Chapter 7

Pulse Forming Lines

——Ankur Patel

Pulse power systems are used to produce high voltage, high current, nano-second duration pulse. Conventionally, pulsed power systems are made up of Marx generator, Tesla transformer or Magnetic switch based system. The pulse generated by any of this method ended up to microsecond pulse due to high inductance of the system. The pulse forming lines are use to compress the microsecond pulse to nano-second range, which has applications in HPM generation and FXR system. Application also requires fast rise time, fall time and flattop. Tapered transmission line is also used to match the source and load impedances. To generate required pulse, the switch turn on time, stray inductance and capacitors, current rating and voltage rating, load impedance needs to be critically designed. Pulsed high voltage generator design is heavily dependent on the knowledge of high voltage and its application time. Size of insulators increases significantly with increase in high voltage application time. Hence, if application time is not taken into consideration sizes of pulse generators will be huge and, in many cases, impossible to realize. Pulse forming lines are coaxial cylindrical structures or parallel metallic strips/plates separated by an insulating medium. This apparently appears like parallel plate capacitors. However, for higher frequency modeling it will appear as ladder network of distributed capacitors connected to each other by inductances. It is commonly known as Pi network and used for modeling of transmission lines in power system engineering. Here it may be noted that in power transmission network length of transmission lines are in hundreds of kilometres because, it is considered 50 Hz as operating frequency. If operating frequency of the system increases to MHz, even few meters of wire will behave as transmission line. Mostly two types of pulse shapers are used worldwide.[1,2]

7.1. Pulse forming line (Single line)

Figure 7.1 (a) shows a basic circuit diagram of pulse forming line. A transmission line of length L is charged to voltage V by a DC voltage, usually by resistor or inductors whose impedance is high enough to limit the charging current to the maximum corresponding to the output power specification of supply. Once the line has been charged the switch is closed and the line is allowed to discharge into the load Z. Mostly, charging is done using much lower frequency pulse, thus during charging these lines behave as capacitors only. While discharged into load, wave front is generated, which travels along the length of the line and gets reflected depending on reflection coefficients of the transmission line at source end and load end. Output pulse width across the load is decided by the double transit time of the line. Travelling speed of the wave front is equal to $c/\sqrt{\varepsilon_r}$ where, $c = 3\times10^8$ m/s and ε_r = relative permittivity of the insulating material. The equivalent circuit of the pulse forming line is shown in Figure 7.1 (b).

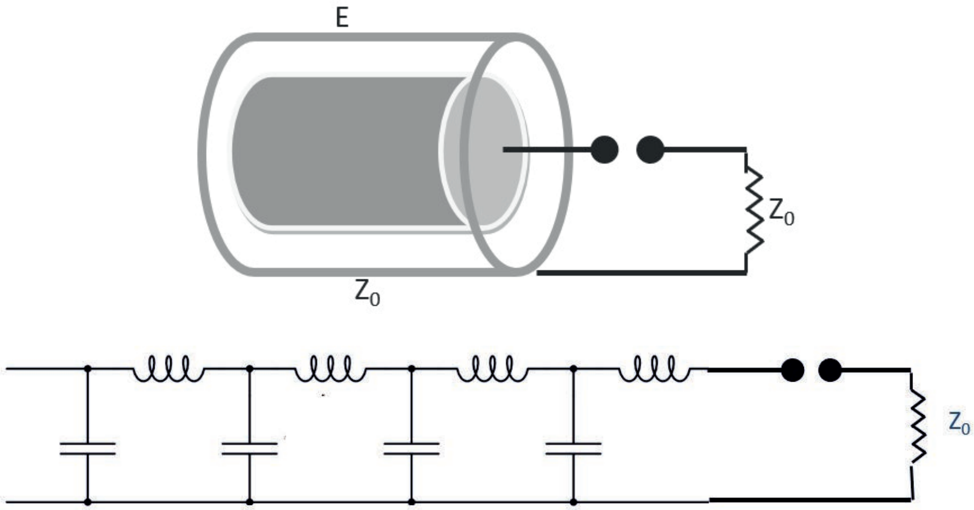

Figure 7.1(a). Typical geometrical structure of Pulse Forming Line and (b) Equivalent circuit of Pulse Forming Line.

