Circuit and Electromagnetic System Design Notes

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Charging of Marx Generators

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Abstract

For Marx generators to operate with a high pulse-repetition frequency, one needs to minimize the time required to charge the capacitors, while not significantly loading the Marx during erection and discharge. Typical design of the charging circuit involves a series string of resistors, or even a series string of inductors, running along the capacitor stack. In this paper we consider parallel charging with inductors and resistors in which the charging elements (and series combinations) are all connected in parallel to the power supplies (two for differential charging).

1. Introduction

In designing Marx generators for large pulse-repetition frequency (PRF) there are many features of one's concern. One of these is the charging time of the Marx capacitors. Typically these are charged with series resistor networks as illustrated in Fig. 1.1. This is a differentially charged set of N capacitors with

$$V_+ = -V_- \qquad \text{(typically 50 } kV\text{)} \tag{1.1}$$

Here the number of capacitors N is taken as even for convenience. When erected the open-circuit voltage presented to the switch to the load is

$$V_0 = NV_- = -NV_+ \tag{1.2}$$

where the Marx voltage here is taken as negative, but could just as easily be taken as positive. Note that due to stray capacitance and loading from the charging resistors (R_s, R_1, and R_g) during the Marx erection the actual output voltage is a little less than V_0 in magnitude. The Marx capacitance (erected, neglecting strays) is

$$C_M = \frac{C}{N} \tag{1.3}$$

This type of Marx can be triggered by various techniques. Triggering the first switch or first few switches produces a strong overvoltage on successive switches leading to an erection wave progressing to the right in Fig. 1.1. This is the standard Marx design often referenced as the "Erwin" Marx [4]. Elaborate schemes for third-electrode triggers in the subsequent switches with resistive (or capacitive) feed from earlier switches (to the left) can also be constructed to speed up the erection process. Such are referenced as "Martin" Marxes [3, 6]. We do not consider the details of the erection process in this paper.

In this paper we concentrate on the charging system for the Marx capacitors, comparing traditional series charging to parallel charging including both resistive and inductive elements. In designing a Marx for high PRF one can consider the time T_0 for a Marx cycle as composed of four parts

$$T_0 = t_{ch} + t_{\mathrm{v}} + t_{sr}$$

$t_{ch} \equiv$ time to charge the Marx capacitors

$t_{\mathrm{v}} \equiv$ high-voltage time

$\equiv$ time Marx has some appreciable portion of V_0 (erection time (or gap running time) plus ring up time (as into a transfer capacitor) plus discharge time

