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A 100 kV, 20 A, 1 ms long pulse solid-state Marx modulator for klystron

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ABSTRACT

Due to difficulties associated with the conventional gas tube based modulators, solid-state switch based klystron modulators are gaining popularity in the scientific community. Research, design, and development of high voltage solid-state modulators for electron and proton accelerators are in progress at Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. A prototype of 100 kV, 20 A, 1 ms pulse duration Marx modulator has been designed and developed. The modulator has been constructed using 34 numbers of Insulated Gate Bipolar Transistors (IGBT), based 3 kV main modules for generation of a 100 kV base pulse. A droop correction scheme, consisting of 24 numbers of 1 kV corrector modules, has been adopted to compensate the droop in the output pulse. Before incorporating the droop compensation technique, the modulator had droop of 16% in the output voltage pulse. A microcontroller based control unit is used for the programmed staggered triggering of all the main modules and corrector modules. Fiber optic based control signal transmission was done to realize electrical isolation between high voltage circuits and control circuits. The modulator has been tested for 100 kV, 20 A, 1 ms pulse duration at 1 Hz, initially without droop compensation and later with the activation of the correction scheme for droop compensation. With the droop compensation scheme, less than 1% droop could be achieved in the output voltage pulse. Output voltage pulses of 1 ms pulse width, 1.4 μs rise time and 9.7 μs fall time at 100 kV have been achieved successfully. The present effort forms a strong basis for further development of this technology for higher average power as well as for replacing the earlier thyratron based modulators.

1. Introduction

Low, medium, and higher energy charged particle accelerators are becoming very important for various scientific, societal, industrial, and medical applications. Raja Ramanna Centre for Advanced Technology (RRCAT) is a national laboratory of India, engaged in development of various types of electron and proton accelerators. Electron accelerators for applications as Synchrotron Radiation Source, Infra-Red Free Electron Laser, and Industrial Irradiation Processing Facility have been developed. RF and microwave systems are considered as the most important part of the RF based accelerators. The RF and microwave system delivers the high RF power of required specifications to the accelerator for desired performance and characteristics of the accelerator beam. Klystrons are customarily used as source of the RF and microwave power and it requires high voltage pulsed power supply for the amplification of low power RF to high power [1]. This high voltage pulsed power supply is called pulse modulator. Different techniques are available for the HV pulse generation depends upon the required parameters of output pulse, cost, size, reliability, maintenance, and complexity. In most of the modulators, a major part of the cost and size are the storage capacitors. The ratio of the total stored energy of all storage capacitors ($\frac{1}{2}nCV^2$) of the modulator to the output pulse energy ($V_0 I_0 t_p$) is an important factor that determines the oversize of the storage capacitors. Where, n is the number of capacitors, C is the value of capacitance, V is the charging voltage of capacitors, V_0 is the output voltage, I_0 is the output current and t_p is the pulse duration of the modulator. This ratio is called oversizing factor. Ideally, the oversizing factor should be one so that all the stored energy should be used in the form of pulse energy and capacitance value of the storage capacitor can be kept as minimum as possible. This reduces the overall size and cost of the modulator. Other important parameter for modulator selection are pulse duration, flat top, ripple, rise and fall times of the output high voltage pulse. A pulse is generally defined rectangular if the rise and fall times of the pulse are less than 10% of the pulse duration [2]. The rise and fall times are usually not specified by the klystron manufacturers. However, they should be kept as minimum as possible to reduce the losses. The power output during rise and fall times of the pulse does not contribute for the generation of high power RF from klystron. Therefore, rise and fall times affect the overall efficiency of the microwave system. The parameters of output pulse of modulator should be well defined for selection of topology for high voltage pulse generation. There are several methods for generation of high voltage pulse for klystron [2]. One of the methods is to charge a transmission line and discharge it into the load by a series switch. It generates a square pulse provided that the switch has fast rise and fall times. However, this technique is suitable for short pulse

