Transformer-less Pulse Power Supply: A Prototype Development

S K Rai [1] P Tandon [2] S Jangid [3] Rahul Varma [4]

Abstract– High voltage pulse generators find extensive use in characterization and testing of high power microwave tubes and plasma devices along with many others industrial applications. The solid-state devices based method is now more popular than the pulse-forming network (PFN) based design, which is an old technique. However, both the methods entail the design of pulse transformer, which involves very critical design issues. This paper describes the prototype design and development of transformer-less pulse power supply, which is based on popular topology "Marx Generator".

Keywords– Marx Generator, pulsar, droop, isolation, PRF

I. Introduction

Today, rectangular electrical pulses of high-voltage and high-frequency have many industrial applications. Some typical applications evolve in surface treatment techniques, food sterilization, waste treatment, characterization of microwave and plasma devices etc [1-3].

Several kinds of models have been widely used for the pulse power supply such as Marx generator, hard-tube type pulse generator, Thyratron type pulse power generator with pulse forming network (PFN) etc [4-6]. The pulse width and shape of these kinds of pulse power supply are load dependent. These generators are usually designed for fixed pulse width and load.

Now days, solid-state devices based pulse generators are more popular. However, the maximum pulse width, overshoot, pulse droop and pulse shape are limited by pulse transformer design, which involves very critical design issues. The Marx Generator topology based transformer-less pulse power supply is new advancement in this. It is completely based on solid-state devices and capacitors charging and discharging [5-12].

In the past, Marx Generators were usually implemented using spark gap technology and had low pulse repetition rates [13]. In recent years, Marx generators based on semiconductor switches are proposed for high pulse repetition rates [14-15].

This paper describes the simple design and prototype development of transformer-less pulse power supply based on "Marks Generator" topology.

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The design calculation is done for Input Voltage = 800V, Output voltage up to 15kV, f_s = up to10kHz, Pulse Width up to 5µs, Droop = 10% and Maximum Pulse Current = 1A.

A combination of 20 modules with suitable gate drivers is used in this application.

II. System Description and Design

The schematic diagram of proposed pulsar is shown in Fig. 1. Incoming single-phase ac supply is rectified and filtered after step-up using transformer and the output dc is controlled by using a variac. The available output dc voltage charges the capacitors (C_1 to C_{20}) using IGBTs (Q_1 to Q_{20}) for specified time and after some delay IGBTs (Q_{21} to Q_{40}) connects all the capacitors in series and so produces the required high pulse to the connected load. Diodes (D_1 to D_{40}) are used to provide unidirectional current flow in both charging and discharging of capacitors.

This system has twenty sub-modules as per design. A single sub-module is shown with the dotted rectangular box (Fig. 1).

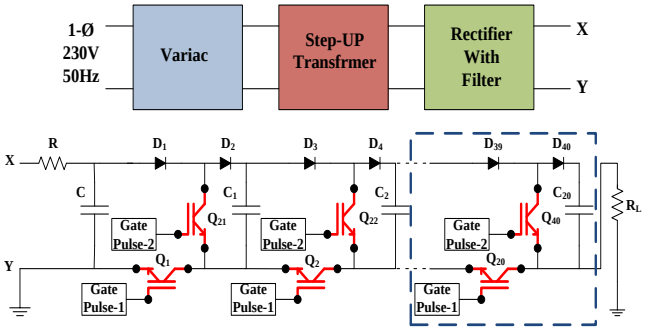

Fig. 1: Schematic diagram of proposed pulsar

The schematic diagram of developed prototype is shown in Fig. 2. Only three sub-modules are tested and an isolation transformer is used for isolation purpose at input side.