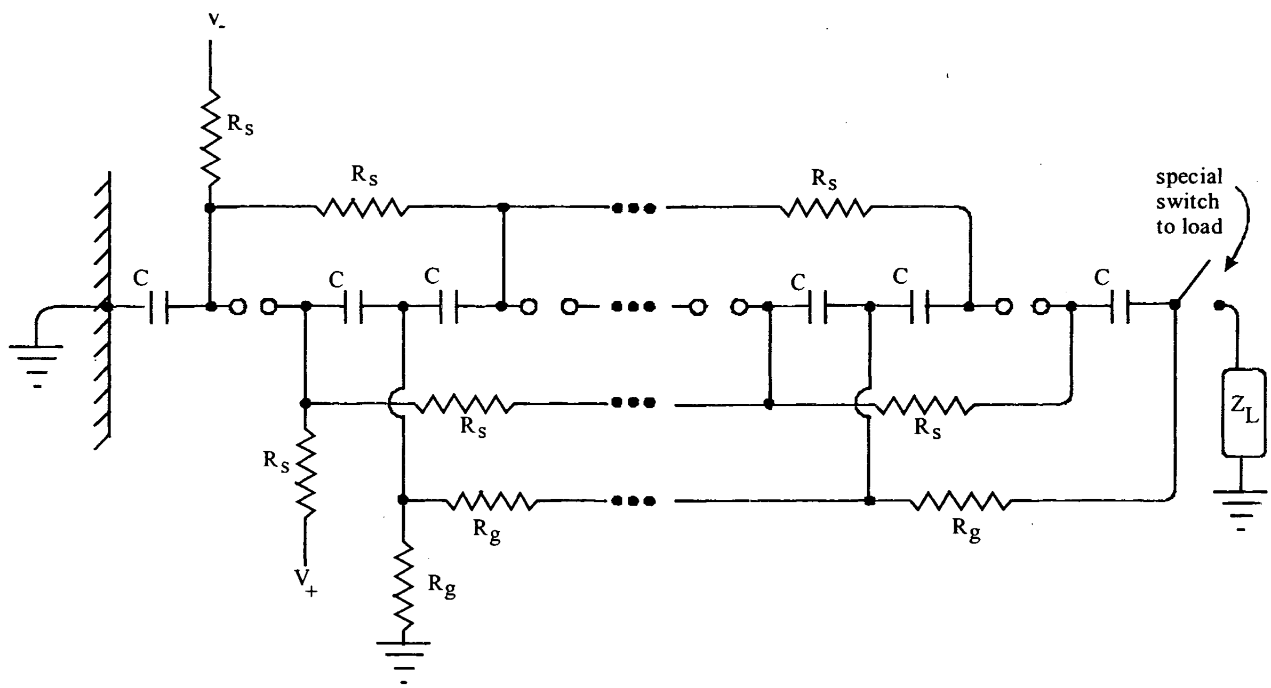


Fig. 1.1 A Series, Differential, Resistively Charged Marx Generator

t_{er} $\equiv$ Marx erection time (or gap running time) (1.4)

t_{dis} $\equiv$ discharge time

$\equiv$ time from switching to load until voltage on load decays to negligible value (compared to V_0)

t_{sr} $\equiv$ switch recovery time (after which Marx capacitors can begin recharging, not addressed here)

Generally, we would like to impose the inequality

$$t_{ch} >> t_v >> t_{dis} \tag{1.5}$$

so that for a fast discharge (in say the 10 ns regime) the high-voltage time in the 100 ns regime does not intrude on the discharge time. Note that if one has a transfer capacitor the ringup time can be lumped with the high-voltage time. Furthermore the high-voltage time needs to be short compared to the charging time so that the charging network does not load down the erected Marx voltage. The switch recovery time is not discussed here.

For purposes of the present discussion (from which one can scale to other conditions) let us use as an example

$$\begin{aligned} Z_L &= 50\,\Omega \\ V_0 &= 50\,kV \\ N &= 20 \\ NV_0 &= 1\,MV \\ t_{dis} &= 10\,ns \\ t_v &= 100\,ns \end{aligned} \tag{1.6}$$

Using, for simplicity,

$$t_{dis} = Z_L C_M \tag{1.7}$$

we have

$$\begin{aligned} C_M &= 0.2\,nF \\ C &= 20\,C_M = 4\,nF \end{aligned} \tag{1.8}$$

Furthermore, let us choose

$$t_{ch} \geq 10\,t_v = 1\,\mu s \tag{1.9}$$

These will be used later to estimate values of resistance and inductance in the charging networks.

2. Series Resistive Charging

Referring to Fig. 1.1, let all the charging resistors be the same, i.e., all R_s are the same. Assuming initial conditions of zero charge on each capacitor, the resistors to ground R_g do not enter into the charging by symmetry (except for the last (rightmost) one which is an exceptional case for even N). As the Marx erects these resistors load the Marx, so we can constrain

$$\frac{N}{2} R_g \, C_M = \frac{1}{2} R_g \, C >> t_v \tag{2.1}$$

which places $R_g >> 50\,\Omega$ in our example. The charging resistors R_s also load the Marx and, noting the two parallel chains of $N/2$ resistors each, we have

$$\frac{N}{4} R_s \, C_M = \frac{1}{4} R_s \, C >> t_v \tag{2.2}$$

which gives $R_s >> 100\,\Omega$ in our example. Of course the loading of both sets of resistors needs to be included. Note that each of the above resistors needs to withstand about 100 kV in our example for some part of t_v.

The charging of the Marx by this series set of resistors takes some considerable time as can be seen by modeling the $N/2$ resistors and capacitors of each half of the charging system as a distributed RC transmission line. This has been worked out for large $N/2$ in [5]. Defining

$$R_T = \frac{N}{2} R_s \quad , \quad C_T = \frac{N}{2} C \; , \quad t_T \equiv R_T C_T \tag{2.3}$$

applying to each of the two halves of the charging system, the approximate solution for the normalized sum of the capacitor voltages $\mathrm{v}(t)$ is given by

$$\mathrm{v}(t) \simeq \left[1 - \frac{8}{\pi^2} \, e^{-\left(\frac{\pi}{2}\right)^2 \frac{t}{t_T}} \right] u(t) \tag{2.4}$$

assuming step excitation $V_{\pm} u(t)$. At $t = t_T$ the charging has reached 93%.

So t_T is basically the charging time t_{ch}, and

$$t_T = \frac{N^2}{4} R_s C = \frac{N^3}{4} R_s C_M >> N^2 t_v \tag{2.5}$$

For our example, then

$$t_T >> 40 \mu s \tag{2.6}$$

So we are looking at a charging time in the hundreds of μs regime.

