Development of a High Voltage, High PRF PFN Marx Generator

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ABSTRACT

A PFN Marx generator which has been designed for repetitive operation is described. The device is nominally capable of generating an output voltage of 1MV into a matched load at a pulse repetition frequency (PRF) of several hundred Hz. The output voltage pulse is rectangular in profile with a duration of 450ns and a risetime of 40ns. There are twenty stages in the generator, with each stage comprising 50m of HVDC 50Ω co-axial transmission line. This results in an overall output impedance of 1kΩ and a stored energy of 500J at a charging voltage of 100kV. The generator is operated in repetitive mode using a resonant charging inductor/diode, an in-line triggered charge transfer switch and an intermediate capacitor store.

INTRODUCTION

Conventional Marx generators have significant disadvantages when they are used to drive some types of load. Firstly, they generate a double exponential voltage profile. For loads which require a flat top voltage pulse during their operation, it is necessary to increase the duration of the tail of the double exponential such that the pulse droop is acceptable during load operation. This long wavetail can affect the insulation integrity of the generator as well as that of the load. In some circumstances, it becomes necessary to employ a high energy crowbar circuit in order to reduce voltage stress after the load operation. Secondly, a long wavetail can mean that there is a significant amount of energy stored in the Marx generator prior to operation and this may limit the maximum pulse repetition frequency (PRF) of the system. Thirdly, the overall electrical efficiency of the system is poor, as much of the Marx energy, which is stored in order to produce the wavetail, is not used to drive the load. Finally, the output impedance of the conventional Marx generator is capacitive and this makes matching to a specific load difficult to achieve resulting in poor energy transfer efficiency from the pulser to the load.

In order to alleviate some of the above problems, researchers have used PFN (pulse forming network) Marx generators to drive particular loads [1]. These devices combine the voltage adding of the Marx generator and the pulse shaping properties of lumped LC lines. The advantages of this type of generator are that the voltage pulse profile is rectangular with a flat top duration which is dependent upon the number of stages and the values of L and C in the lumped line, and that the output impedance is well defined. This means the generator can be well matched to a specific load ensuring a high degree of energy transfer to the load during the pulse. Also, there is no significant energy wasted in a long pulse wavetail.

Lumped line PFN Marx generators have three disadvantages. Firstly, they can contain a large number of components which can lead to problems of reliability and maintenance. Secondly, the large component count can increase the cost of the generator. Thirdly, operation at high voltage normally requires the generator to be oil insulated.

An alternative type of PFN Marx generator design is based on distributed transmission lines, and in particular high voltage co-axial transmission lines [2, 3]. This approach can be advantageous in several ways. Firstly, as co-axial transmission line is used, the generator can be air insulated. Secondly, co-axial transmission line is a well established high voltage technology and is known to be reliable. Thirdly, it possesses excellent frequency response characteristics enabling relatively high speed pulse generator systems to be constructed. The generator described here is constructed from 100kVdc co-axial transmission line which is used for each PFN section.

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THE PFN MARX GENERATOR DESIGN

The electrical specifications of the generator were determined by the value of the load it was designed to drive. The load itself represents an open circuit for the initial phase of its operation (several ns) and after turn on it represents an impedance of 1kΩ. The driving potential across the 1kΩ load was required to be 1MV and therefore the generator had to be capable of producing an output voltage of 2MV into an open circuit. This would result in 1MV across the load after it had turned on, provided that the output impedance of the generator was 1kΩ. Using 100kVdc co-axial transmission line required that the generator be comprised of twenty stages, with each stage charged to 100kV. With each stage contributing an equal amount to the output impedance, which was required to be 1kΩ, the stage impedance was 50Ω. Therefore, the co-axial transmission line which possesses a characteristic impedance of 50Ω, was configured as a single pulse forming line in each stage and not in any series or parallel stacked configuration. The pulse length required for this particular load was 500ns which resulted in each stage having a 50m length of transmission line (two way transit time at 5ns/m). The total length of transmission line in the generator is 1000m, and the total capacitance is 100nF (100pF/m). At a charging voltage of 100kV, the energy stored in the generator is 500J, and a peak power of 1GW is generated in the pulse.