The propagation velocity of such a step v_p is given by

$$v_p = \frac{c}{\varepsilon_r}\,, \tag{7.1}$$

c: Velocity of line

ε: Permittivity of line

The duration of pulse that is simply given by

$$t_p = \frac{2l}{v_p} \tag{7.2}$$

The closing time and opening times of switch are much shorter than the duration of pulse generated. It is also important for a short duration pulse, the stray inductance part of the circuit which connects the output end of the line to the load should be minimized. If this is not the case the rise time of the pulse will be limited by this stray inductance with a time constant given by

$$tr = \frac{L_S}{Z_l + Z_0} \tag{7.3}$$

A series of voltage/time diagrams which show the potential of the line at various times after the switch is closed. Such a series of diagram is given in Figure 7.2 in which the impedances of load and line are matched. As the switch closes, the voltage on the load rises from zero to a value determined by the initial charging voltage V, the characteristic impedance of line *Zo.*

Voltage on the load is given by,

$$V_l = V\frac{Z_l}{Z_l + Z_o} \tag{7.4}$$

In the case where impedances of the line and load are equal then voltage on the load will be *V/2*. Simultaneously a voltage step V_s is propagated away from the load towards the charging end of the line. The step has an amplitude V_s is given by,

$$V_s = V\left(\frac{Z_l}{Z_l + Z_o} - 1\right) = V\left(-\frac{Z_o}{Z_l + Z_o}\right) \tag{7.5}$$

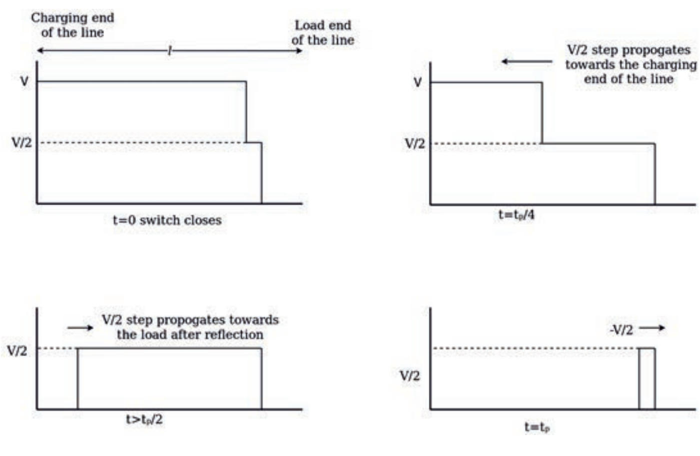

Figure 7.2. The potential distribution on line.

In the case of the line and load impedances being equal this step will simply be *V/2*. The *–V/2* signal propagates towards the charging end of line. On the source side, it experiences the open circuit and the reflection coefficient is equal to 1. So the potential at the charging end of the line falls to zero and a voltage step of amplitude V_s propagate towards the load, altering as it goes potential on the line. Again, if the line and load are matched this step has amplitude –

$V/2$ and it propagates, it completely discharged, the potential on the load falls to zero and the pulse terminates. If the impedances of the line and load are not matched, further reflection of the propagating step occur at the load and resulting output has a more complicated shape rather than that of a single rectangular pulse.

7.2. Blumlein Pulse forming Line

Blumlein is used to shape the pulse like single PFN but in this case the voltage remains same as charging voltage as against the single PFL where output voltage becomes half. The matched impedance is this case is $2Z_o$ and length of the each line is L. The potential distribution on the line is shown in Figure 7.4.

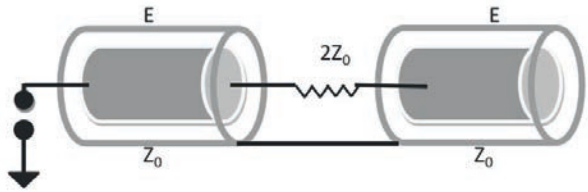

Figure 7.3. The potential distribution on line.