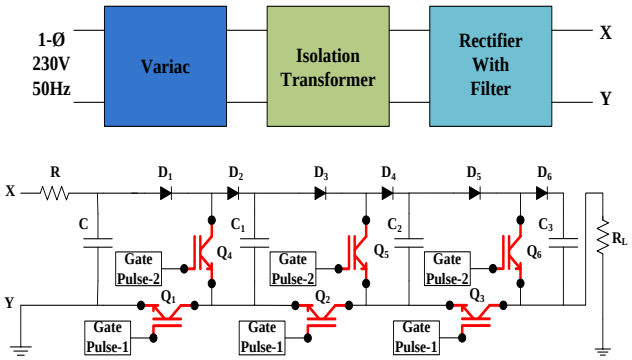

Fig. 2: Schematic diagram of developed prototype

The working of the prototype can be understood by capacitors charging schematic diagram (Fig. 3) and discharging schematic diagram (Fig. 4). Initially, when gate pulse-1 is applied to IGBTs (Q_1 to Q_3), all the capacitors (C_1 to C_3) are connected in parallel fashion to the DC voltage source and charged fully (Fig. 3). During this period load is connected to ground via IGBTs and so the output voltage is about zero. After charging, gate pulse-2 is applied with some delay to the IGBTs (Q_4-Q_5), all the capacitors are connected in series and the voltage (V_c+V_{c1}+V_{c2}) is appeared across the connected load (Fig. 4). During series connection, capacitors discharge and in the next cycle again these are charged fully and so on. All the diodes are forward biased during charging time but during discharging only odd numbered diodes (D_1, D_3 & D_5) work, rest of the diodes (Even numbered: D_2, D_4 & D_6) are in reverse biased mode and prevent capacitor discharge by short circuit.

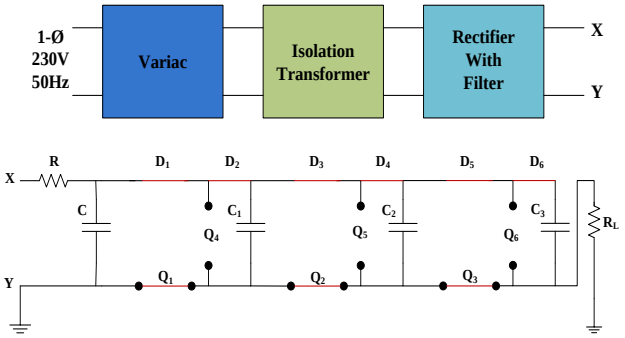

Fig. 3: Schematic diagram of capacitors charging

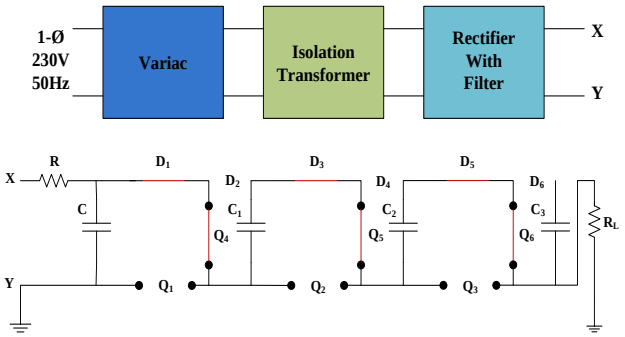

Fig. 4: Schematic diagram of capacitors discharging

Each IGBT has its own isolated gate pulse and gate drive supply. The gate pulses are applied using fiber optic. The gate pulse width of charging IGBTs is fixed but for series connecting IGBTs, it is variable and so the output pulse varies accordingly. The prototype is tested with resistive load. Moreover, no pulse transformer is required in this approach. Details of design calculation and construction of sub-systems are discussed in the following sub sections.

A. Design Calculations

Design Specifications:

Input Voltage: up to $800V$
Output Voltage: up to $15kV$
Pulse width: up to $5\mu s$
Pulse Frequency: up to $10kHz$
Droop: 10%
Maximum pulse current: $1A$

$$No.of\ Modules = \frac{MaxoutputVoltage}{MaxInputVoltage} = \frac{15kV}{800V} = 18.75$$

$$C_{equ.} = \frac{MaxPulseCurrent \times MaxPulseWidth}{Droop} = \frac{1A \times 5\mu s}{10\%of\,15kV} = 3.3nF$$

$$SingleCapacitorValue = C_{equ.} \times (No.ofModules + 1)$$
$$= 3.3nF \times 21 = 69.3nF$$

$$CapacitorVoltageRating \succ MaxInputDCvoltage(800V)$$

$$PeakDiodeCurrent \succ \frac{MaxInputDCvoltage}{R = 50\Omega} = \frac{800V}{50\Omega} = 16A$$

$$AverageDiodeCurrent \succ$$
$$PeakDiodeCurrent \times MaxPulsewidth \times MaxFrequency$$
$$= 16A \times 5\mu s \times 10kHz = 0.8A$$

$$PeakInverseVoltageof\ Diode \succ MaxInputDCvoltage = 800V$$

$$Max(V_{CE})of\ IGBT \succ MaxCapacitorvoltage = 800V$$

So twenty modules are decided as per above calculation with resistance R=50Ω, which is decided as per the required charging time of the capacitor. All the capacitors (C & C_1 to C_{20}), all diodes and all IGBTs are selected 1 µF/2kV, 6FMLR120 (6A/1200V) and IXGH15N120CD1 (30A/1200V) respectively with the reference of above calculations. The fixed gate pulse width of 80 µs is decided for charging IGBTs.

B. Gate Pulse Generator

The optical coupling based open loop gate pulse generator has been designed to trigger the IGBTs [16].

Gate Pulse Generator Specifications:

Pulse Frequency: up to 10kHz
Pulse-1 (for charging IGBTs): 80 µs (Fixed)
Pulse-2 (for series Connecting IGBTs): up to 5 µs
Delay (Pulse-1 to Pulse-2): 10 µs (Fixed)

The above specified gate pulses details are generated using the concept as shown in Fig. 5 and realized by using NE555 and 4047BP as shown in Fig. 6, which has both pulse width and frequency control facilities. The generated gate pulses are transmitted optically by using transmitter HFBR1521. Since, same pulse is required by several IGBTs, so ULN2003 (Seven Darlington Array) is used with transmitters. The pulse generator system is shown in Fig. 7.

