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A New Generation of High Voltage Pulsed Power Converters

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Abstract—**Improving efficiency and flexibility in pulsed power supply technologies are the most substantial concerns of pulsed power systems specifically for plasma generation. Recently, the improvement of pulsed power supply becomes of greater concern due to extension of pulsed power applications to environmental and industrial areas. A current source based topology is proposed in this paper which gives the possibility of power flow control. The main contribution in this configuration is utilization of low-medium voltage semiconductor switches for high voltage generation. A number of switch-diode-capacitor units are designated at the output of topology to exchange the current source energy into voltage form and generate a pulsed power with sufficient voltage magnitude and stress. Simulations have been carried out in Matlab/SIMULINK platform to verify the capability of this topology in performing desired duties. Being efficient and flexible are the main advantages of this topology.**

Keywords-pulsed power supply, high voltage, current source, voltage source, power converter, DC-DC topology, plasma.

I. INTRODUCTION

Pulsed power is accumulating energy over a relatively long period of time and releasing it very quickly which is a process aiming to increase the instantaneous power. The characteristics of this pulse including voltage level and rising time are determined based on the load requirements.

Although, single shot based pulsed power generators with extremely high peak power have been considered initially for military and nuclear fusion applications, repetitively operated pulsed power generators with a moderate peak power have been recently developed mainly for industrial applications such as food processing, medical treatment, water treatment, exhaust gas treatment, concrete recycling, ozone generation, engine ignition, ion implantation and etc [1, 2]. Marx Generators (MG) [3], Magnetic Pulse Compressors (MPC)[4], Pulse Forming Network (PFN)[5], Multistage Blumlein Lines (MBL)[6] etc, are the most popular technologies which have been utilized so far as pulsed power supply. Efficiency, flexibility and intricacy are major drawbacks of these power supplies. Controlling power flow is a critical skill as well which can improve the efficiency of power supply systems. On the other hand these pulsed power systems require high voltage high power switches in which their voltage blocking and switching time are limited.

The switches technology utilized for pulsed power generation has been varied with respect to the development of power semiconductor devices over past few decades. Thyristor, IGBT, MOSFET, etc are some of those switches mostly classified as solid state semiconductor switches. Since pulsed power applications demand for high dv/dt, fast switches with short switching transients have critical role in pulsed power supply topologies.

Most pulsed power applications have resistive-capacitive characteristics [7]; therefore, a current source topology seems to be a proper candidate to supply such loads. With respect to this issue a combination of current and voltage sources is considered in this paper to develop the initial concept of high voltage pulse generation with low voltage switches [8]. The circuit depicted at the top of Fig. 1 reveals a general configuration for the proposed topology. Same sort of fast and low-medium voltage semiconductor switches and diodes are used between two energy storages in order to control the energy delivery process. In this configuration the inductor and the capacitors, which can be supposed as the current and voltage sources, are in charge of supplying energy and generation of appropriate voltage level and stress respectively.

II. TOPOLOGY

A. General Configuration

The topology considered in this paper is based on the positive buck-boost converter concept. The general concept of this topology is presented in Fig. 1.

An AC-DC converter rectifies grid AC voltage into a DC voltage and supplies rest of the circuit. The source voltage charges an inductor, L, through switches, S_S, and S_1, S_2…, S_n, composing a current source. The level of current, stored in the inductor during charging mode, can be controlled via an appropriate duty cycle of S_S.

A freewheel diode, D, which is connected between the switch and the inductor, conducts the current in order to