3. Series Inductive Charging

If the series resistors R_s are each replaced with inductors L_s then the charging system behaves as a lumped-element LC transmission line. For large N we have

$$Z_c = \left[\frac{L_s}{C}\right]^{\frac{1}{2}} \equiv \text{characteristic impedance for each transmission line forming half of the charging system}$$

$$t_r = \left[\frac{N}{2} L_s \frac{N}{2} C\right]^{\frac{1}{2}} = \frac{N}{2}[L_s \ C]^{\frac{1}{2}}$$

$\equiv$ transit time along transmission line (3.1)

$$t_L = [L_s C]^{\frac{1}{2}} = Z_c \ C$$

= transit time for one section

$$t_r = \frac{N}{2} t_L = \frac{N}{2} Z_c \ C$$

If we put step excitation $u(t)$ into each line the capacitors are all charged to $V_{\pm}$ at time t_r .

At this point one need not close the switch to the load. The transmission-line waves (two) can reflect (positively) at this open circuit and propagate back to the left and in Fig. 1.1, reaching there at a time 2 t_r . The capacitors are all charged to 2 $V_{\pm}$ (the individual capacitors are now required to take this double voltage and the currents in all the inductors are zero. Erecting the Marx at this time, the open-circuit voltage at the load switch is 2 V_0 . For good performance we would like

$$t_v << t_L \tag{3.2}$$

so that the capacitors are discharged before current can build back up in any inductors. This in turn implies in our example

$$Z_c = \frac{t_L}{C} >> \frac{t_v}{C} = 25\,\Omega$$

$$L_s = \frac{t_L^2}{C} >> \frac{t_v^2}{C} = 2.5\,\mu H$$

$$
\begin{aligned}
t_r &= \frac{N}{2} t_L \gg \frac{N}{2} t_V = 1\,\mu s \\
t_{ch} &= 2 t_r \gg 2\,\mu s
\end{aligned}
\tag{3.3}
$$

So a charging time in the tens of μs regime is acceptable, and is much faster than the resistive case in (2.6).

There is a disadvantage to using this type of charging system [9]. This has some of the characteristics of a resonant charging system. As such the L_S and C elements can resonate together if the currents through the inductors and charge on the capacitors are not all zero at the end of the discharge into the load. In addition the output of the power supply must have low impedance compared to Z_c and rise in a time short compared to t_r .

4. Parallel Resisitive Charging

Another circuit topology for the charging network is a parallel one as in Fig. 4.1. In this case, there is a direct connection from each capacitor through charging elements to the V_- or V_+ power supply. Consider first the case of parallel resistors R_p by setting L_p to zero.

With zero initial charge on the capacitors and charge voltage $V_\pm \, u(t)$, we have the voltage on each capacitor (except for the last one due to the influence of R_g)

$$\frac{V(t)}{V_\pm} = \left[1 - e^{-\frac{t}{\tau}}\right] u(t) \qquad \tau = R_p C \tag{4.1}$$

this well-known waveform rises to 90% in about 2.3 τ , so we might choose

$$t_{ch} \simeq 2.3\tau \tag{4.2}$$

or some larger number.

During the Marx erection process these resistors load the capacitors, removing some charge. With the Marx switches closed the symmetry of the network allows both negative and positive power supply voltages to be set to zero. We have a resistance of $R_p / 2$ to ground just after each odd numbered capacitor. For the present let us assume that $R_g >> R_p$ so that we can neglect the presence of the R_g resistors. Let us then consider how much the R_s loading reduces the erected Marx voltage V_0. (Again the rightmost R_g is a special case that needs to be comparable to R_p. This is neglected for the present.)

The initial currents in the R_p resistors after full voltage is reached are given by the voltages $2V_n / R_p$ for odd n as indicated in Fig. 4.2, where now

