Generation of Pulsed Power for Radar Application

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Abstract—**This paper proposes an efficient method for generation of high power train of pulses which are widely used in many fields. Pulse generators store energy in the form of electric or magnetic field for certain duration and by closing a switch at the load side, complete energy will be discharged to the load in the required form of pulses. The pulse generators are widely used in Radar application to drive magnetron loads with desired magnitude, pulse repetition frequency (PRF) and pulse duration or width. Line type modulator where a Pulse Forming Network (PFN) of type E is used as an energy storage element for generation of pulses. In this work, it is desired to produce rectangular pulses of magnitude 5 kV, PRF of 1.6 kHz and pulse duration of 4 microseconds with minimum rise time required for Radar application to drive load. MATLAB simulation is carried out in order to realize pulses of desired specification and a scaled down hardware setup is developed to verify the system performance.**

Keywords—Pulsed Power, PFN, FPGA, Magnetron Load

I. Introduction

Radar was produced for military use by a few countries amid World War II. Radar is a system which uses radio waves for finding the position, angle and velocity of an object. A Radar system comprises of a transmitter [1] creating electromagnetic waves, an antenna for transmitting and accepting the signals and a processor for determining the properties of the object. Present day Radars are all pulsed sort with magnetron [2] to create electromagnetic oscillations. To excite the magnetron at proper frequency and appropriate level it is important to supply high voltage and high power pulses to it. In addition to that, the shape of the pulses is of essential significance for proper magnetron operation. These pulses will start exciting the magnetron with high voltage pulses which then emits electromagnetic waves. These electromagnetic waves will be transmitted by the transmitter so as to know the position and velocity of the object under consideration. The pulse generators used can be of various types though the main function remains the same i.e. to excite the load with train of high voltage pulses.

The pulse generators used in various applications like Radar stores energy either in electrostatic form or electromagnetic form and discharges not all but only fraction of the energy or all of the energy which was stored to the load in the required form of pulses. Pulsed power applications requires the use of high quality rectangular pulses [3]-[4] i.e. it should have very fast rise and fall time with a flat pulse top. The rising time of the pulse, its fall time, width or duration and repetition rate of the pulse are some of the important specifications for a pulse generator.

Basically there are two types of pulse generators. One is a Hard-tube Pulser where the energy storage device is basically a condenser which is initially charged to some required amount of voltage V, thus making available 1/2 CV^2 of electrical energy. The term "hard-tube" here indicates the nature of the switch used in the pulser and is mainly a high-vacuum tube having a control grid. In this type of pulser only a fraction of the stored energy is discharged during the pulse. The other one is a Line type Pulser where the energy storage device is a lumped constant transmission line. Since this type of energy storage device not only serves as a source of electrical energy but also as the pulse shaping element during the pulse, it is popularly known as PFN [5]-[8]. The PFN in a line-type pulser consists of capacitances and inductances which can be put together depending upon the performance in any one of a number of possible configurations. The numerical values of the capacitances and inductances of such a network can be calculated to give an arbitrary pulse width or duration and pulse shape. The energy which is being stored in the PFN through a suitable charging circuit is discharged into the load which is considered to be of constant impedance as soon as the switch at the load side is turned on. Nowadays selection of switches [9]-[11] is of high importance so as to obtain desired pulses from the pulse generator. A Field Programmable Gate Arrays (FPGA) controller can be used for switching operation. In the present work, Pulse Width Modulation (PWM) signals are generated at constant duty cycle [12] for switching operation.

Section II gives detailed information about the mathematical modeling of a PFN. Section III deals with the modeling of a charging circuit. Section IV gives information on the discharging circuit and its elements. In section V MATLAB/Simulink model of a line type pulser is described. In section VI hardware set-up of the considered system is discussed. Section VII is devoted to the conclusion.

II. Modelling of PFN

The microwave oscillators for which nowadays most pulsers are designed require the utilization of basically a rectangular pulse [3]-[4]; the open-ended lossless transmission line is considered as a starting point in the discussion. Consider a lossless transmission line of length l for producing an ideal rectangular pulse as shown in Fig. 1.

