SOLID-STATE HIGH VOLTAGE NANOSECOND PULSE GENERATOR *

Fei Wang, Tao Tang, Charlie Cathey, Andras Kuthi and Martin Gundersen?
Department of Electrical Engineering – Electrophysics
University of Southern California
Los Angeles, CA 90089-0271

Abstract

Pulses shorter than 50 ns are essential for further study on transient plasma ignition and streamer physics. Design and operation of a compact full solid-state pulse generator is presented. The pulse generator can create 20 ns FWHM, 60 kV amplitude pulses into 300-ohm load. It is comprised with IGBT switched resonant charging circuit; two steps of magnetic pulse compressor and a semiconductor opening switch (SOS) based pulse generator. The use of low cost mass-produced rectifier diode as an opening switch was reported.

I. INTRODUCTION

Transient plasma ignition has been demonstrated, in recent years, a powerful and energy efficient way of engine ignition [1]. Combustion processes are conventionally ignited by high temperature air (as in diesel engines) or spark discharges, which in turn initiate thermal decomposition of fuels into radicals [2]. Combustion rates can be enhanced if radicals are initially produced by other means in addition to thermal decomposition. For example, external energy sources such as plasma jets [3,4], high-energy electron beams [5,6], and excimer laser beams [7,8] can be injected into the reactive media, and enhancement of combustion rates has been observed with these methods. Simulations predict that direct dissociation of methane and/or oxygen can enhance the combustion rates of methane/oxygen/ argon [9] and methane/air [10] mixtures, and theoretical studies [11] also predict that plasma-assisted combustion may, in addition to improving combustion rates, result in reduction of undesirable combustion products such as NO.

The transient plasma discharges were comprised of a volume-distributed array of streamers. Generally the streamer velocity and channel radius are of the order of 10^7-10^8cm/s and 1 mm to 100 µm.

For these studies, a high repetition rate pseudospark switched pulse generator was design and built in Univ. of Southern California. The pulse generator can generate 90 kV voltage pulses with 50 - 75 ns FWHM [13]. Transient plasma was successfully created into a coaxial structure ignition cell for pulse detonation engines (PDEs) with 50 mm gap from anode to ground. More details on experiment setup can be found in [14]. For some other applications, however, such as ignition of internal combustion engine and combustion control, the discharge gap may be as small as several millimeters, in which case 75 ns pulse would be too long to maintain transient plasma phase due to the streamer to spark transition after streamer bridging the gap. Pseudospark switched line-type pulser can not generate faster or narrower pulse than 50ns due to inherent limitations of the pseudospark device. Therefore, a pulse generator with shorter pulse was demanded. In addition to the pulse width requirements, modern applications require switches in pulse generator to be high performance, low maintenance and long lifetime. Solid-state switches such as IGBT, MOSFET, DIODE, need no pre-heating, housekeeping. So, for compact pulsed power, solid-state switches have intrinsic advantages over gas switches. Semiconductor opening switches are usually specially made SOS-diodes for megavolts applications [15]. Low cost rectifier diode was proved to be capable of generating pulses as short as 3 ns at low voltage applications [16]. The pulse generator descript in this paper is full solid-state pulse generator using standard rectifier diode as opening switch for transient plasma applications.

II. DESIGN

The pulse generator is expected to deliver pulses of V_{out} *~60 kV* peak amplitude and t *~20 ns* FWHM. The design includes 3 stages: the first stage is resonant charging stage to step up voltage from 900 V to 15 kV. The second stage is magnetic pulse compressor. A unit of semiconductor opening switch, which comprised with 60 series connected rectifier diodes, switches the final stage.