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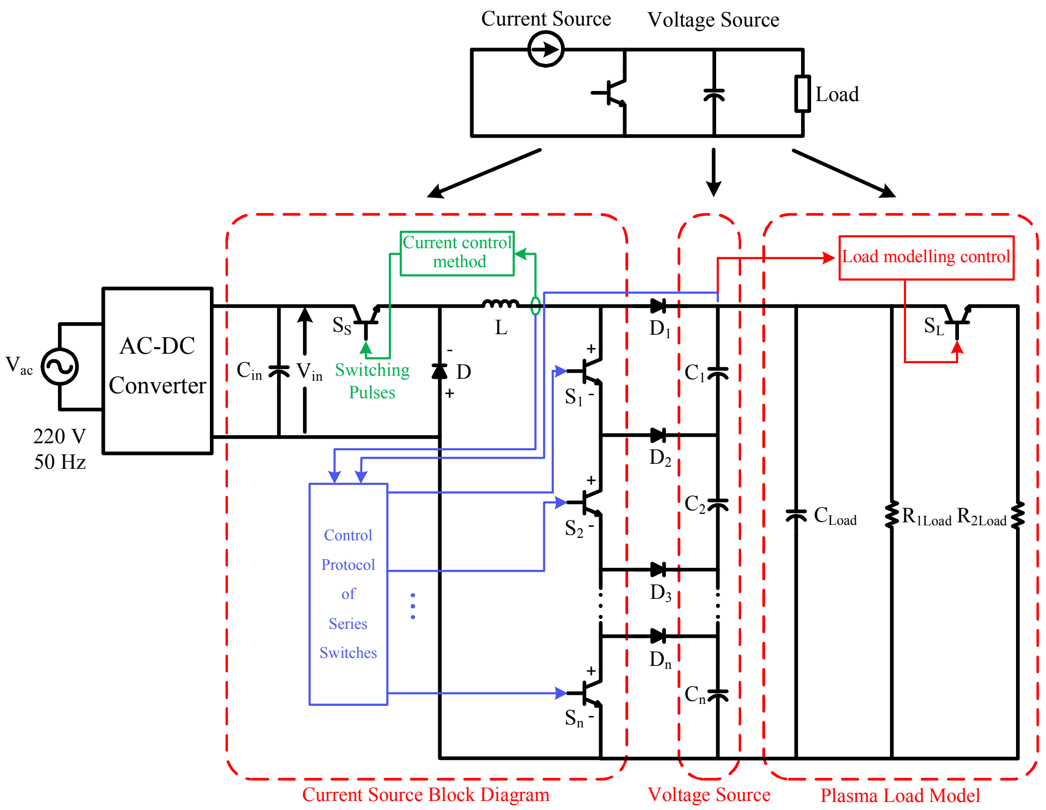


Figure1. Pulsed power supply configuration with multi switch-diode-capacitor units

provide a current loop and keep the current constant, while S_S is switched off. The switches, S_1, S_2…, S_n, are connected to a series of capacitors through diodes which compose switch-diode-capacitor units. These units in a group association act as a combined voltage source and generate desired high voltage at the output. The inductor current flows through the unit's switches while they are on. As soon as the switches are turned off, the inductor current flows to the capacitors through the diode, D_1. The received energy from the current source is stored in the capacitors in the form of voltage.

Most pulsed power applications have resistive and capacitive properties which can be modeled as a sample load with a capacitor, C_{Load}, a switch, S_{Load}, and two resistors, R_{1Load} & R_{2Load} as shown in Fig. 1. The capacitor represents the capacitive specification of the loads and switching between large and small resistors, R_{1Load} & R_{2Load}, simulates the break down phenomena happening while pulsed power applies to the loads.

As shown in Fig. 2, a double unit configuration is investigated in this paper as a simple model. The results can be extended for a multi unit topology.

B. Switching Modes

The operation modes of this topology are separated into two major groups. Switching states depicted in Fig. 3(a) & (b) and Fig. 3(c) & (d) are classified in current source category and voltage source category, respectively.

1) First mode: Charging inductor (S_S: on, S_1: on, S_2: on)

As demonstrated in Fig. 3(a), in this switching state, all the switches, including current source switch, S_S, and units switches, S_1 & S_2, are turned on to increase the inductor current. Therefore the input voltage, V_{in}, appears across the inductor and the charging time can be calculated as follows.

$$V_L = V_{in} - (V_{S_S} + V_{S_1} + V_{S_2}) \tag{1}$$

$$V_L = L(di/dt) = L(\Delta i/\Delta t) \tag{2}$$

If the inductor is supposed to be with no initial current charge, $\Delta i = I_{\max}$ then $\Delta t = (L \cdot I_{\max})/V_L$.