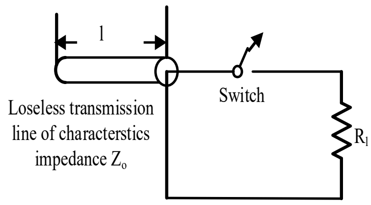

Fig. 1. Schematic diagram for producing an ideal rectangular pulse

The ac impedance, Z, of the lossless transmission line as shown in Fig. 1 is given by (1) [1].

$$Z = Z_0 cothjw\delta \quad (1)$$

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Where Z_0 is the characteristic impedance of the lossless transmission line and δ is the one way transmission time. The laplace transform (LT) of (1) is given by (2).

$$Z(s) = Z_0 coths\delta \quad (2)$$

The current equation in laplace domain is given by (3).

$$i(s) = \frac{V_0}{s(R_l+Z_0 coths\delta)} \quad (3)$$

Where V_0 is the initial voltage of the transmission line and R_l is the load impedance. The equation for current in time domain can be obtained by inverse LT of (3) and is given by (4) [1].

$$i(t) = \frac{Vo}{Zo+R_l}(1-U(t-2\delta) - \frac{Zo-R_l}{Zo+R_l}[U(t-2\delta)-U(t-4\delta)]+\dots) \quad (4)$$

Where U(t) is a step function. If $R_l = Z_0$, i.e. if the load impedance is equal to the line impedance, the current waveform as seen from (4) will be of rectangular shape and of single pulse having amplitude $I_l = V_0/2Z_0$ and width $\tau = 2\delta$. Current and voltage pulses for different load impedances are shown in Fig. 2.

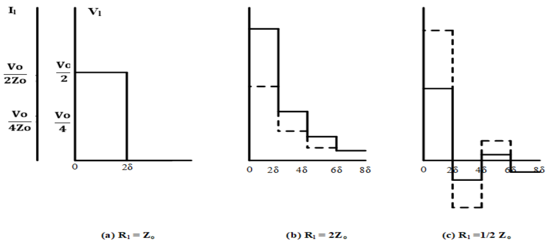

Fig. 2. Discharging of Current (broken lines) and voltage (solid lines) pulses in a lossless transmission line to a resistance load

As seen from Fig. 2, if there is a mismatch between the load and line impedance, the pulses obtained are of series of rectangular steps which is undesirable [1]. Also for producing pulses in microseconds, the length of the transmission line or cable has to be very high which is unreasonable. Hence a substitute of a line reproducing system is essential for any practical application.

A. Line Simulating Network

In line simulating network the transmission line is having lumped parameters. The line simulating network is shown in Fig. 3.

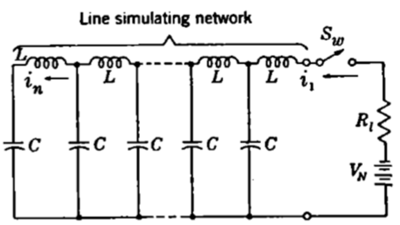

Fig. 3. Line simulating network

The current equation for the line simulating network in the laplace domain is given by (5) [1].

$$\lim_{n\to\infty} i_l(s) = \frac{V_N}{2\sqrt{\frac{L_N}{C_N}}s}(1-e^{-2\sqrt{L_N C_N}s}) \quad (5)$$

As seen in (5) the current pulse is of rectangular shape and of width $2\sqrt{L_N C_N}$ where L_N is the total inductance, C_N is the total capacitance, n is the number LC sections of the network and V_N is the source voltage. In this kind of network, pulses show overshoots and oscillations towards the start and end of the pulse since we don't utilize an infinite section. Different techniques that reproduce a transmission line are acquired by representing the transmission line as functions of impedance and admittance in an infinite series [5] of rational function.

B. Guillemin's Theory

Guillemin's analyzed the difficulties associated with a line simulating network and concluded that it is difficult to deliver a discontinuous pulse with infinite rate of rise and fall by a lumped network. So it was suggested that the theoretical pulse that will be used for analysis should purposely have limited rise and fall times. The first Guillemin's network was designed depending on a trapezoidal pulse [5] shape as shown in Fig. 4 having finite rise and fall time. The method used by Guillemin's theory to structure of the PFN relies upon the Fourier series arrangement of the desired output pulse.