The resonant circuit shown in Fig 1 is used to charge the stages of the PFN Marx generator to 100kV. The circuit consists of a high voltage power supply and its associated protection circuitry, an intermediate capacitor C_2, a triggered corona stabilised (TCS) transfer switch (S), an air cored charging inductor (L) and a blocking diode stack (D_b). The PFN Marx generator is represented by C_{PFN} for the charging cycle. The transfer switch is used to control the PRF at which the PFN Marx generator is operated. At present the maximum continuous PRF is limited by the primary power supply to ~70Hz, and higher PRFs are only achievable in a burst mode during which C_2 acts as a reservoir. For higher continuous PRFs, an upgrading of the power supply would be necessary.

Preliminary testing of this device involved firing four assembled stages using a conventional array of spark gaps in a column. The output voltage pulse generated by the four stages is shown in Fig 2. The voltage pulse is rectangular in profile with a flat top duration of 450ns and a risetime of 45ns (10%-90%). The charging voltage was 30kV and the load impedance was 2kΩ which gave rise to the reflections observed after the main pulse.

THE CHARGE TRANSFER SWITCH DESIGN

The charge transfer switch [4] is a crucial component in the system as it is used to determine the PRF at which the system is operating. This means that the resonant inductor can be of a fixed value and, more importantly, the stage switches in the PFN Marx generator can be given a period in which to recover their hold-off voltage. In this case, the transfer switch is a triggered corona stabilised (TCS) switch [5, 6]. The process of corona stabilisation which occurs in the switch during operation enables the switch to function at high PRFs compared to conventional spark gap switches. High PRF capability is essential in this application to ensure consistent opening of the switch at the end of a charging cycle to isolate the PFN Marx generator from the power supply and capacitor C_2.

The switch is an in-line device which means that it has to be capable of operating satisfactorily whilst at a potential of 50kV on the low voltage side of the inductor before charging and with a voltage difference of 50kV across it at the end of the charging cycle. Therefore the triggering circuitry must be isolated and activated via a fibre-optic link. The trigger circuit is shown schematically in Fig 3. In order to ensure that closure of the transfer switch is achieved every time, a fast rising trigger pulse is used. This trigger pulse is generated using a stacked Blumlein cable generator [7] which is charged to a voltage 20kV. The output pulse from the Blumlein is rectangular in profile, rising in 10ns, with a duration of 60ns and peak voltage of 70kV. The Blumlein generator is itself fired on command using a secondary TCS switch which is a smaller version of the main charge transfer switch and is also capable of high PRF operation. The trigger pulses for the secondary TCS switch are generated by an autotransformer which is capable of generating impulses of >10kV with risetimes of ~25μs up to a PRF of 3kHz. Above this PRF the output voltage decreases up to an upper limit of 10kHz. The autotransformer is fired on the primary side using a power MOSFET. The energy source for the autotransformer is a 12V battery. The power MOSFET is controlled optically which therefore means the overall trigger circuit can be electrically isolated from ground.

Performance tests of the transfer switch trigger circuit have indicated that PRFs of several kHz are readily achievable. In fact, the maximum PRF achieved to date is 10kHz. This is for an output trigger pulse of 52kV into an open circuit. Obviously, the transfer switch will not be required to operate at this level of PRF, but this performance clearly indicates the potential of the corona stabilisation method for high PRF switching. An example of this high PRF capability is shown in Fig 4. The lower trace on the oscillogram is the charging voltage waveform of the Blumlein generator and the upper trace is the trigger voltage waveform. The time interval between successive discharges of the Blumlein generator is 100μs which is representative of a PRF of 10kHz.

The main TCS switch will be required to transfer a charge of 10mC per shot, compared to 0.06mC transferred by the secondary TCS switch. This will obviously affect the PRF capability of the main switch, and the target has been set to 1kHz maximum. This represents a charge transfer rate of 10C/s. Design and construction of the transfer switch are ongoing and trials in a test circuit are under way.

DISCUSSION

A 1MV high PRF PFN Marx generator system has been designed which will be capable of sustained PRFs of ~70Hz and burst mode operation up to several hundred Hz, the upper limit being determined by the charge transfer switch and the stage switches in the Marx generator.

Although, this PFN Marx generator was designed for a particular load, it is clear that this type of Marx circuit can be used to drive a number of different loads. The electrical parameters of the generator, such as the output impedance, the pulse duration, the energy per pulse and the output voltage, can be readily altered by changing the configuration of the transmission lines. For example, the output impedance of the device can be changed by using a number of PFNs in parallel for each stage, and the pulse length can be altered by altering the length of transmission line which comprises each stage.

