Chapter 28

Repetitive Solid-State Marx Adder Type Pulse Modulator

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A 10 MeV beam energy RF Linear Electron Accelerator is used for various industrial applications from food irradiation to medical waste sterilization. An Electron Gun on the front end is the source of the bunched electron beam of typically 40 keV energy. The repetitive Solid-State Marx Adder type Pulse Modulator is used as a high voltage pulsed power supply for the Electron Gun. It feeds the high voltage pulses of typical specifications 40 kV, 1 A, 10 μs and 250 Hz to E-Gun's cathode terminal w.r.t. a grounded anode which is also shorted with the body of accelerator. The 40 keV e-beam is then injected in the linear accelerator (LINAC) cavity resonating at 2856 MHz. Accelerator cavity consists of several cavity resonators, each operating in a TM_{010} mode. Electron bunches are further accelerated by the axial electric field, whose peak values are of the order of $\sim$15 MV/m. Radio Frequency power amplification device known as the "Klystron" is the power source which is used to provide RF power to the LINAC. RF power is fed to the LINAC cavity using RF Plumbline constructed from WR284 waveguide and its compatible parts. The RF Plumbline is pressurized with SF_6 gas to avoid arcing due to high electric fields or potential gradients formed. Accelerator's Electron Beam current is measured by a Fast Current Transformer (FCT) that is connected at the exit of LINAC cavity. A solenoid focusing magnet is used to minimize beam spread. Accelerator assembly is evacuated using Turbo-molecular pump and Sputter Ion Pumps that are connected to the beam line. EE-type core based Scan magnet is mounted on a scan chamber. A scan horn with a total angle of 600 is connected to the scan chamber. 'Ti' window is connected at the end of scan horn to separate Ultra High Vacuum (UHV) region (in which vacuum pressure is of the order of 10^{-8} mbar to 10^{-6} mbar) from the atmosphere. Accelerated electron beam scanning at 1.1 Hz over a length of 1 m comes out of the Titanium window and impinges on the batch of products being irradiated which is placed on a conveyer moving a defined speed (which is controllable). This helps in giving a uniform irradiation dose to the batch of products.

The schematic of a horizontal configuration of the complete system is shown in Fig. 28.1. The 10 MeV 5 kW system under development at EBC, Kharghar is a horizontal configuration system. Similar assembly can be designed in a vertical configuration in which E-Gun is at the top and scan horn at the bottom. The 10 MeV 3 kW RF LINAC facility at EBC, Kharghar, BARC is a vertical configuration system.

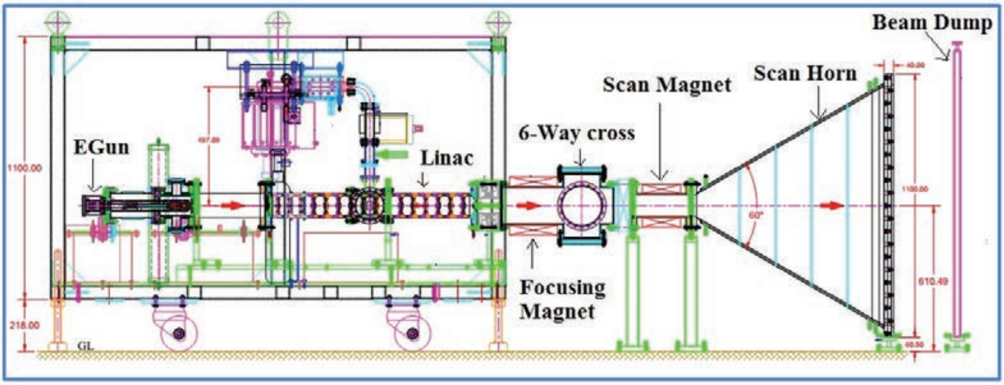

Figure 28.1: Schematic of a RF LINAC designed in a horizontal configuration.

28.1 Introduction to Pulse Modulators

Linear accelerator applications need identical repetitive pulses with almost square shape, having very fast rise and fall times. The flat top is also very critical. Generating pulses, which most closely approach the ideal pulse waveform, is therefore, a critical objective of pulsed, high power system design.

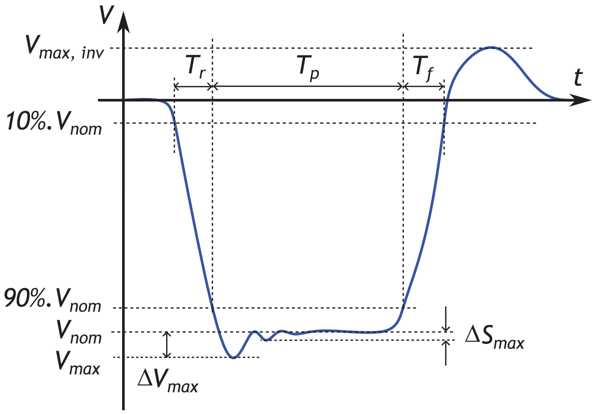

Figure 28.2: Pulse parameters defined.

