>
</tr>
</tbody>
</table>

Table 2.6 Technical Challenges involved in capacitor based PPS system (Robert Guenther et al 2002)
2.8 COMPARISON OF ENERGY STORAGE DEVICES

In the electric gun research the pulse power system is one of the most critical components for the successful deployment of such a system. Due to the development of the high energetic propellant the conventional guns have reached a high level of capability after hundreds of years of development. Energy densities in such propellants are impressively high: several MJ/kg. It is difficult to achieving same levels of energy density in a system that stores and transfers electrical energy. The available non-propellant energy storage options are listed in Table 2.7.

Table 2.7 Comparison of energy storage devices and its specification (Ian McNab 1997)

<table>
<thead>
<tr>
<th>Device</th>
<th>Method of storage</th>
<th>Energy Equation</th>
<th>Assumption</th>
<th>Typical state of the art parameters</th>
<th>Energy density MJ/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor</td>
<td>Electrostatic</td>
<td>$\varepsilon E^2/2$</td>
<td>High energy density plastic film</td>
<td>$E = 400$ v/m $\varepsilon_r = 10$</td>
<td>7</td>
</tr>
<tr>
<td>Rotor</td>
<td>Inertia</td>
<td>$IM\omega^2$</td>
<td>High speed composite/conductor rotor</td>
<td>$P = 1500$ kg/m³</td>
<td>135</td>
</tr>
<tr>
<td>Inductor</td>
<td>Magnetic</td>
<td>$B^2/\mu_0\mu_r$</td>
<td>High field air cored inductor</td>
<td>$\mu_r = 1$</td>
<td>640</td>
</tr>
<tr>
<td>Battery</td>
<td>Electrochemical</td>
<td>LiMs operating at $480^0$ c</td>
<td>1.72 v</td>
<td>4000</td>
<td></td>
</tr>
</tbody>
</table>

2.9 MERITS AND DEMERITS OF ENERGY STORAGE SYSTEMS

The merits and demerits of each pulsed power supply systems are given below.
(a) **Battery**

The main advantage of battery energy storage device in comparison to other energy storage devices is that it has higher energy density. The battery pulsed power supply gives low maintenance and reliable operation. This is achieved with a limited number of moving parts, reliable redundant components, personnel training, and subsystem diagnostics before each discharge. Many of the safety checks and diagnostics are performed automatically by the control subsystem. But the battery pulsed power system is not suitable to deliver higher power as it has lower power density. To get higher voltage and higher current larger number of low voltage unit placed in series and parallel. It is not suitable for repetitive applications as it takes time to charge. It needs inverter to transform the battery D.C output via A.C to high voltage D.C

(b) **Capacitor**

The advantage of capacitor based pulsed power supply system is that the system has a simple construction. The system consists of the capacitors, pulse shaping inductors, the high power switches, the protection diodes for the capacitors, a charging power supply, and a trigger and control section for the switches. All the components are available in the market and they have a good performance record in the rail gun application. Depending on the requirement the system is easily upgraded by using single or multiple units. The life time maintenance cost for a capacitor based system is less since there are no moving parts. If one capacitor fails, it is still operable in slightly degraded capacity. The draw back of the capacitor based pulsed power supply is voltage reversal of capacitor. It reduces the life time of capacitor.
(c) **Inductor**

The inductor can store higher energy than capacitor. But it has several drawbacks. It needs opening and closing switches for the same current through the inductor. Higher value of losses also occurs in this circuit due to switching operation. Since the time constant of the inductor pulsed power supply is high, so obtaining the required current pulse width is difficult. So the feasibility of such type of circuit for high caliber PPS impossible.

(d) **MHD Generator**

The advantage of MHD generator is that the system has relative simplicity. It is one pass system and can be triggered simply and repetitively. By using the PMHDG pulsed current width long duration and short duration can be easily generated however generating the millisecond order of current pulse for rail gun application is difficult. In general, the relatively low conductivity of most plasma limits the current that can be obtained from MHD generators. This is more of a concern for EM rail gun applications.

(e) **Compulsator**

The main advantage of compulsator energy storage device is that it has high energy density, power density and lack of additional power condition. But it has several draw backs. The system is complex and more expensive and immature technology. The system is not easily up gradable. It needs additional machines to operate in parallel to increase the output power. Also it is not commercially available.

(f) **Flywheel energy storage device**

The main advantage of FES system is that it has capability of producing extra energy when it is needed and remove excess energy when it
is present. It can be charged and discharged at high rates for many cycles. The main drawback of this system is it has lower energy density and it not suitable for repetitive pulsed applications.

2.10 SUMMARY

In order to select a suitable energy storage device to design a 500-kJ, pulsed power supply for rail gun application in this chapter different types of pulsed power supplies which produce pulsed output are studied. Detailed feasibility studies have been done on different available PFN’s. For each type of energy storage devices the technical challenges involved in improving the system component in pulsed power supply system have been discussed. It has been observed that each type has its own advantages and disadvantages. So a logical compromise has been made taking into account of the constraints which are posted by the desired energy requirement. Based on the resources and the proposed application it has been decided that the 500-kJ pulsed power supply will be designed as a capacitor based system.

However, the Government of India has given the value of energy stored by the pulsed power supply system and velocity of the projectile. The electromagnetic rail gun is a current operated device and the force acting on the projectile is depends on square of the current which flows through the rails. Achieving the higher velocity of the projectile is depends on how the energy storage device discharging the energy into the rail gun. The 500kJ PPS system, developed in this work, is used to give electrical energy to the rail gun, but achieving the desired velocity with a given energy is depends on current delivered by energy storage device. So in 500kJ PPS design, only current is considered, instead of energy, in order to get desired velocity of the projectile.