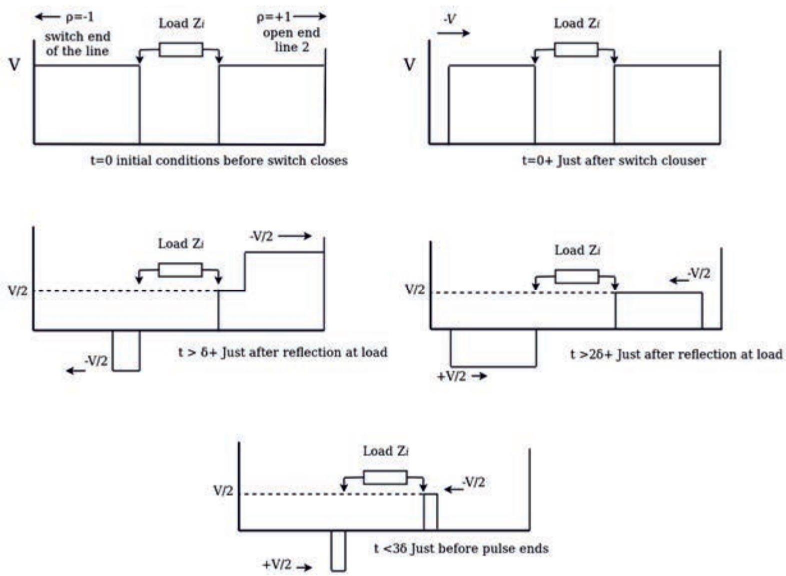

Figure 7.4. Voltage distributions along the line in blumlein.

7.3. Triangular pulse output of Pulse forming line

Pulse forming line works in the principle of travelling wave along transmission line. Wave travels with a certain velocity (decided by the relative permittivity of the insulation) along the length of the line, and pulse width equal to double transit time is obtained across matched load. Rise time of this square pulse is decided by the slew rate of the switch that initiates discharging of the PFL. Slew rate of the switch has two dependencies. First one is the turn on time of the switch itself, in case of high voltage applications, sparkgap switches has turn on time of approximately 10-50 ps. Second most important parameter is the construction of the line. This decides inductance and radial wave travel time of electrical wave during switching. If inductance is high or diameter is more, it tends to generate slow rising switching phenomena. This in a way affects the rise time of the output pulse. If diameter is comparable with the length of the line, this phenomenon becomes extremely vivid. This is due to the fact that wave travel time along the length of the line becomes comparable with that across the radius. Eventually, instead of a square output, a more triangular shaped pulse is obtained. To avoid such a situation length of the line is advised to be kept at least three times of the diameter, in case of a cylindrical PFL.

Accelerator and pulse power division has developed various pulses forming line and its parameters are listed in the following table 7.1.

Table 7.1. Pulse forming line developed by APPD.

S. NO	Pulse power system	Type of PFL	Dielectric material	Length of line	Time duration	Impedance	Charging voltage of PFL
1	KALI-200	Coaxial	Transformer oil	-	--- ---		----
2	KALI-1000	Coaxial	Demineralised water	0.8 m	50 ns	7	490 kV
3	KALI-5000	Cylindrical Blumlein	Castor oil	6 m	100 ns	20	1000 kV
4	LIA-200	Coaxial	Demineralised water	0.8 m	50 ns	7	200 kV
5	KALI-30 GW	Cylindrical Blumlein	Transformer oil	6 m	80 ns	30	1000 kV
6	LIA-400	Strip line	Mylar	5 m	100 ns	0.5	60 kV
Note: The time duration and impedance obtained practically found to be on higher side due to increase in length to view of mechanical assembly and electrical breakdown constraints, final spark gap switches.							

References

[1] Smith, Paul W. Transient electronics: pulsed circuit technology. John Wiley & Sons, 2011.

[2] Smith, Ian. "Linear induction accelerators made from pulse-line cavities with external pulse injection." Review of Scientific Instruments 50, no. 6 (1979): 714-718.