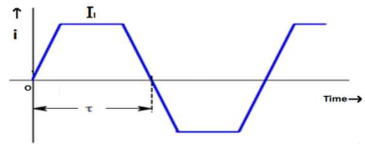

Fig. 4. Trapezoidal alternating current wave

The current i(t) of the trapezoidal wave is an odd function and we know from Fourier series that it contains sine terms only and no cosine and constant term. So the current equation can be written as seen in (6).

$$i(t) = I_l \sum_{n=1,2,3\dots}^{\infty} b_n sin\frac{n\pi t}{\tau} \quad (6)$$

Where I_l is the peak current amplitude and τ is the pulse width. Each term of the Fourier series represents a sine wave of amplitude b_n and frequency $n/2\tau$. Now consider the LC loop for generating sine terms as shown in Fig. 5.

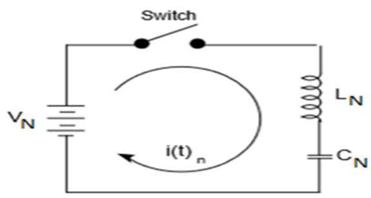

Fig. 5. Circuit for generating a sinusoidal steady state current

Current produced by the circuit as shown in Fig. 5 is given by (7).

$$i(t)_n = \frac{V_N}{\sqrt{\frac{L_N}{C_N}}} sin(\frac{t}{\sqrt{L_N C_N}}) \quad (7)$$

Comparing the frequency and amplitude terms of (6) and (7), the final equation for L_N and C_N is given by (8) and (9).

$$L_N = \frac{Z_N \tau}{n\pi b_n} \quad (8)$$

$$C_N = \frac{\tau b_n}{n\pi Z_N} \tag{9}$$

Where $Z_N=V_N/I_l$, is the equivalent impedance of the LC circuit. For the network to produce the required wave shape, it must consist of a number of LC sections which are connected in parallel, as shown in Fig. 6.

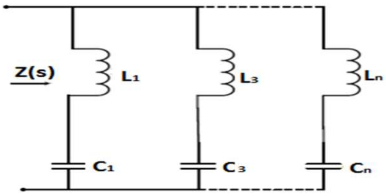

Fig. 6. Type C PFN

Where $L_1, L_2, \ldots L_n$ and $C_1, C_2, \ldots C_n$ are found out from (8) and (9). But the issue of type C PFN circuit is that the physical inductors practically are having some parasitic shunt capacitance which distorts the shape of the wave and capacitors values. Different combinations of inductors and capacitors were tried to find out the best performance. It is concluded that PFN of type E [6]-[8] is having the best performance which is shown in Fig. 7 with total inductance $\tau Z_N/2$ and total capacitance $\tau/2Z_N$ divided equally between all areas. The taps from each condenser are placed in the solenoid in such a way so as to get equal inductances for all segments.

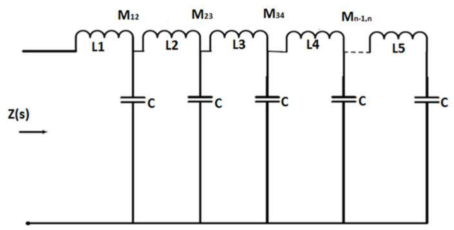

Fig. 7. Type E PFN

III. Charging Circuit for Line Type Pulser

In line-type pulsers, all of the energy stored in the PFN is typically discharged into the load and it is important energize the system during the interpulse interval [8]. To charge the PFN at a required voltage, a reactor can be used. The advantage of using a reactor as charging element is that the PFN voltage reaches to approximately twice the source voltage and hence reducing the requirement of a high magnitude DC voltage from the source side. Few assumptions are being made in design of the charging circuit. One of them is that the PFN is represented by the capacitance, the impact of the PFN inductances can be neglected on the charging circuit. The other assumption is that the pulser switch is assumed to be perfect; its deionization is assumed to be immediate after the discharge of the network.

