Chapter 2

Pulsed Power Topologies

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Pulsed power is a process of delivering energy into a system in a very short duration of time. As it is evident, for same amount of input energy, faster the energy is delivered, more powerful the system is. The effective time duration makes pulsed power to take part in varieties of applications. For example a millisecond pulse duration application is launching a projectile in Rail-gun system, whereas few tens of nano-second pulse duration is required for generation of microwaves, X-rays etc. The required pulse duration demands various pulsed power generators. As pulsed power generation is of short duration of pulse of energy, the energy needs to be stored first. The required energy storage device is to be chosen such a way that, it fulfills the energy discharge time in the required application. Table 2.1 shows approximate energy density and energy discharge time of some of the storage devices [1].

Table 2.1. Approximate values of energy discharge time & energy density of storage devices

Energy storage device	**Energy density (J/cc)**	**Energy discharge time (s)**
Capacitor	0.5 – 0.8	10^{-6}
Normal Inductor	10	10^{-3}
Super Conductors	10^{2}	10^{-3}
Rotating Machines	10^{3}	10^{3}
Batteries	10^{3}	10^{4}
High Explosive	10^{4}	10^{-6}

2.1. Energy Storage Devices

Pulsed power applications use varieties of energy storage devices. The medium of energy storage may be mechanical or electrical or chemical. A rotating machine is very common example of mechanical energy storage device. As given in Table 2.1, though a rotating machine is having high energy density but energy discharge time is very slow. Capacitors and inductors store their energy in the form of electrical energy. Capacitors store energy in the form of electric field and inductors store in the form of magnetic field. Both of these electrical energy storage devices have wide range of applications. Explosives store energy in the form of chemical energy. Explosive driven pulsed power devices have applications where system needs to be small in size and deployable. In the coming sections we will discuss in detail about these storage schemes and pulse compression techniques.

2.1.1. Capacitor Bank

Capacitor is the most widely used part in pulsed power generator. Stored energy, E_c in capacitor is given by,

$$E_c = \frac{1}{2} C V_{ch}^2 \tag{2.1}$$

Here C is the capacitance and V_{ch} is the charge voltage. Capacitor discharges its energy to a circuit combination of inductor L, and resistance R. The discharge current is given by,

$$I = \frac{V}{\omega L} e^{\left(-\frac{R}{2L}\right)} \sin(\omega t) \tag{2.2}$$

In general the resistance of the circuit is very small, so the discharge is typically underdamped. In a capacitor bank, a series and/or parallel combination of capacitors are connected as per load requirement.

2.1.2. Inductive Energy Storage device

In an inductive energy storage device, energy is stored in the form of magnetic field. The energy density (energy per unit volume) is given by,

$$\epsilon_m = \frac{B^2}{2\mu_0\mu_r} \tag{2.3}$$

Here, B is the magnetic field associated with current, I. Though inductive energy storage devices have higher energy density compared to capacitive energy storage, but drawback is continuous current flow is required in this case.

An example of inductive energy storage device in pulsed power is exploding wire opening switch (OS). In OS, the resistance is increased from few tens milliohms to few hundred ohms in the span of ten to hundreds of nano-second by adiabatically depositing electrical energy due to current flow. The fast rate of rise of resistance causes very high di/dt (rate of change of current). This, in-turn causes pulsed very high voltage generation across an inductor. The resistivity at any instant is given by Eq. (2.4), where the parameters depend on the phase of the material [2].

When material is in complete solid phase, $0 \le J_{AC} \le J_S$

$$\eta = \eta_0 e^{\frac{J_{AC}}{J_S}\ln\left(\frac{\eta_S}{\eta_0}\right)}$$

When material is in combination of solid and liquid phase, $J_S \le J_{AC} \le J_{SL}$

$$\eta = \frac{\eta_S}{\sqrt{1 - \frac{(J_{AC}-J_S)(\eta_{SL}^2-\eta_S^2)}{(J_{SL}-J_S)\eta_{SL}^2}}}$$

When material is in complete liquid phase, $J_{SL} \le J_{AC} \le J_L$

$$\eta = \eta_{SL} e^{\frac{J_{AC}}{J_L}\ln\left(\frac{\eta_L}{\eta_{SL}}\right)}$$

When material is in combination of liquid and vapour phase, $J_L \le J_{AC} \le J_{LV}$

$$\eta = \frac{\eta_L}{\sqrt{1 - \frac{(J_{AC}-J_L)(\eta_{LV}^2-\eta_L^2)}{(J_{SL}-J_S)\eta_{LV}^2}}} \tag{2.4}$$

Here J is action integral and subscripts denote the phases as detailed below. η is the resistivity at any time instant, also depend on the phase of the material.

S: solid phase, *SL*: combination of solid & liquid phase, *L*: liquid phase, *LV*: liquid-vapour phase, *V*: vapour phase. Typical schematic of OS assembly is shown in Figure 2.1.