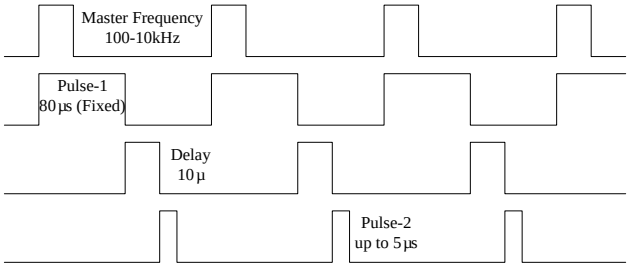

Fig. 5: Followed concept to generate of gate pulses

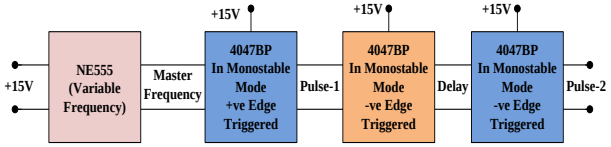

Fig. 6: Block diagram of pulse generator

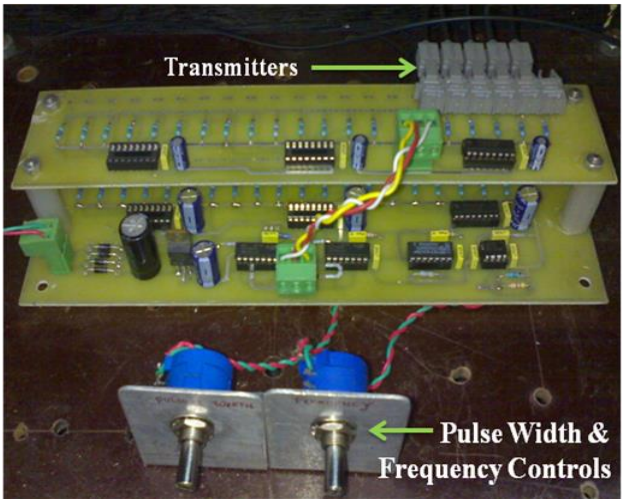

Fig. 7: Pulse generator system

C. Isolated Gate Driver

The required floating gate drive supply for all IGBTs is realized with simple arrangement as shown in Fig. 8 [16]. A high voltage insulated wire acts as primary of the transformer, which passes through the ferrite ring core behaving as secondary. It is driven by low voltage high frequency inverter (15V, 20kHz). The induced voltage in the secondary is rectified, filtered and regulated to generate isolated gate drive supply for each IGBT. The optically transmitted gate pulse is received and transferred into the electrical pulse using optical receiver HFBR2521. The gate driver IXDD414CI is used for fast switching of IGBTs. The inverter system, gate driver system with optical receiver, gate driver power supply and received gate pulses waveform are shown in Fig. 9, 10, 11, 12 and 13 respectively.