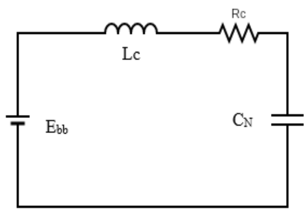

Fig. 8. Equivalent charging circuit for a line type pulser

The charging circuit is represented as shown in Fig. 8. The differential equation as far as the instantaneous charge q_N for this circuit is given by (10).

$$L_c\frac{d^2q_N}{dt^2} + R_c\frac{dq_N}{dt} + \frac{q_N}{C_N} = E_{bb} \tag{10}$$

Where R_c, L_c is the resistance and inductance of the charging inductor, C_N is the total PFN capacitance and E_{bb} is the power supply voltage. At the time of discharge, the final equation of the network voltage is given by (11).

$$V_N(T_r) = 2E_{bb}-V_N(0) \tag{11}$$

Where $V_N(0)$ is the initial voltage across the system or PFN capacitance. It is clearly seen from (11) that the PFN voltage at the time of discharge reaches to approximately twice the source voltage. Resonant charging is used for this modulator. At the time switch is closed, L_c and C_N will consolidate to form a resonant circuit. The voltage on the system will be double the supply voltage till main switch is turned on. The case where the initial current in the charging inductance is equal to zero is designated as "resonant charging" [1] and the condition is given by (12).

$$wT_r=\pi \tag{12}$$

Where T_r is the pulse recurrence time and w is the resonant frequency. Equation (12) indicates that the charging inductance is inversely proportional to the PRF and is given by (13).

$$L_r = 1/\pi^2 f_r^2 C_N \tag{13}$$

Where $f_r = 1/T_r$, is the PRF.

IV. Discharging Circuit of a Pulse Generator

The discharging circuit as shown in Fig. 9 includes a PFN, switch and the load. The PFN needs to create a rectangular pulse output if it is connected through a switch to the load, whose impedance is equal to the characteristic impedance of the PFN. At whatever point the switch is closed the complete energy which was stored initially in the PFN needs to be discharged through the switch to the load, for that the characteristic impedance of PFN must to be equal to the load impedance. But in practical cases 20-30% of mismatch is allowable for operation of pulsers. This mismatch in impedances has little impact on discharging circuit [1].

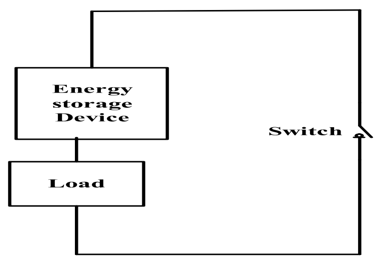

Fig. 9. Basic discharging circuit of pulser

The energy storage device that is used is a cascaded combination of L and C i.e. a PFN. The switch is a very important device as it is the one which initiates the discharge of the energy from the PFN to the load. So the proper selection of the switch is a very important task. Now there are few important things which are to be considered for selection of switches.

A. Selection of Switches

Switches are used to initiate the discharge of PFN into the load to get pulsed output. So the switch should be selected in such a way that it has the following requirements:

- The switch should not conduct during the time when the supply charges the PFN; the switch should remain off till the PFN reach a particular voltage and a particular recurrence time.
- The switch should be able to close at a very fast speed and at predetermined times i.e. it should be able to close at a very high pulse recurrence frequency.
- The switch resistance has to be as small as possible during discharge of the pulse so that energy loss is as small as possible.
- The switch should be able to carry high current during the pulse i.e. it should have high current carrying capability.

There are various options available for selection of switches in the pulse generators. In recent couple of years the interest for substitution of thyratrons as switch has expanded steeply, and the innovation for solid state switches has improved definitely, particularly in the medium frequency range. Pulse generator with solid state devices as switches can deliver high repetition rate. Some of the switching devices used by pulsed power generators are Silicon Controlled Rectifiers (SCRs), Insulated-Gate Bipolar transistors (IGBTs) and Metal Oxide Semiconductor Field Effect Transistors (MOSFETs). The pulse can be produced by utilizing transistors and SCRs as switch yet their performance by and large is inferior to that of a power MOSFET. The voltage levels can be increased by cascading a number of MOSFETS in series. Consequently, solid state devices, for example, power MOSFETs are turning the consideration of scientists towards the structure of new pulse generators of high speed with limited size and cost [9]-[10]. Another preferred standpoint of utilizing MOSFET as a switch is that it's on state resistance is less.