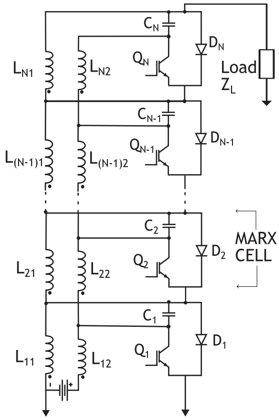

Figure 28.3: IGBT based Marx Adder.

Historically, vacuum switch tubes or thyratrons, individually or in combination with pulse forming networks (PFNs) [139] and pulse transformers, have been used for this purpose. In modern pulsed power systems, fast solid state switches, like MOSFETs and IGBTs, are used to generate short high power pulses. Since each device is limited in its power-handling capability, solid-state switches are connected in various topologies to obtain the required output pulsed power. The Transformer-less Marx Adder [143, 144] is one of the preferred pulse modulator topology.

28.1.1 A Repetitive Solid-State Marx Adder Type Pulse Modulator

In this section we will discuss the design & development of a Solid-State Marx Adder circuit in general. For illustration and better understanding, we will be discussing a real design, in context of a typical requirement of repetitive pulses of specifications viz. 40 kV (Pulse voltage, V_{nom}), 1 A (Pulse current, I_{nom}), 10 μs (Pulse width, T_p) and 250 Hz (Pulse repetition frequency, PRF). These are the specifications of pulses required for E-Gun of RF LINACs discussed in this chapter.

28.1.2 Circuit Topology & Operation

The N-Stage IGBT based Marx Adder circuit which forms a part of study, analysis and development is shown in Fig. 28.3. This topology can be studied by dividing the whole circuit into blocks; which is labelled as a MARX cell. A number of cells are stacked to obtain the desired output voltage at the load Z_L.

Each Marx cell has a capacitor (CN), an IGBT (QN) and a freewheeling diode (DN). In the 'Charging Period', the IGBTs are in the OFF state, the capacitors are charged from a relatively low DC voltage source (V) in parallel, through the chain of Common-Mode (CM) inductive isolators (L_{N1} –L_{N2}) or inductors. The common-mode chokes offer very low impedance during charging period as the charging current flowing in the two coils on the same core is differential in nature and assuming ideal case, it completely cancels the generated magnetic fields, resulting in no flux in the core or its vicinity. In a current limited DC power supply of voltage V, the current limit of charging current is set such that before the end of the charging period, the capacitors are able to attain the voltage equal to the DC source voltage V. At this point, the circuit is in a ready condition and can be pulsed anytime later. For generating the required HV pulse output across the load (Fig. 28.3) appropriate pulsed gate voltages are applied in synchronization to all the IGBTs to turn them ON. When all the IGBTs get fully turned ON, the circuit configuration changes in such a way that all the charged capacitors form a series connection across the load. This is referred to as 'Discharging Period or Pulse Duration'. Hence the desired HV output appears across the load for the duration of the pulse. During this discharging period, the CM inductors hold the voltages and do not allow significant currents to rise and flow through them and hence provide voltage isolation between the various Marx cells which are floating at different voltages and also with the ground referenced DC voltage source. Due to the mutual coupling between the two identical coils wound on the same core, one above the other and in the same direction, the net inductance as seen by the external circuit is twice of the self-inductance of the single coil wound on the same core. Hence we can design both the coils with half the number of turns that would have been needed if the coils were present alone or wound on separate cores. And after the pulsed gate voltages are removed, the circuit returns to its initial configuration in which capacitor bank's charge which had got depleted during discharging period or pulse duration, will get replenished from the DC voltage source.

To trigger the 'N' no. of IGBT semiconductor switches, which will all start floating at different voltages during the discharging period (or pulse duration); their Emitter terminals will attain voltages in steps of the DC source voltage V, ranging from 0 Volts upto −(N-1) V Volts, a galvanically isolated gate drive is needed. The value of voltage isolation needed between the driving side of IGBT gate drive and the IGBT Gate & Emitter terminals, depends upon the floating voltage attained by that particular Marx cell housing the IGBT to be driven. This requirement arises since during the discharging period, the capacitors in the Marx Adder are stacked in series and each Marx cell floats at a certain added voltage depending upon the no. of stages below it.