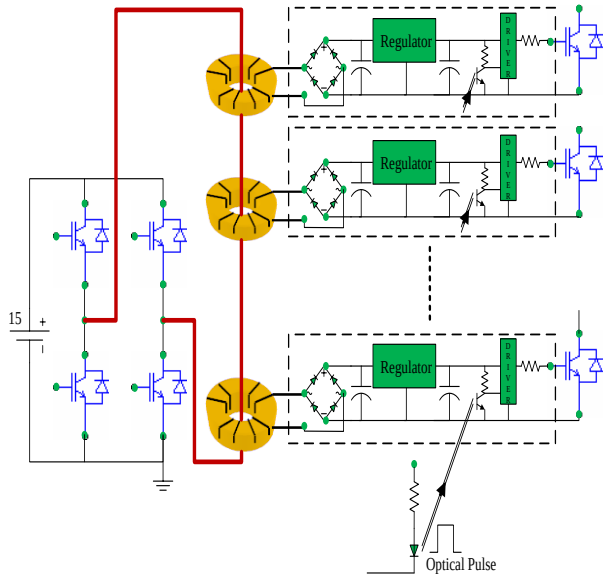

Fig. 8: Schematic diagram of floating gate drive supplies and controls

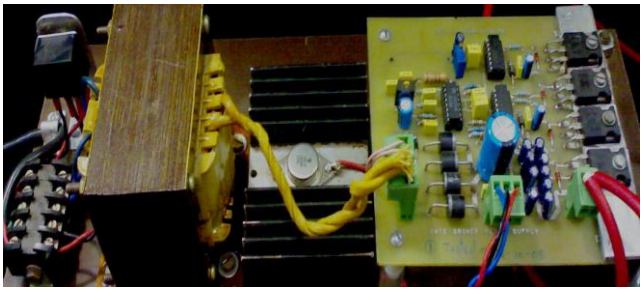

Fig. 9: Inverter of gate drive supplies

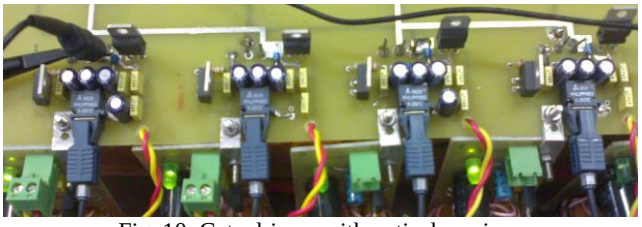

Fig. 10: Gate drivers with optical receiver

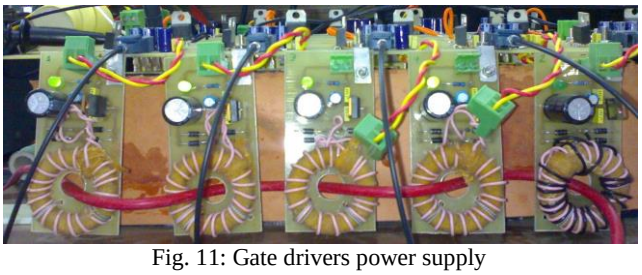

Fig. 11: Gate drivers power supply

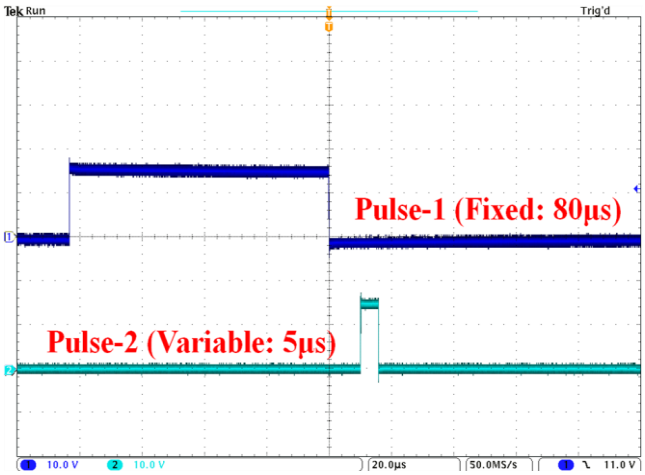

Fig. 12: Received gate pulses (Both waveforms: 10V/div, 20µs/div)

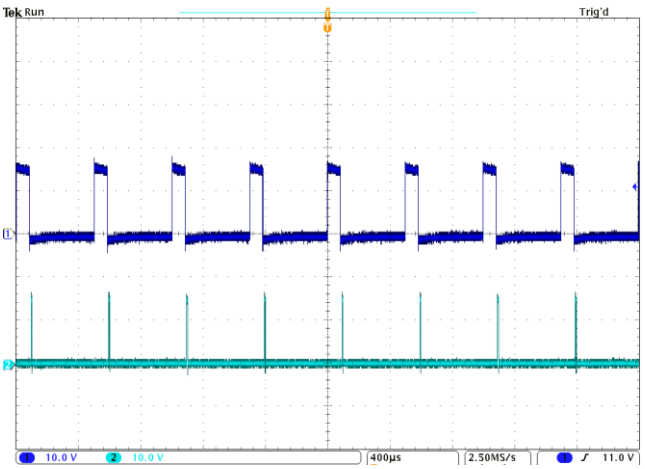

Fig. 13: Received gate pulses [Multiple Pulses- Upper: Pulse-1, Lower: Pulse-2 (Both waveforms: 10V/div, 400µs/div)]

III. Test Result

Presently, the prototype is tested with only three modules as shown in Fig. 2 but design calculations are considered for twenty modules as shown in Fig. 1.

The test results are shown for the input DC voltage of 200V and output voltage is obtained 600V, which is as per the design. The developed prototype is tested successfully with resistive load for maximum rated pulse current at 600V pulse voltage, over the entire range of the pulse width and pulse repetition frequency (PRF).

The rise time of the output pulse is found about 30ns. However, the induced noise at the gate of the charging IGBTs at switching time of series connecting IGBTs is an issue to be rectified.

The test setup, developed prototype, top view of prototype and different waveforms are shown in the figures given below.