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? e-mail: mag@usc.edu

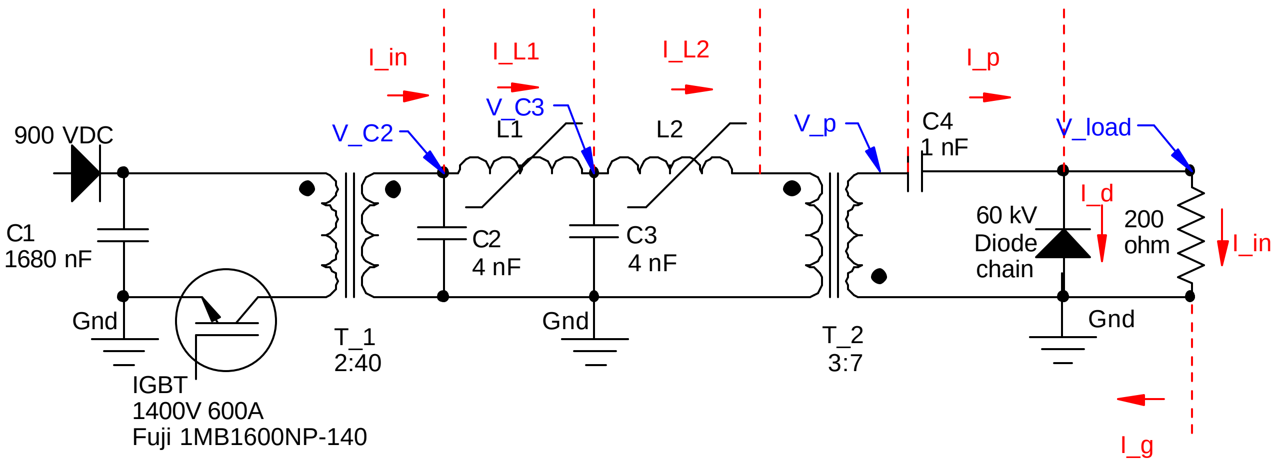

Fig. 1. Circuit schematic of 60 kV solid-state pulse generator

Energy was pumped from compression stages to diode by a saturable transformer with ratio 3:7. The circuit schematic is shown in Fig. 1.

A. *Output stage: SOS-based generator*

The design starts from the required pulse shape and amplitude at the load and works backward to the main energy source. The actual pulse is generated by a diode acting as an semiconductor opening switch (SOS), interrupting the current in an inductor and commuting it into the load resistance as shown in Fig. 2. The operating cycle begins with switch S_2 closed and S_1 open, so the first capacitor is fully charged and the second is empty. Then switch S_2 opens and the subsequent closing of switch S_1 generates a half cycle of forward pumping current through the diode. This establishes stored charge in the diode depletion layer and transfers the initial charge from the first to the second capacitor. At the end of this half period the second switch S_2 closes and starts a reverse current through the diode depleting the stored charge. In an ideal circuit with ideal switches and circuit elements the two capacitors and the two inductors must be equal. For constant capacitor voltage the peak inductor current is

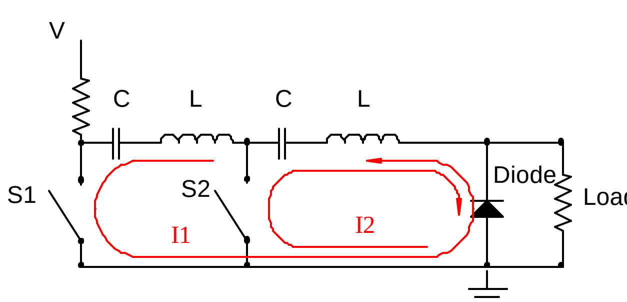

Fig. 2. Principle of SOS-based generator: I_1 is the current flow in pumping cycle; I2 is the current flow in pulse generating cycle

proportional to the circuit admittance, $I \propto \sqrt{\frac{C}{L}}$. During the forward current phase the total circuit inductance is 2L and the net capacitance is C/2. During the reverse current phase the net inductance is only L and the net capacitance is C. Both phases have the same resonant frequency. Thus the peak reverse current will be twice the peak forward current, and the charge will be extracted at exactly a quarter period, at the peak of the reverse current. The opening of the switch S_1 recharges the first capacitor and completes the cycle.

We chose silicon rectifier diode MR2510 rated as 1 kV 35 amps. Each of these diodes is in a button like package. A unit with 9×60 diodes was built, which can hold a voltage of 60 kV, 315 amps DC current and pulse current more than twice the DC rating.