Besides, there is a need to give gate pulses to all the IGBTs in synchronization to get the full output voltage and the desired output pulse shape. To achieve this, from the galvanic isolation options viz. use of Optical fiber and Transformer isolation, we have used the transformer isolation method to magnetically couple the gate drive signals of 15V pulse voltage to the IGBT gate terminals w.r.t. their emitter terminals. A low-power transformer having a single primary and multiple secondaries is used to drive the IGBT Gate-Emitter terminals. The transformer has to be constructed such that there is atleast the required amount of isolation present between the primary side and each of the various secondaries which directly drive the IGBTs, depending upon the floating voltage generated. But we have constructed the transformer with equal isolation between primary and each of the secondaries, and value of isolation is more than the maximum isolation needed (keeping design margin) for the top most stage or the Marx cell floating at highest voltage i.e. '-(N-1)V' Volts.

The freewheeling diodes (D_1, D_2,...D_N) present in any Marx cell can bypasses a stage and with start to conduct if the IGBT in that cell fails to turn-on at all or is unsynchronised from the others and turns-on a little late than others. This simple action will avoids an over voltage across the slow IGBT that may be upto -(N-1)V Volts, if all others have turned ON and only one is remaining. The circuit without freewheeling diodes is just the 'Series-Switch topology'. That configuration is relatively more complex and has several disadvantages as compared to the Marx Adder topology.

In the present section, we discussed, in general, the repetitive Solid State Marx Adder modulator's topology using IGBT as the switching device and its various technical aspects. In the following section, we will be discussing a typical design which has an application in both RF Linear Electron Accelerator Systems in EBC, Kharghar and which were introduced in the starting of this document.

28.2 Design of a Solid-State Marx Adder - Pulse Output of 40 kV, 1 A, 10 μs, 250 Hz

The design & development of a 84-Stage Marx Adder was done to demonstrate the feasibility of multiple stage Marx Bank approach. The desired pulse ratings were 40 kV, 1 A, 10 μs pulse width with a repetition rate of 250 Hz. Allowed rise time was required to be lesser than 1 μs (since pulse width was 10 μs and we want to limit rise time within 10% of this value.) and % droop in the pulse flat top portion was to be lesser than 5% of the nominal pulse voltage Vnom. A 50 kΩ, 1 kW non-inductive resistor was the test load (Z_L) of the system. The switches, Q_1 to Q_N used in each of the 84 stages of this circuit were 1.2 kV IGBTs (Make: International Rectifier, Part No.: IRG4PH50UD).

28.2.1 Capacitor Selection

Choice of the rating of the capacitors, C_1 to C_N, was decided by the maximum permissible percentage droop $\Delta V/V_{nom} \times 100\%$ in the pulse voltage. This percentage droop was specified to be lesser than 5%. Thus, the minimum value of capacitance required can be calculated from the following equation:

$$\Delta V = \frac{1}{C}\int_0^{\tau} I dt \tag{28.1}$$

Substituting the values of $\tau = 10$ μs, I = 1 A and ΔV as 5% of peak operating voltage of IGBT as 470 V, we get

$$C = \frac{10\mu s \times 1A}{5\%\ of\ 470V} = 0.425\ \mu F$$

Each capacitor used here was an axial snubber capacitor (less stray inductance) which was rated 4.7 μF, 600 V (Make Alkon® Electronics). The capacitance rating of the capacitor is nearly 10 times of the minimum required value, but since there was no size or cost constraint, hence we had selected this, the more the better. The calculated droop which will result by using this was 0.448%.

Figure 28.4: 84-Stage Marx Adder circuit with 50 kΩ resistive load and 60 kV HV Probe.

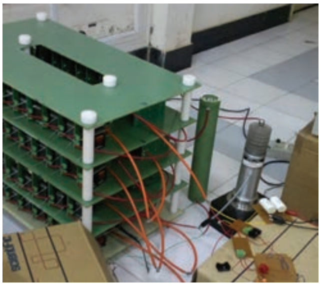

Figure 28.5: 84-Stage Marx Adder circuit from front showing 60 kV HV cable (orange colour).

28.2.2 Common Mode Inductor Design

Design of Common Mode Inductor is based on limiting the current rise in the inductor coils in the discharging period or pulse duration, during which the coupled inductors are in their blocking mode, to a certain percentage of the nominal pulse current I_{nom} of the Marx Adder. By circuit analysis it was found that, due to the effect of mutual coupling, each coil having an inductance value of L, offers an impedance corresponding to 2L in both coils, assuming ideal coupling coefficient k = 1 in the analysis. We wish to design that the maximum allowable current change or rise from t = 0 μs to t = 10 μs, is 10% of the full load current of 1 A. The minimum value of L can be calculated from the following equation,

$$\Delta I = \frac{1}{2L} \int_0^{\tau} V dt \tag{28.2}$$

Substituting the values of τ = 10 μs, ΔI and V = 470 V in Eq. (28.2), the value of L can be calculated as shown

$$L = \frac{10\mu s \times 470V}{10\%\ of\ 1A \times 2} = 235\ mH$$

Thus at least 23.5 mH inductance is required in each coil of CM choke. Using a pair of EE 6527 core made from CF 138 (Mn-Zn ferrite) material (Make: Cosmo Ferrites®), 40 mH CM chokes were made and used.