B. Generation of PWM signal

PWM signals are used in the switching operation. In the present work, switches are used for the discharge of energy which was stored in the PFN during the charging period to the load at a constant duty cycle. Normally the pulse width desired for Radar application are in microseconds and hence the duty cycle of the switch i.e. the time for which it should be on is very small. To generate a PWM signal with fixed duty cycle, a constant reference signal is compared with a sawtooth carrier signal whose frequency is same as the desired PRF [12]. Initially as the value of the reference signal is more than the carrier signal, a high pulse PWM signal is generated and the switch is assumed to be on. As soon as the carrier signal becomes more than the reference signal, a low pulse PWM signal is generated and the switch is assumed to be off during this period as shown in Fig. 10. The concept works in the opposite way as well. Practically nowadays using the same concept, FPGA controller [11] is used for switching operation of MOSFET.

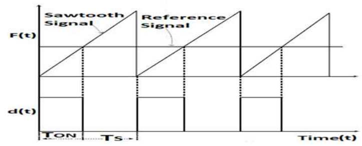

Fig. 10. Constant duty (d) PWM

C. Magnetron Load

Cavity magnetrons are used in Radar application to produce the electromagnetic waves. They work on the principle of LC oscillation. The magnetron is as a self-energized microwave oscillator where electrons and magnetic field [2] interacts to create a powerful field required in radar operation. Magnetron consists of anode, cathode poles and a permanent magnet. The anode in a magnetron is designed with cavities, so as to achieve oscillation. The magnetron receives high voltage of electricity through a cable produced by the pulse generator and as a result of that the electrons are emitted from the cathode pole. The electrons emitted from the cathode moves towards the anode at a very high speed in a curved path because of the magnetic field produced by the permanent magnet and induce opposite polarity charges on the cavity surfaces. As a result of that LC oscillation is introduced in the magnetron since the curved surface of the cavity acts like an inductor. To extract the oscillation from the magnetron, an antenna is used which converts the extracted oscillation into electromagnetic waves and sends them to the microwave guide.

V. MATLAB/SIMULINK MODEL

The MATLAB/Simulink model of the proposed system is shown in Fig. 11. All the components of the system are used and modified in order to generate pulses of desired specification. The DC source voltage is obtained from a single phase full bridge rectifier. DC voltage obtained from the rectifier has some ripples which is removed using a suitable value of RC filter. PFN of type E is used with number of sections equal to ten.

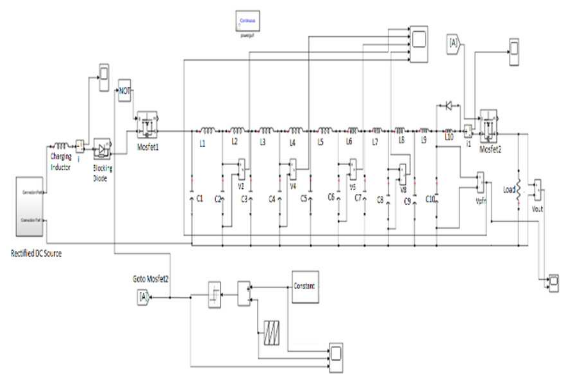

Fig. 11. MATLAB/Simulink model of pulsed generator

The charging inductor is used so that the PFN reaches to approximately twice of the source voltage when the MOSFET at the source side is on. As soon as the PFN reaches to the desired voltage i.e. of 10kV, it starts discharging its energy by switching on the MOSFET to the load which is considered as a resistive one of 50 ohms for simplicity though practically a magnetron is used as a load. A blocking diode is used for extra protection purpose so that the PFN capacitors do not discharge any of its energy to the source during the discharging period. The voltage across some of the PFN capacitors during the discharging process is shown in Fig. 12.

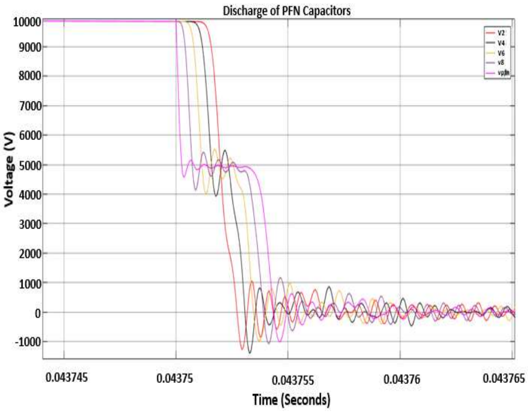

Fig. 12. Voltage across PFN capacitors

To generate switching pulses at constant duty cycle, a constant reference signal is compared with a sawtooth carrier waveform whose frequency is same as required PRF. The switching pulses obtained for switching on the MOSFET is shown in Fig. 13.