The use of TCS switches for the charge transfer switch and the trigger generator switch have meant that when complete, the system will be capable of operating at high PRFs. Also, if TCS switches are used in the PFN Marx switching arrangement, further improvements in the reliability of the system would be gained. In this regard, the development of the TCS switches has been the crucial element in the generator design and has enabled a realistic target PRF of up to 1kHz to be set.

ACKNOWLEDGMENTS

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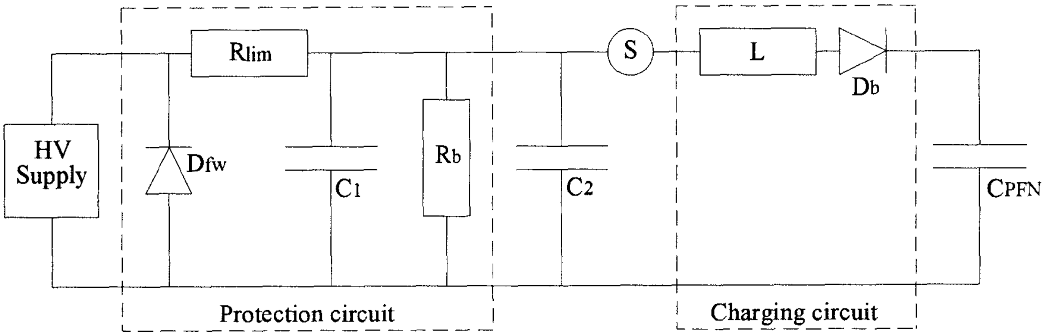

Figure 1 A schematic diagram of the resonant charging circuit.

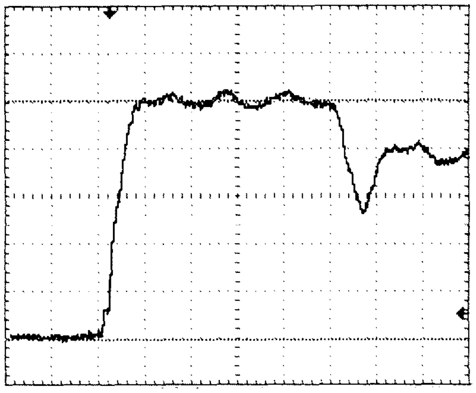

Figure 2 Output voltage pulse from four stacked stages [3]. (1V/div, 250ns/div)

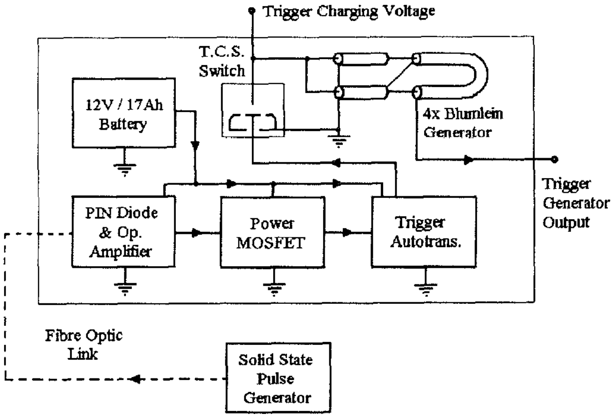

Figure 3 A schematic diagram of the trigger generator circuit [4].

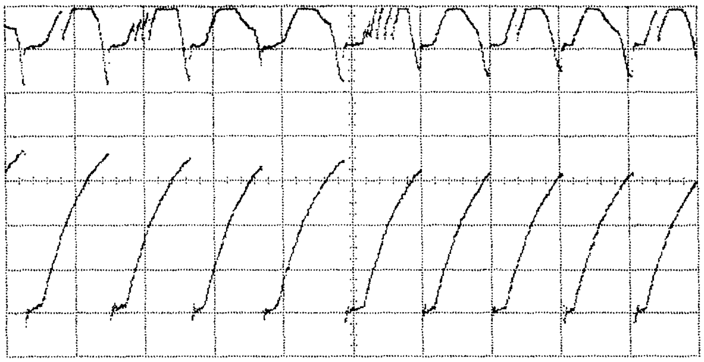

Figure 4 Repetitive operation of the trigger generator. The lower trace is the charging voltage of the Blumlein generator, and the upper trace is the output voltage of the autotransformer. (5V/div, 100μs/div)