Switch S1 is the saturable inductor L2. During pumping cycle, the inductances L in Fig. 2 are saturated inductance L2 and the leakage of transformer T2. Switch S2 is saturable transformer T2. Pulse generation cycle begins with the saturation of T2. The inductance L in this cycle is the saturated secondary inductance of transformer T2, which is also the final energy storage inductance L_{store}. L_{store} can be calculated from the fall time of the designed pulse width t_f, because the inductor current decays with the time $\frac{L_{store}}{R_{load}}$, where the resistance R_{load} is that of the load. The minimum current interrupt by the diodes is estimated from the peak voltage required at the load $I_2 = \frac{V_{out}}{R_{load}}$. However, the nonlinear diode capacitance needs to charge to the full output voltage, and the charge absorbed by this and all stray capacitance increases the current requirement significantly.

The quarter period of the L-C circuit must be shorter than the diode recovery time for fast current turn-off. A

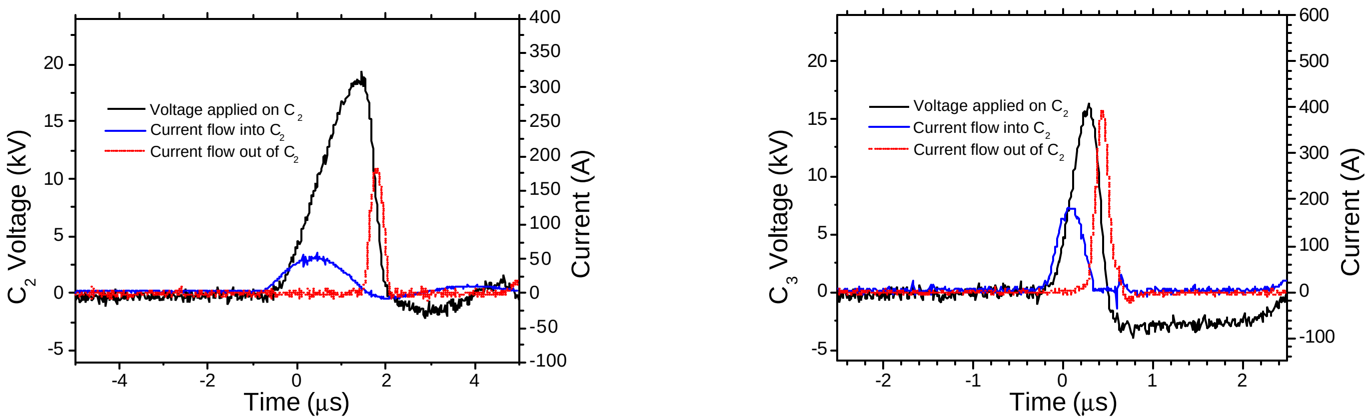

Fig. 3. Voltage and current plot for the (a) first compression (b) second compression

diode fully saturated with charges will have a delay to turn-off given by the recovery time presented in the data sheets, which is 3 μs in our case. Thus, the diode should not be saturated. We use 9 diodes in parallel. It needs a pumping current pulse as short as 200 ns to be provide by magnetic pulse compressor.

B. *Magnetic pulse compressor*

The basic concept of magnetic compressor is to drive sufficient current through a winding on a magnetic core such that the applied *H* produces a flux density *B* in the core in excess of the core's saturation flux. In doing so the inductance of the winding changes form a relatively high value to a very low value and the inductor behaves as a magnetic switch.

In this paper, two stages of magnetic compressors and a saturable transformer are employed. Both saturable inductors L_1, L_2 in magnetic pulse compressors and saturable transformer T2 are built on HITACHI finemet cores FT-3KM F4627H. External core dimensions are: OD = 50.0 mm, ID = 23.4 mm, H = 28.2 mm and effective core area A_e = 178.1 mm^2. The core saturates at B_s = 1.23 T and reset B_r=0.61 T. The relative permeability is 15×10^3 at 100 kHz.