28.2.3 Design of HV Isolated Gate Drive

The gate drive uses magnetic isolation principle in the isolation transformer having single-turn primary and 84 secondaries. The number of turns required in each of the 84 secondary windings of the isolation transformer depends upon the core characteristics, the pulse duration τ and the voltage required in the secondary winding needed to drive the IGBT G-E terminals. The saturation flux density of the high permeability torroidal Metglas® core (made from 2714A alloy) which was used is Bsat = 0.57T (Make: MAGNAPERM® Part No.: MP2008P4AF). In the design, the maximum flux swing was limited to ΔB_{max} = 0.2 T. We know from Faraday's Law that

$$V = N\frac{\Delta B_{max} A_c}{\tau} \tag{28.3}$$

$$N = \frac{15V \times 10\mu s}{0.2T \times 0.248 \times 10^{-4} m^2} = 30.24$$

Using Eq. (28.3), N works out to be ∼31 for V = 15 V. The single turn primary, passing through the 84 toroidal cores, is a High voltage cable (Make: Zeonics®) having an insulation breakdown strength of 60 kV(rated). Each torroidal core has a secondary winding having 31 turns wound on it. The secondary winding terminals are connected to IGBT G-E terminals.

28.2.4 Test Set-Up & Results

Figs. 28.4 and 28.5 below, show the 84-stage Marx Adder circuit in side view and front view respectively. The 84 stages are organized in 4 layers, each comprising of 21 Marx stages. The single turn primary of the gate drive isolation transformer is the 60 kV HV Cable (Orange colored) which is passing through the 84 torroidal cores which are mounted on the PCBs.
The output pulse voltage waveform across the 50 kΩ/ 1 kW non-inductive resistive load, measured with the help of a 60 kV 2000X High Voltage probe (Make: Iwatsu®) is shown in Fig. 28.6. With scaling factor set to 1000:1 on the oscilloscope, peak voltage of 20 kV indicated in the waveform corresponds to a value of 2 × 20 kV = 40 kV. The recorded pulse

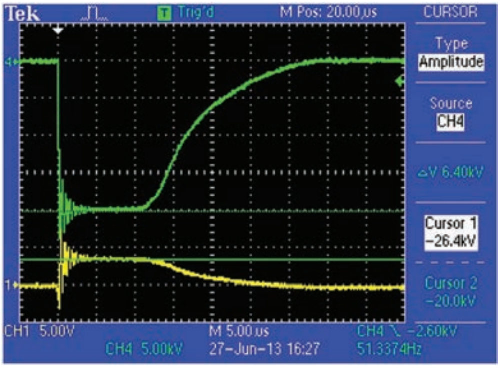

Figure 28.6: Output voltage pulse of 40 kV (pk) on CH4 and current pulse of 0.8A (pk) on CH1 from 84-Stage Marx Adder.

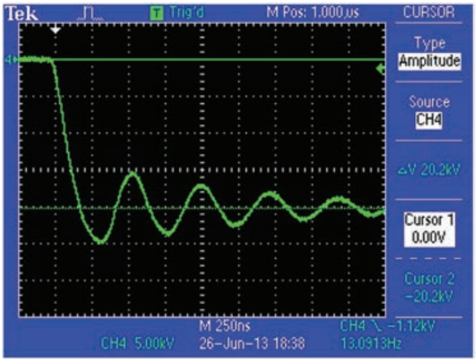

Figure 28.7: Output voltage pulse of 40 kV expanded in time showing 0-100% rise in 150 ns.

flat top is approx. 12 μs at PRF of 50 Hz. At a pulse voltage output of 40 kV, the 0% to 100% rise time was measured to be nearly 150 ns as shown in the voltage pulse waveform of Fig. 28.7 in which rising edge was expanded in time.

28.3 Summary

The chapter has started with an introduction to industrial RF linear electron accelerator and its various sub-systems. Then a brief introduction to pulse modulators was discussed, which was followed by an introduction to repetitive solid-state marx adder type pulse modulator, explaining its circuit topology & operation in details. Then the design of a solid-state marx adder for a pulse output of 40 kV, 1 A, 10 μs, 250 Hz was explained, in which capacitor selection, common mode inductor design and design of HV isolated gate drive, its test setup and results are discussed.