$$V_n = n V_- \qquad I_n = \frac{2}{R_p} V_n = \frac{2n}{R_p} V_- \tag{4.3}$$

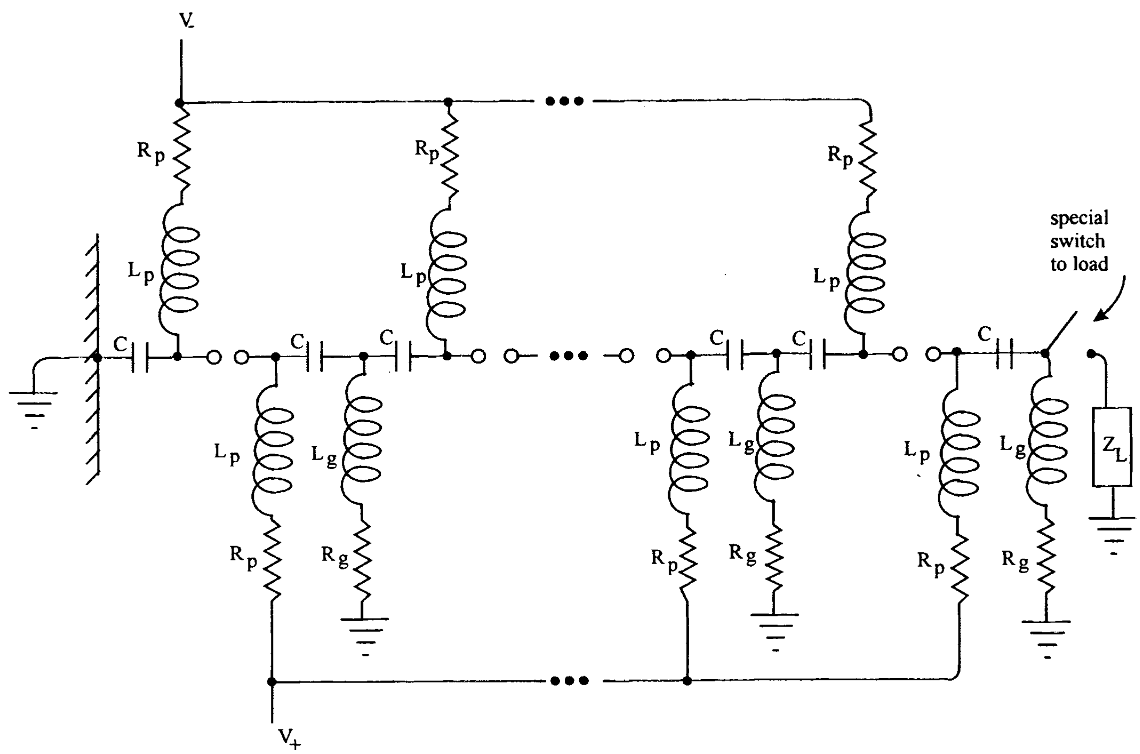


Fig. 4.1. Parallel, Differential, Resistively and Inductively Charged Marx Generator.

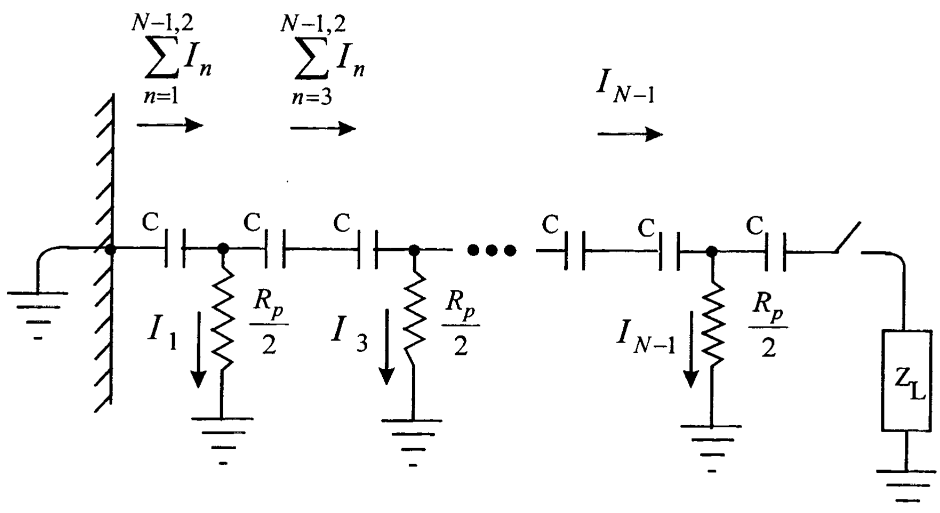


Fig. 4.2 Loading by Parallel Charging Resistors After Full Marx Voltage is Reached

here t_V is assumed short enough that the voltages have not been significantly reduced by the R_p. These currents remove charge from the capacitors and hence decrease the voltages. Considering just the leading terms (first time derivatives) we have

$$
\begin{aligned}
\frac{dV_1}{dt} &= -\frac{1}{C}\sum_{m=1}^{N-1,2} I_m = -\frac{2}{R_pC}\,V_-\sum_{n=1}^{N-1,2} m \\
&= -\frac{1}{2R_pC}\,N^2 \\
\frac{d}{dt}\left[V_n - V_{n-2}\right] &= -\frac{2}{C}\sum_{m=h}^{N-1,2} I_m = -\frac{4}{R_pC}\,V_-\sum_{m=n}^{N-1,2} m \\
&= -\frac{1}{R_pC}\,V_-\left[N^2 - [n-1]^2\right] \text{for odd } n \text{ with } 3 \le n \le N-1 \\
\frac{d}{dt}\left[V_N - V_{N-1}\right] &= 0
\end{aligned}
\tag{4.4}
$$