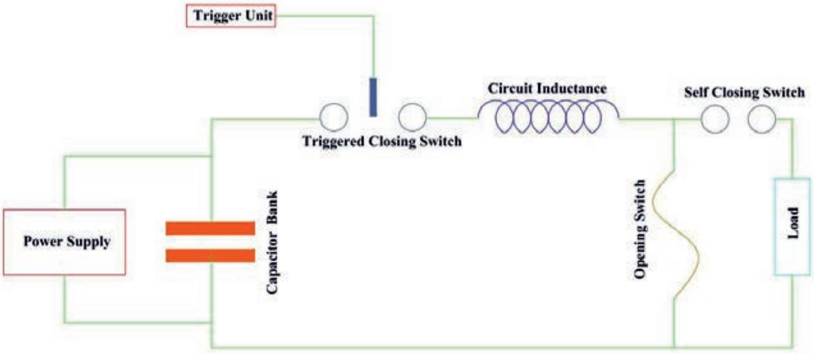

Figure 2.1. Opening Switch Schematic.

If the circuit inductance is very small and as the OS inductance is few hundred of nH, a very high current flows through the circuit. When the OS opens due to presence of inductance in the circuit a high di/dt is applied across the self closing switch. This switch closes when the voltage across it crosses the self breakdown voltage. Thus transferring the energy to the load by impedance transformation from low impedance to high impedance. Here to mention, capacitor bank has been used to deliver initial pulsed power to the OS load.

2.1.3. Marx Generator

A Marx Generator (MG) is a device where n numbers of capacitors are charged in parallel and discharge sequentially in series. This topology of pulsed high voltage generation makes the input voltage low but the output voltage very high. In MG the load impedance is matched with MG output impedance to get a non-oscillating output voltage. For critically damped impedance matched load, the MG output voltage V_{op} is given as in Eq. (2.5).

$$V_{op} = 0.7nV_{ch} \tag{2.5}$$

MG output is typically of few μs time duration. But some applications need output of few ns. For this type of output a pulse forming line (PFL) is used.

2.1.4. Pulse Forming Line

A pulse forming line (PFL) is used for pulse sharpening. The pulse duration depends on transit time of the input pulse. As in transmission line the pulse duration of PFL is given by,

$$t_{pulse} = 2t_{tr}$$

$$t_{tr} = \frac{l_{PFL}}{v_{PFL}}$$

$$v_{PFL} = \frac{1}{\sqrt{\mu_0\mu_r\epsilon_0\epsilon_r}} = \frac{1}{\sqrt{L_{PFL}C_{PFL}}} \tag{2.6}$$

Here l_{PFL} is the length of the PFL. L_{PFL} & C_{PFL} are the inductance and capacitance per unit length of the PFL.

2.1.5. Tesla Transformer

A tesla transformer is another kind of pulsed high voltage generator works on the principle of transformer action. Here a charged capacitor is discharged across the primary of the Tesla transformer through switch. The primary inductance and secondary inductance & capacitances are so chosen that it operates in resonant mode, i.e. $L_1C_1 = L_2C_2$, where 1 & 2 represent primary & secondary of transformer. As coupling coefficient $k = 1$ is not feasible in any air core transformer, air core tesla transformer is so tuned that at $k = 0.6$ maximum secondary voltage is achieved. Tesla transformer with magnetic cores are designed at $k = 1$ coupling coefficient.

2.1.6. Linear Transformer Driver

A Linear Transformer Driver (LTD) is another pulsed power generator, where it works both as pulsed power generator and PFL. Here, in a brick, a series combination of capacitors, which are initially charge in opposite polarity, are discharged through a spark-gap switch. This causes a voltage across the primary of the cavity. Figure 2.2 shows the brick of LTD. A parallel combination of bricks in a cavity defines the total current carrying capacity. A series combination of cavities defines the total output voltage. So if each cavity generates voltage V_c, for n-cavity, the output voltage will be nV_c. The inner shell acts as secondary of 1:1 transformer whereas the cavity flange is the primary. A load of matched impedance is connected across the primary and secondary of the nth cavity. In LTD as we move forward towards load-end, impedance of the system increases. So, if one cavity gives output impedance of Z_c, then output impedance of the LTD having n-cavities will be $Z = nZ_c$.

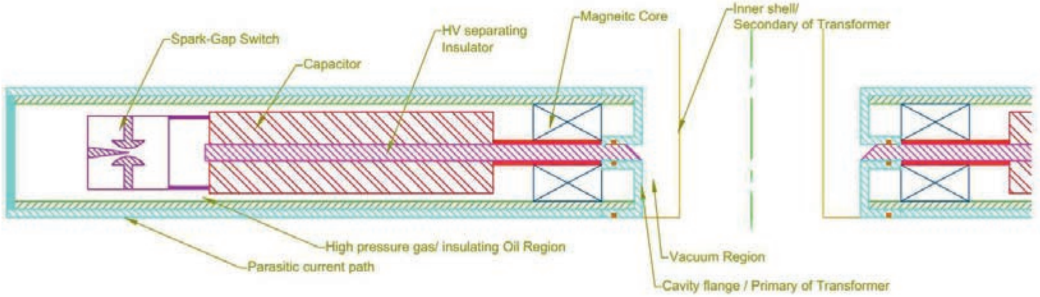

Figure 2.2. Brick of LTD.