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durations in the range of nanoseconds. An extension of this is the pulse forming network (PFN) type modulator that uses an LC (Inductance and capacitance) network, resembling a lumped transmission line, which is able to overcome this limitation with the sacrifice of the flat top of the pulse and accepting some ripple. The flat top of the pulse depends on the number of LC sections used in pulse forming network. Higher numbers of sections produce better flat top characteristics with increased cost and complexity [3,4]. The modulator delivers nearly full stored energy of the PFN capacitors to the klystron load, therefore oversizing factor of the PFN type modulator is almost one. The PFN modulator technology is well proven and well established for generation of high voltage pulses [5,6]. However, it is practicable up to few tens of microseconds pulse duration, above which they become very bulky and practically unviable because of large inductor and capacitor requirements [7]. The modulator also employs a pulse transformer for high voltage generation, which increases rise and fall times and introduces droop and overshoot in the pulse [2]. The pulsed output voltage is required to be constant during the pulse. Any droop in the output voltage pulse causes phase and amplitude variations in the RF output of the klystron [8]. The PFN based modulators also have fixed pulse width output for a particular design. The second basic topology to generate high voltage pulses is to charge a capacitor and discharge it by a series switch into the load for a defined duration. This method overcomes the limitation of fixed pulse width, which can be modified by the trigger pulse of the series switch. This topology is the basis of hard tube modulators, which were used earlier for high voltage pulse generation [9]. A vacuum tube was used as a switch for discharge of a capacitor into the load. The advantages of hard tube modulators are short rise and fall times. The use of this topology was limited due to low life and higher operating cost [10]. However, after the advent of solid-state technology and the innovation of novel high power solid-state switches, new solid-state technologies based on the above topology are being designed and developed. These solid-state modulators require minimal maintenance and sustain long lifespan as compared with the tube based modulator technology [11]. In solid-state hard switched modulator, a high voltage power supply is switched on for a defined pulse duration into the klystron load through a high voltage solid state switch. The rating of both the high voltage switch and the power supply is required to be equal to the rating of klystron voltage. Presently the maximum rating of available IGBT switch is 6.5 kV [12]. For high voltage operation, several switches need to be connected in series. Based on this technique, modulators up to voltage levels of 135 kV have been realized, but the technology is intricate [13]. This high voltage switch can be avoided using a pulse transformer with a sacrifice of fast rise and fall times [14]. Moreover, the technology of the pulse transformer for long pulses in the range of milliseconds is complex. For the long pulse duration, the pulse transformer should have high volt-second product and a reset winding is also required for complete utilization of core [15]. As an alternative approach, resonant converter type modulator is used. It utilizes dc–dc converter along with high frequency transformer for generation of high voltage pulses. The width of the output pulse is controlled by modulating gate drive of the dc–dc converter module by a pulse of desired width [16]. The transformer development of the modulator is very complex for high frequency, high power applications. Moreover, losses in the transformer increases with increase in switching frequency and heat removal from cores will be difficult in practical cases. Therefore, switching frequency up to 25 kHz is used in high power modulator of the range of few megawatts peak power [17–19]. However, for low power application high switching frequency can be used. The limitation in switching frequency for high peak power application demands larger filter components in order to filter out the ripple. This causes slow rise and fall times of the order of few tens of microseconds [18,19].

Marx generator based topology has been designed for generation of high voltage pulses to resolve the shortcomings of conventional hard switched and converter based modulators [20,21]. This technology is based on Marx generator, in which bunch of capacitors are charged in parallel by RC charging and generate high voltage in series connection by means of spark gaps. However, inability to turn off spark gap switch restricts the generation of pulses for a defined duration. In a Marx modulator, resistors are replaced by common mode chokes for lossless capacitor charging and isolation during high voltage pulse, while solid-state switches replace the spark gaps for the generation of controllable pulse. This technique is suitable for short pulses up to few microseconds range, beyond which common mode chokes become bulky for isolation of millisecond pulses. Thus, for long duration, solid-state switches are used for parallel charging as well as for series discharging of the capacitors [22]. A well-defined number of storage capacitors are charged in parallel by means of solid-state switches in the charging path. These capacitors are connected in series for high voltage pulse generation for a definite duration by means of solid-state switches in the discharge path. The rise and fall times of the pulses are dependent on the turn on and turn off time of the switches while the droop depends on the value of the capacitance. However, unlike PFN modulators, large oversize factor of the capacitors is required to maintain the droop within a specified limit in the output pulse of the modulator. This increases the overall size, cost, and stored energy of the modulator. Keeping in view of these technical requirements and difficulties, droop compensation becomes necessary to reduce the over sizing factor and for better utilization of stored energy of capacitors. In the present paper, design, development, tests and results of 100 kV, 20 A, 1 ms Marx modulator with droop compensation scheme has been presented. The important parameters of the Marx modulator are summarized in Table 1.

Table 1
Important specifications of pulse modulator.

Parameter	Value
Maximum output Voltage	−100 kV
Maximum output current	20 A
Pulse width	1 ms
Rise Time	1.4 μs
Fall time	9.7 μs
Droop without correction	16%
Droop with correction	< 1%
Peak to peak Ripple in output voltage	1%

2. Component selection, construction and working

The Marx modulator consists of two units, namely, the main Marx unit and the corrector Marx unit. The main Marx unit generates the 100 kV base pulse, while corrector Marx unit compensates the droop of the base pulse by staggered triggering of its modules. The main Marx unit is composed of 34 main modules while corrector Marx unit consists of 24 corrector modules.

Each main module has been developed using solid-state IGBT switches. 4.5 kV, 60 A QIS4506001 IGBTs made by POWEREX have been selected for the charging and discharging of the capacitors. Main module voltage was chosen as 3 kV by considering sufficient safety margin of switch voltage capability. For development of 100 kV voltage pulse, 34 main modules are required in the main Marx unit. Each main module comprises an energy storage capacitor (MC1), a charging IGBT (SW1), and a discharging IGBT (SW2). Fig. 1 shows the schematic of the 100 kV Marx modulator. Without droop compensation, the required value of capacitor in each module for the percentage of droop 'd' in output voltage pulse is $\frac{Nt}{R*ln(1/(1-d))}$, Where N, R, and t are number of main Marx modules, value of load resistance (5 kΩ) and duration of output pulse, respectively. For 1% droop (d = 0.01) in the 100 kV, 20 A, 1 ms output pulse, the value of required main capacitor is 676 μF without any droop compensation. In this case, 34 main capacitors are charged to 3 kV by a capacitor charging power supply for developing 100 kV output voltage. The total stored energy in the capacitors is 103.4 kJ and the output pulse energy of the 100 kV, 20 A, 1 ms pulse is 2 kJ. Therefore, the over sizing factor is ~51. The over sizing factor of modulator can be brought down