where the summation of odd integers is found in [8]. The second upper index in the summation indicates that m increments in steps of 2. Summing these derivatives we obtain the derivative of the Marx voltage (open circuit) as

$$
\begin{aligned}
\frac{d}{dt}V_N = \frac{d}{dt}V_{N-1} &= \left[\sum_{m=3}^{N-1,2}\frac{d}{dt}\left[V_m - V_{m-2}\right]\right] + \frac{d}{dt}V_1 \\
&= -\frac{1}{R_pC}\,V_-\left[\left[\sum_{m=3}^{N-1,2}\left[N^2 - [m-1]^2\right]\right] + \frac{N^2}{2}\right] \\
&= -\frac{1}{R_pC}\,V_-\left[\left[\frac{N}{2} - 1\right]N^2 + \frac{N^2}{2} - \sum_{m=1}^{N-1,2}[m-1]^2\right] \\
&= -\frac{1}{R_pC}\,V_-\left[\frac{N-1}{2}N^2 - \sum_{m=0}^{N-2,2} m^2\right] \\
&= -\frac{1}{R_pC}\,V_-\left[\frac{N-1}{2}N^2 - \sum_{m=0}^{\frac{N-2}{2}}[2m]^2\right] \\
&= -\frac{1}{R_pC}\,V_-\left[\frac{N-1}{2}N^2 - 4\frac{N-2}{12}\left[\frac{N-2}{2}+1\right]\left[2\frac{N-2}{2}+1\right]\right] \\
&= -\frac{1}{R_pC}\,V_-\left[\frac{N-1}{2}N^2 - \frac{1}{6}[N-1]N[N-2]\right] \\
&= -\frac{1}{R_pC}\,V_-[N-1]N\left[\frac{N}{2} - \frac{[N-2]}{6}\right]
\end{aligned}
$$

$$= -\frac{1}{R_p C} V_- \frac{1}{3}[N-1]N[N+1] \tag{4.5}$$

Normalizing this by V_0 we obtain

$$\frac{1}{V_0}\frac{dV_N}{dt} = -\frac{1}{R_p C}\frac{N}{3}[N-1][N+1] = -\frac{1}{R_p C}\frac{N}{3}\left[N^2-1\right] \tag{4.6}$$

This can be used to define a time constant t_p for the loading of the charging resistors as

$$\begin{aligned} t_p &= -\left[\frac{1}{V_0}\frac{dV_N}{dt}\right]^{-1} = \frac{3}{N\left[N^2-1\right]} R_p C \\ &= \frac{3}{\left[N^2-1\right]} R_p C_M \\ &\to \frac{3}{N} R_p C_M = \frac{3}{N^2} R_p C \text{ as } N \to \infty \end{aligned} \tag{4.7}$$

Constraining

$$t_p >> t_v \tag{4.8}$$

we have for our example

$$R_p = \frac{N^2}{3C} t_p >> \frac{N^2}{3C} t_v \simeq 3.3\ K\Omega \tag{4.9}$$

Considering the charging (4.2) gives for our example

$$t_{ch} \simeq 2.3\ R_P C \simeq 2.3\frac{N^2}{3} t_p >> 2.3\frac{N^2}{3} t_v \simeq 31\ \mu s \tag{4.10}$$

which is a modest improvement over (2.6).

The rightmost charging resistors need to withstand a megavolt (in our example) for about 100 ns, a significant stress.

5. Parallel Inductive Charging

One can, of course, consider parallel inductive loading where the resistances R_p are replaced by inductances L_p. In this case the capacitors are resonantly charged and reach their peak voltages $2\,V_{\pm}$ in one half cycle given by

$$t_{ch} = \pi\left[L_p C\right]^{\frac{1}{2}} \tag{5.1}$$

which we require to be large compared to t_v. This gives

$$L_p = \frac{t_{ch}^2}{\pi^2 C} >> \frac{t_v^2}{\pi^2 C} = 0.25\,\mu H \tag{5.2}$$

when erected the open-circuit voltage at the load is $2V_0$.