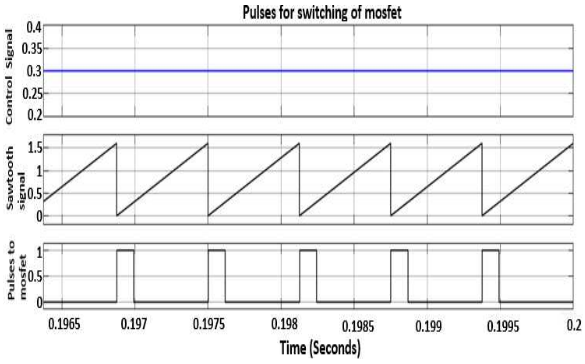

Fig. 13. Waveforms for switching of MOSFET

The output current pulse is shown in Fig. 14. The exponential increase of the PFN voltage and the output pulse voltage across the load for the proposed system is shown in Fig. 15. As soon as the PFN reaches the desired voltage it discharges its energy to the load and the output pulses obtained as seen in Fig. 16 is of rectangular type with magnitude of 5 kV, pulse width of 4μs and 1.6 kHz of PRF.

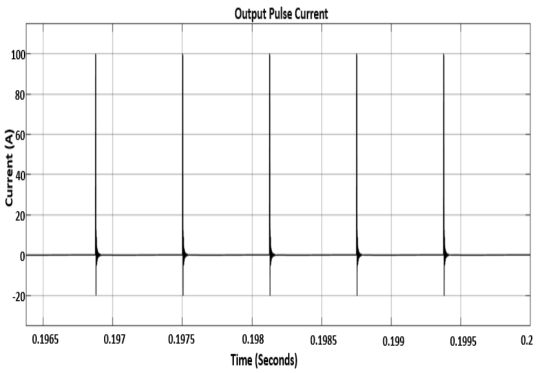

Fig. 14. Output pulse current waveform

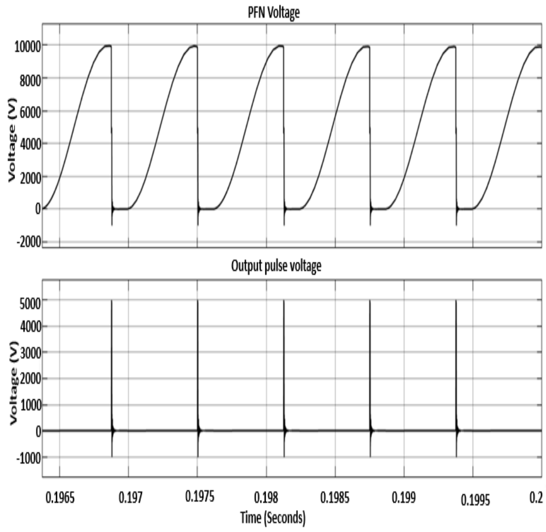

Fig. 15. PFN voltage and output voltage waveform

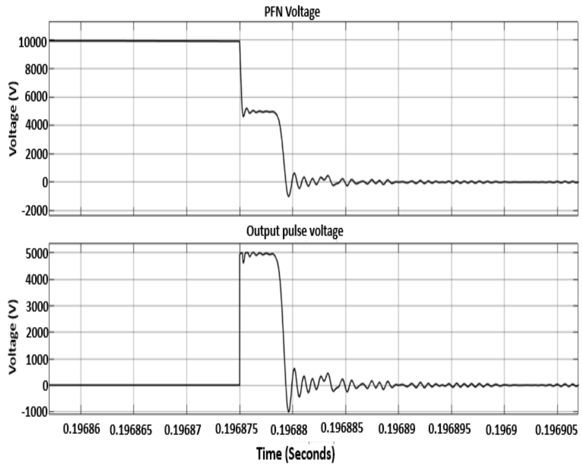

Fig. 16. PFN voltage and output voltage waveform (single pulse)

VI. Experimental Set-Up

To verify the results obtained from simulation, a scaled down hardware implementation of the proposed line type pulser is assembled as shown in Fig. 17 using a ten section PFN and a charging inductor. The capacitor and inductor values of the PFN which can be measured using a LCR meter are chosen based on the discussions in section II and are shown in Table 1. Air core inductors are used in the PFN. An FPGA controller is used to provide the gating pulses to the MOSFET.