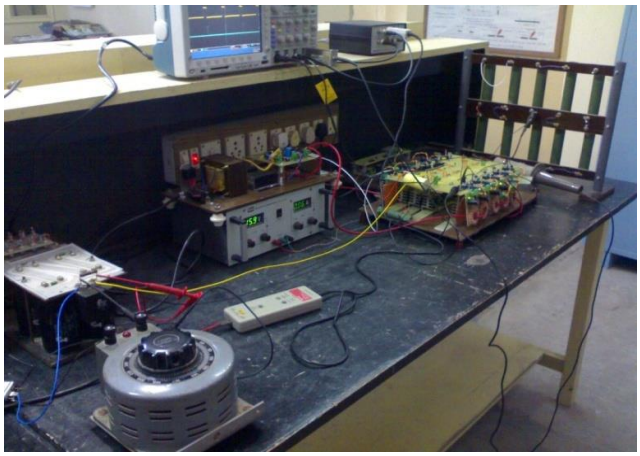

Fig. 14: Test setup

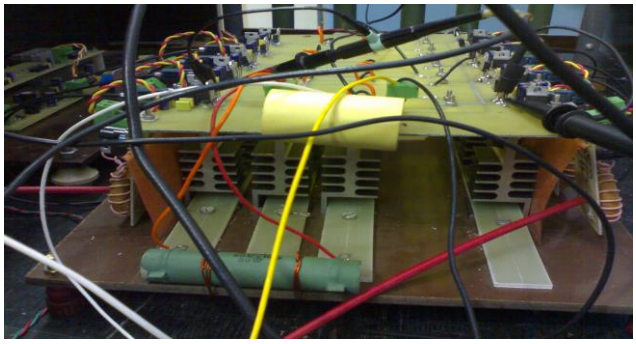

Fig. 15: Developed prototype

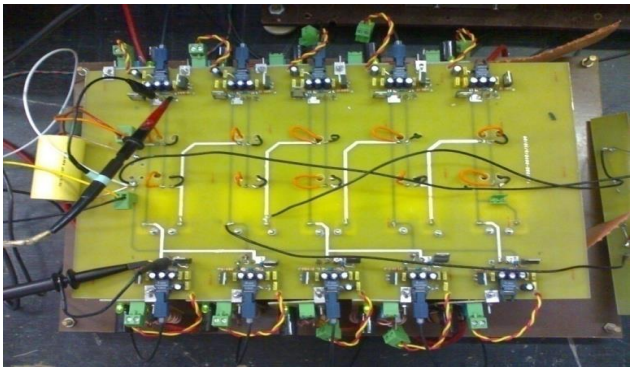

Fig. 16: Top view of developed prototype

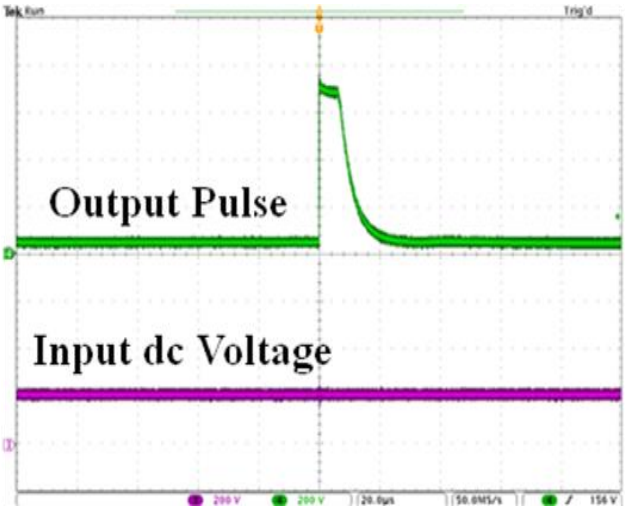

Fig. 17: Output pulse with input dc voltage (Both waveforms: 200V/div, 20µs/div)

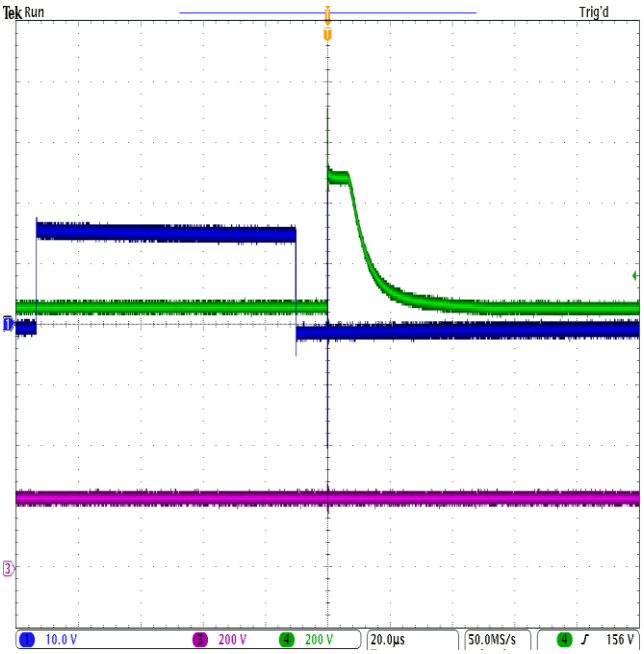

Fig. 18: Output pulse (Upper) with input dc voltage (Lower) and gate pulse-1 (Middle) (Both waveforms: 200V/div, 20µs/div)