The analysis of the previous section can be modified for this case. Replace R_p by sL_p where $s = \Omega + j\omega$ is the Laplace-transform variable or complex frequency. In (4.3) we then have a leading term

$$I_n = \frac{2n}{L_p} V_- \, tu(t) \tag{5.2}$$

Inserting this in (4.4) and (4.5) we obtain

$$\frac{d}{dt} V_N = -\frac{1}{L_p C} V_- \frac{1}{3}[N-1]N[N+1]tu(t) \tag{5.3}$$

So it is the second time derivative that is significant and we have

$$\frac{1}{V_0}\frac{d^2 V_N}{dt^2} = -\frac{1}{L_p C}\frac{1}{3}[N-1][N+1] \tag{5.4}$$

Our loading then decreases the voltage proportional to time squared. We then define the time constant as

$$t_p \equiv \left[-\frac{1}{V_0}\frac{d^2V_N}{dt^2}\right]^{-1} = \left[\frac{3}{[N-1][N+1]}\right]^{\frac{1}{2}}\left[L_pC\right]^{\frac{1}{2}}$$
$$\rightarrow \frac{\sqrt{3}}{N}\left[L_pC\right]^{\frac{1}{2}} \text{ as } N \rightarrow \infty \tag{5.5}$$

Constraining

$$t_p >> t_v \tag{5.6}$$

we have for our example

$$L_p \simeq \frac{N^2}{3C}t_p^2 >> \frac{N^2}{3C}t_v^2 \simeq 0.33\,mH \tag{5.7}$$

This result replaces (5.2), being a more severe constraint. This implies a charging time

$$t_{ch} = \pi\left[L_pC\right]^{\frac{1}{2}} \simeq \frac{\pi N}{\sqrt{3}}t_p >> \frac{\pi N}{\sqrt{3}}t_v \simeq 3.6\,\mu s \tag{5.8}$$

This parallel inductive charging time can then be in the tens of μs regime, similar to the series-inductive-charging result in (3.3). As with series inductive charging this case can have resonances that may be troublesome.

6. Series Resistors and Inductors for Parallel Charging

Now let the parallel charging elements comprise the series combination or resistors and inductors as in Fig. 4.1. During the charging cycle the voltage on each capacitor is

$$\frac{\tilde{V}(s)}{V_{\pm}} = \frac{\frac{1}{sC}}{R_p + sL_p + \frac{1}{sC}} \frac{1}{s} = \left[1 + sR_pC + s^2 L_p C\right]^{-1} s^{-1}$$

$$\sim \; \equiv \; \text{Laplace-transform over time } t \tag{6.1}$$

$$s = \Omega + j\omega \; \equiv \; \text{Laplace-transform variable or complex frequency}$$

If $L_p = 0$ we have

$$\frac{\tilde{V}(s)}{V_{\pm}} = [1 + s\tau]^{-1} s^{-1}$$

$$\frac{V(t)}{V_{\pm}} = \left[1 - e^{-\frac{t}{\tau}}\right] u(t) \tag{6.2}$$

$$\tau \equiv R_p C$$

consistent with (4.1).

For the special case of critical damping we have

$$\tau = R_p C \equiv 2\left[L_p C\right]^{\frac{1}{2}} \tag{6.3}$$

giving a second order pole as [7]

$$\frac{\tilde{V}(s)}{V_{\pm}} = \left[1 + \frac{s\tau}{2}\right]^{-2} s^{-1}$$

$$\frac{V(t)}{V_{\pm}} = \left[1 - \left[1 + \frac{2t}{\tau}\right] e^{-\frac{2t}{t}}\right] u(t) \tag{6.4}$$

For comparison the two time domain waveforms in (6.2) and (6.4) are plotted in Fig. 6.1. As we can see the critically dumped waveform starts more slowly but crosses over the R_pC waveform at $t/\tau \simeq 1.25$ to give a similar charging time. In more detail we can see that the early-time behavior is better for the resistive/inductive case due to its initial quadratic behavior as in (5.4). This slows the initial charging to keep voltage off the Marx switches longer than the ramp behavior of the resistive case. The late-time behavior is also better for the resistive/inductive charging because, as we can see, the voltage more rapidly approaches the full-charge value. To give a few numbers, for $t/\tau = 2.5$ the resistive charging is 0.92 versus 0.96 for resistive/inductive charging, a change from 8% lack to 2% lack from final value. For $t/\tau = 3.3$ the resistive charging is 0.963 versus 0.99 for resistive/inductive charging, a change from about 4% lack to 1% lack from final value.