The schematic of LTD is given as in Figure 2.3. Here C is the capacitance of all the bricks of the cavity. S are the switches of the bricks. $L3$ is inductance of the vacuum coax. $L4$ is primary inductance. *L1* represent parasitic inductance of the primary brick circuit and *L2* is the parasitic inductance of the convolute between switch and vacuum coax. *R* is the resistance of the circuit. For proper LTD operation, *L4* should be much higher compared to (*L2*+*L3*). Also *L1* & *L2* should be as low as possible compared to *L3*.

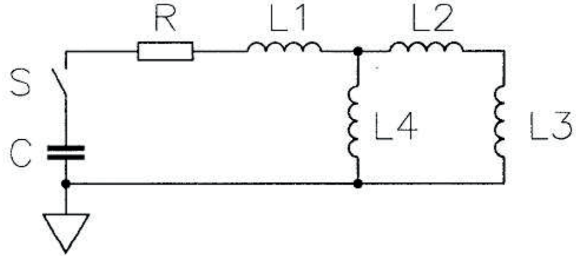

Figure 2.3. LTD Schematic

For low output voltage and high repetition rate LTD, semiconductor based switches can be used. An example of the same can be found in the reference [3]. But for high voltage and high current applications typically spark-gap switches are used.

There are two space regions of operation in LTD. First one is electrostatic region. Here the high voltage insulating medium is high pressure gas or insulating oil and these need to be decided on the operating DC voltage of LTD cavity which is normally few tens of kV to 100 kV. The other operating region may be called as electro-dynamic region. Here the insulating medium is typically vacuum and the insulation is decided based on pulsed output voltage of few tens of nanosecond duration. Here two modes of operation are possible. If the inner shell is designed to be anode and outer shell primary to be the cathode, we call it positive adder topology. In this case the gap distance between these electrodes to be decided based on maximum breakdown electric field strength of vacuum, which is ~20 kV/mm. The electric field (ε) at the inner shell is given in Eq. (2.7) where cavity voltage is V. In other case, in negative adder topology, the inner shell is designed to be cathode having outer radius, r_i and the outer shell as anode, having inner radius, r_o.

$$\varepsilon = \frac{V}{r_i \ln\left({}^{r_o}/_{r_i}\right)} \tag{2.7}$$

In this negative adder there will be an added advantage of insulation as explained next. Very large electric field, present in these devices, causes electron emission, ectons [4] from cathode and causes voltage breakdown and thereby forming plasma channel. In negative adder, electrons emitted from cathode can be streamlined parallel to the axis towards the load, along the equi-potentials, causing a parapotential flow [5]. This forms a Magnetically Insulted Transmission Line (MITL). Thus in MITL, electrons are diverted along equi-potentials insulating the anode and prevents from voltage breakdown. The total current required for MITL is given by Eq. (2.8)[6]. $\gamma = \gamma_0$ when $V = V_0$ at the anode. $\gamma = \gamma_m$ when $V = V_m$ at the space in between anode and cathode. There is a radius between anode and cathode where I_0 is minimum.

$$I_0 = gI_\alpha \gamma_m \left(ln\left[\gamma_m + (\gamma_m^2 - 1)^{1/2}\right] + \frac{\gamma_0 - \gamma_m}{(\gamma_m^2 - 1)^{1/2}} \right) \tag{2.8}$$

$g = \left(ln\left(\frac{r_0}{r_i}\right) \right)^{-1}$, is geometric factor for co-axial transmission line $I_\alpha = 8500\ A$, a constant $\gamma = 1 + \frac{eV}{m_0 c^2}$

2.1.7. Linear Induction Accelerator

If we replace the inner shell of LTD by a column of electron beam, then the system is Linear Induction Accelerator or LIA. Here, an electron beam of few kA current is injected into the cavity bore. The beam is then accelerated due to induction by pulsed voltage generated in cavities. So LIA works as an electron accelerator. The beam attains the energy of neV at the load end of the accelerator, where it is consisting of n cavities. And each cavity is generating a pulse of V voltage. The prominent drawback of LIA is the beam suffers lots of instabilities as it gets accelerated towards the load end. A multi-pass, circulating beam LIA can be designed where the number of cavities and thereby length of LIA can be reduced [7]. But this needs a complicated magnetic guide for beam bending.

2.2. Conclusion

An overview on various types of pulsed power generators has been documented here. The references have explained the same in detail. We have developed some of the pulsed power generators in our laboratory.

References

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