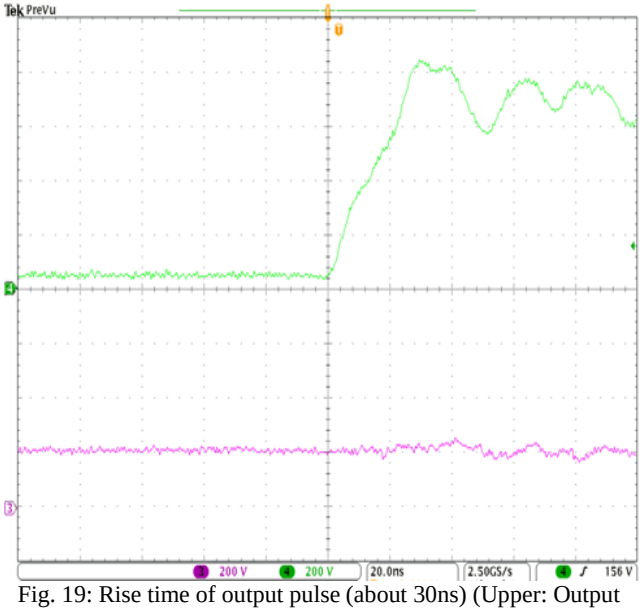

Fig. 19: Rise time of output pulse (about 30ns) (Upper: Output Pulse, Lower: Input DC voltage, Both waveforms: 200V/div, 20ns/div)

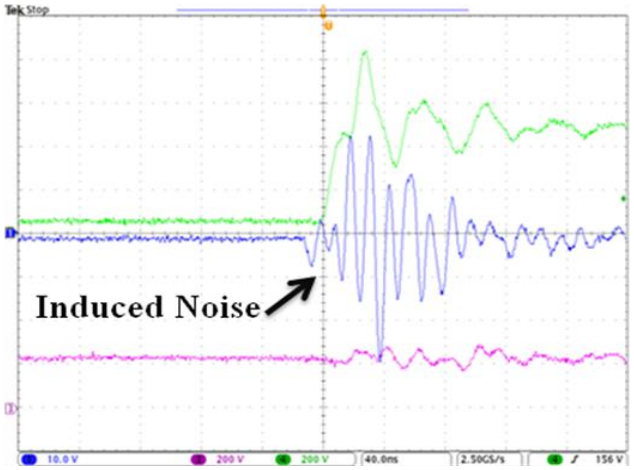

Fig. 20: Induced noise at the gate of charging IGBT (Upper: Output Pulse, Middle: Induced Noise, Lower: Input DC voltage, Upper & Lower waveforms: 200V/div, 40ns/div, Middle waveform: 10V/div, 40ns/div)

IV. Conclusion

In this paper, the design and development of the prototype of transformer-less pulse power supply based on "Marx Generator" are described. The design calculations are done for the following specification:

Input Voltage: up to 800V
Output Voltage: up to 15kV
Pulse width: up to 5μs
Pulse Frequency: up to 10kHz
Droop: 10%
Maximum pulse current: 1A

The optical coupling based open loop gate pulse generator has been designed to trigger the IGBTs, which has following specifications:

Pulse Frequency: up to 10kHz
Pulse-1 (for charging IGBTs): 80μs (Fixed)
Pulse-2 (for series Connecting IGBTs): up to 5μs
Delay (Pulse-1 to Pulse-2): 10μs (Fixed)

As per the design, twenty modules have been selected to achieve required output. The test results for the prototype with three modules have been presented and are found as per design and requirement.

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Biographies

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