During the Marx erection, the current passing through R_p is initially limited by L_p which takes most of the voltage drop. If we use the results of Section 5 for determining the required inductance to make t_p large compared to t_{er} we have

$$t_p \simeq \frac{\sqrt{3}}{N}\left[L_pC\right]^{\frac{1}{2}} >> t_{\mathrm{v}} \tag{6.5}$$

giving for our example

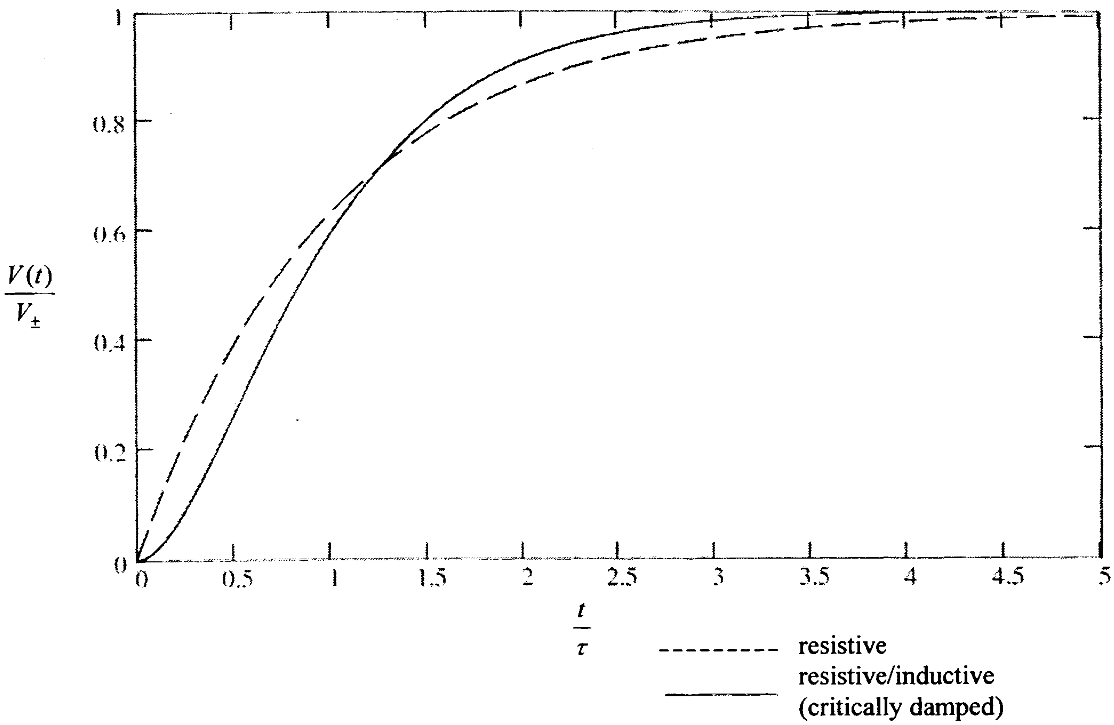
$$L_p \simeq \frac{N^2}{3C}t_p^2 >> \frac{N^2}{3C}t_{er}^2 \simeq 0.33mH \tag{6.6}$$

Then we have

$$\begin{aligned} \tau &= R_pC = 2\left[L_pC\right]^{\frac{1}{2}} \simeq \frac{2}{\sqrt{3}}Nt_p >> \frac{2}{\sqrt{3}}Nt_{\mathrm{v}} \simeq 2.3\,\mu s \\ R_p &= 2\left[\frac{L_p}{c}\right]^{\frac{1}{2}} \simeq \frac{2}{\sqrt{3}}\frac{N}{C}t_p >> \frac{2}{\sqrt{3}}\frac{N}{C}t_{\mathrm{v}} \simeq 0.575\,k\Omega \end{aligned} \tag{6.7}$$

This is a significant improvement over purely resistive parallel charging, allowing charging in tens of μs.

A significant advantage of the series R_pL_p is that during the Marx erection most of the voltage is across L_p instead of R_p, thereby protecting the resistor to some degree. By increasing L_p (and R_p proportionally) then t_{er} becomes a smaller portion of t_p and less voltage appears across R_p during this time. Another advantage of the inclusion of the inductors is that, at the beginning of the charging cycle, the current through each inductor is approximately zero (a ramp as in (5.2)). This can help by giving the Marx switches more time to recover).