The windings of saturable inductors L_1 and L_2 are 38 and 7 turns respectively. Windings are evenly distributed along toroid core to minimize the inductance after saturation. Capacitors on both compression stages are equal to 4 nF. The compression cycle begin with a pulse charge from transformer T_1 to capacitor C_2. For the first compression stage, as shown in Fig.3 (a), charging time is

$t_{ch} = \frac{A_e n_1 B_s}{V}$ where n_1 is 38 turns; discharge time is

$t_{dis} = p\sqrt{\frac{L_{sat1} C_2}{2}}$ where L_{sat1} is saturated inductance of

L_1. The compression ratio is $\frac{t_{ch}}{t_{dis}}$, which is also equal to the ratio of peak current flow out of and into capacitor C_2.

The second compression can be analyzed in exactly the same way. Plot is shown in Fig. 3 (b). The first and second compression stages contribute 3.7 and 2.1 compression ratios. Overall compression ratio of the two compression stages is 7.8. Energy transfer efficiency from first to second compression stage is 74%. Energy loss is primarily because of the improper saturation timing; part of energy was not transferred but oscillated between compression stages, which can be seen in the voltage signal in Fig. 3 (a).

The saturable core transformer has 3 turns in primary and 7 turns in secondary. The primary windings are directly connected to the output of magnetic pulse compressor. Transformer output current was shown in Fig.4. The negative part of 220 ns is pumping though diodes. The positive interrupt current by diodes is about 500 A. It is more than twice of the peak pumping current, because Saturated secondary inductance of T_2 is less than half of the combination of transformer leakage and saturated L_2

C. Primary charging stage

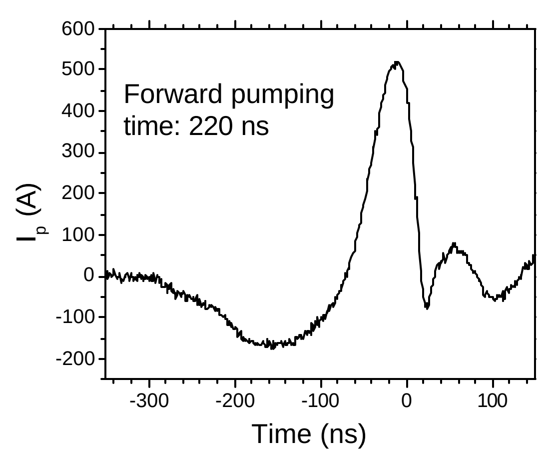

Fig. 4. Output current from saturable transformer

Primary energy storage capacitor C_1 is high current snubber capacitors, which was charged to 900 V and switched by IGBT Fuji 1MP 1600-NP. Voltage step up to 18 kV by a metglass core transformer with 2:40 turn ratio.

The present system uses a DC power supply. In the future the pulse generator will be charged directly from rectified 3-phase 208 V

III. OPERATION

Typical output into 300-ohm resistive load is shown in Fig. 5. The pulse amplitude is ~60 kV, and the FWHM is ~20 ns.

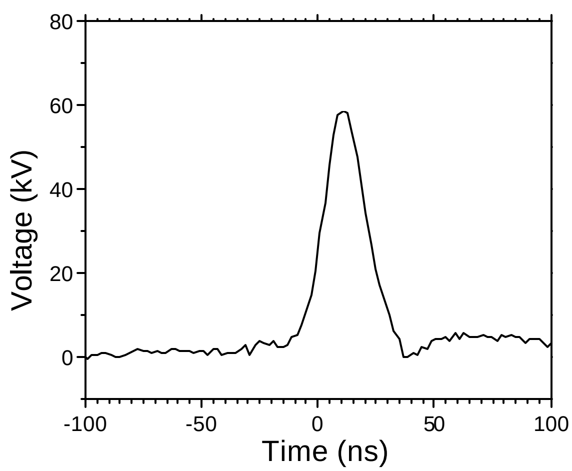

Fig. 5. Output of pulse generator into 300-ohm resistive load

IV. FUTURE WORK

Optimize the timing on compression stages. Redesign primary resonant charging system to enable the pulser to be powered by 3-phase wall plug directivity. Protect diodes chain from unevenly distributed reverse voltage pulse and compensate stay capacitance along diode chain by series capacitors.

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