The output pulses are obtained after PFN discharges its energy to the load. As the PFN capacitors reaches to approximately twice the applied voltage of 30V, switching pulses from the FPGA controller is applied to the MOSFET so that output pulses of approximately equal to the source voltage is obtained at the resistive load of 50 ohm at a pulse recurrence frequency of 1.6 kHz as shown in Fig. 18. It is imperative that the all of the energy stored in the PFN is discharged to the load and again recharged to the equal required level during the interpulse interval so that equal magnitude of voltage is obtained for each pulse.

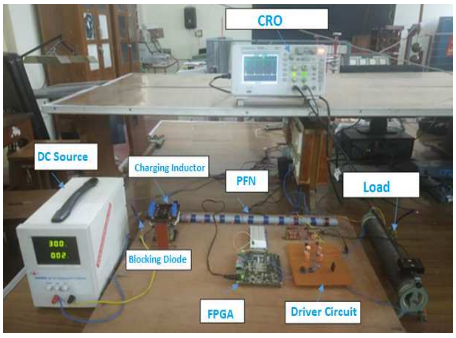

Fig. 17. Hardware implementation of the proposed system

TABLE I. PFN DESIGNING ASSUMPTION

PFN Parameters	*Type*	*Value*	*Numbers*
Capacitor	Ceramic	4 nF	10
Inductor	Air core inductor	10 µH	10

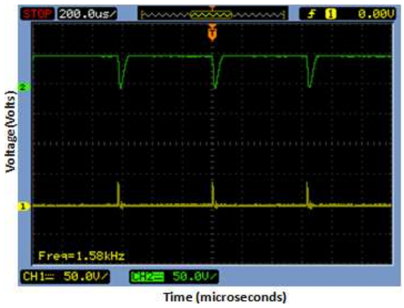

Fig. 18. PFN and output pulse voltage waveform

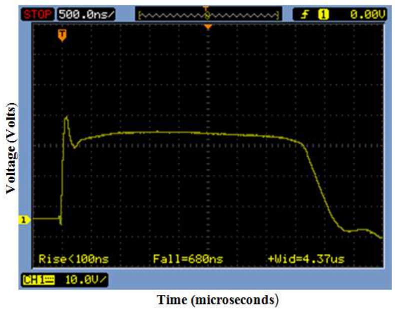

Fig. 19. Output voltage pulse waveform

The output pulse voltage as shown in Fig. 19 is very close to being a rectangular one and of width 4 microseconds. The pulse voltage is having a rise time which less than 100ns and hence the response is very fast. Initially a minimal overshoot is obtained due to the sudden release of energy from the PFN which can be neglected. By varying the number of PFN sections or inductor and capacitor values of each PFN section, the pulse width can be varied.

VII. CONCLUSION

In this work, pulsed power is generated using a line-type pulser with continuous pulses to excite a load with required width, frequency and magnitude. Simulation of the proposed system is carried out and a scaled down hardware set up is developed to verify the simulation results. The modeling of the PFN for pulse generation is discussed which is used for storing and discharging of the energy to get the required pulses. It is observed that when inductor is used as a charging element the PFN voltage reaches to approximately twice the source voltage so that there is minimum requirement in the input voltage to get a desired output pulse voltage. The switch which initiates the discharging process from the PFN to the load is of very high importance and it is found that semiconductor switches are of more advantageous and hence in this work MOSFET is used as a switch. By switching the MOSFET at a desired frequency, pulses of required width, magnitude and PRF is obtained. In this work a fixed load is used whose impedance is matched with characteristic impedance of the PFN to transfer maximum energy to load but if a pulse transformer is installed at the load side, loads of variable impedance can be used since by varying the transformer parameters load and PFN impedance can be matched. Also there will be less voltage requirement at the source side and at the PFN capacitors so that the PFN capacitors of minimum size can be used.

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