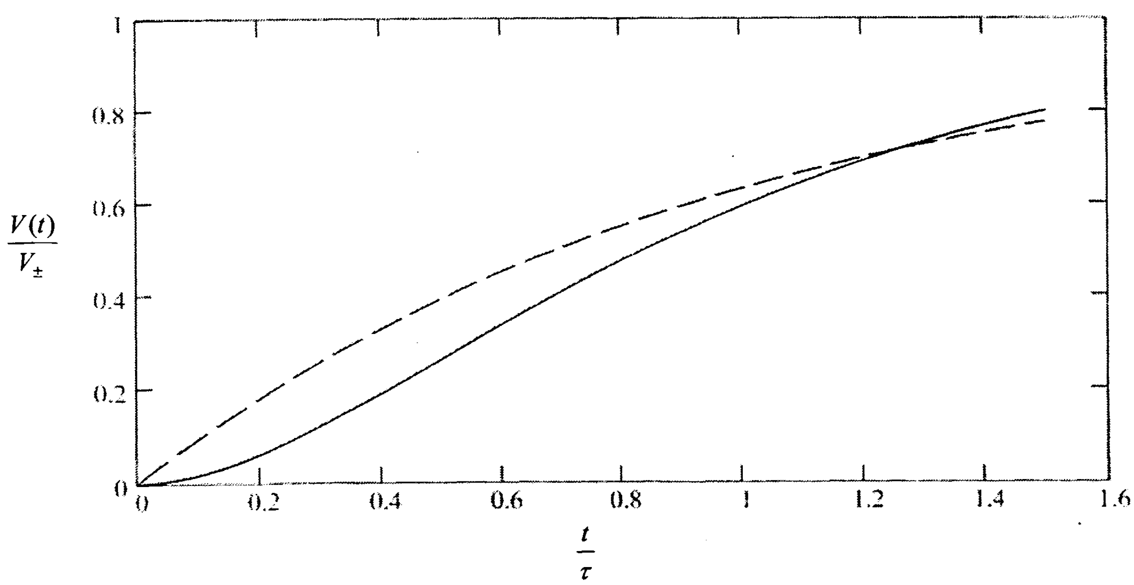


Fig. 6.1 Parallel Charging Waveforms

7. Concluding Remarks

Of the several techniques for Marx charging, inductive charging (series and parallel) is faster than resistive charging. It also has a voltage-doubling property. The parallel resistive charging is modestly faster than the series resistive charging. Parallel charging has the advantage that all the Marx capacitors are charged in approximately the same time. Parallel charging with series R_p, L_p is about as fast as inductive charging with the critical damping avoiding resonances. The inclusion of L_p in the parallel charging also has the advantage that after the Marx discharges the inductors limit the initial charging current, thereby giving more time for the Marx switches to recover. The inductors also protect the resistors by taking most of the voltage during the Marx high-voltage time. Not considered here is the use of combinations of resistors and inductors in the series charging-circuit topology. It can also be noted that various hybrids of series and parallel charging networks are also possible.

In this paper we have assumed a differential charging system. This is in contrast to the single-ended form sometimes used [5]. While the differential form has much to recommend it, there is a lack of symmetry in the last (rightmost) parallel charging and grounding elements (fig. 4.1). In order to maintain the same charging time for the last capacitor we can set

$$\begin{aligned} L_p &= L'_p + L'_g \\ R_p &= R'_p + R'_g \end{aligned} \tag{9.1}$$

where the prime denotes the modified values of these last elements. This increases the loading there, and to minimize this, consistent with (9.1) we can set

$$\begin{aligned} L'_p &= L'_p = \frac{L_p}{2} \\ R'_p &= R'_g = \frac{R_p}{2} \end{aligned} \tag{9.2}$$

The loading when the Marx is erected is about four times that of the other L_p, R_p elements. While this is at a position of near-maximum erected voltage, for large N this is a small correction. Furthermore, this loading occurs for a time less than t_V since it occurs after the last Marx switch is closed. An alternate approach which removes this exception is to select N odd.

The inclusion of inductors in the charging network has a potential problem in that the large magnetic fields produced by a coil can couple to other parts of the Marx including other coils. If desired, one can suppress this coupling by designing a coil which suppresses the external magnetic field while retaining a large internal magnetic field. See [1] for the general theory. A simpler bisolenoidal form which suppresses the magnetic-dipole term is discussed in [2]. In this latter case for each loop turn its magnetic-dipole moment is cancelled by another loop turn with opposite sense, but displaced as part of a second parallel solenoid so that the magnetic fluxes do not cancel.

As the foregoing calculations indicate, the charging time t_{ch} needs to be much greater than some multiple of the Marx high-voltage time t_V. This may be overly conservative in that the Marx loading during the high-voltage time does not begin (approximately) until the Marx switches leading up to the particular parallel (and ground) loading elements have all closed. So for many of the elements, especially the last (rightmost) few, the loading occurs for a time somewhat less than t_V. Because the voltage on these last elements is near the full Marx voltage here, this loading is the most significant here. So some average of effective value of t_V may be more useful in the loading formulae.

One can reduce t_{ch} and thereby increase the PRF by decreasing t_V, but this is another subject.

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