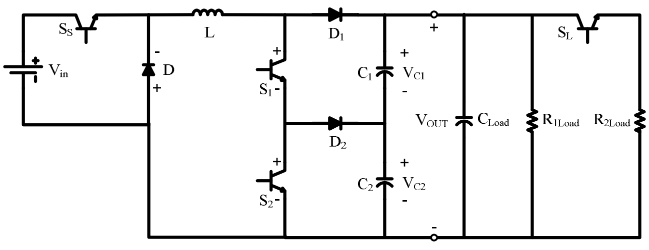
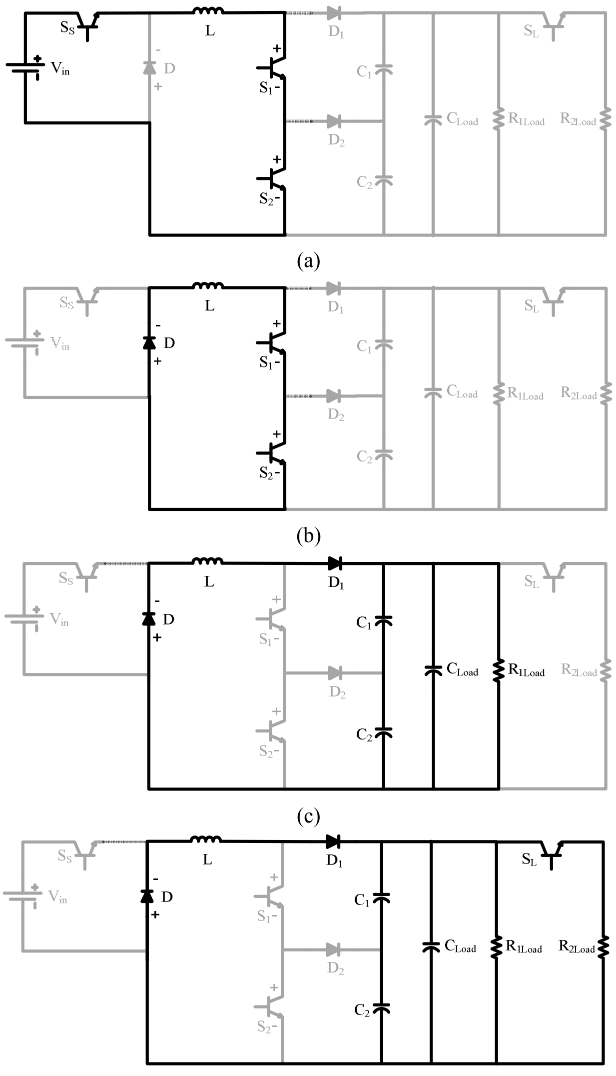


Figure 2. A pulsed power supply with two switch-diode-capacitor units and a non-linear load



(a) (b) (c) (d)

Figure 3. Switching states of the proposed power supply circuit (a) Inductor charging (b) Circulating the inductor current (c) Charging the capacitors (d) Supplying the load

2) Second mode: Circulating the inductor current (S_S: off, S_1: on, S_2: on)

As soon as the inductor current crosses a defined amount, the control system turns off the current source switch, S_S, and disconnects the input voltage source, V_{in}, from the rest of topology. Henceforth, the freewheel diode, D, conducts and lets the inductor current to be circulated through S_1 & S_2. In this mode, which is illustrated in Fig. 3(b), the low voltage drop across the diodes and switches discharges the inductor moderately. As the total voltage across the inductor is not significant, the discharging effect can be neglected and the circulating current is considered to be constant. This switching state keeps the current stored in the inductor and allows the load system to be prepared for the next cycle of energizing.

$$V_L = -(V_D + V_{S_1} + V_{S_2}) \tag{3}$$

3) Third mode: Charging capacitors (S_S: off, S_1: off, S_2: off)

In this switching state, the current source delivers the inductor current to the capacitors and charges them. As exhibited in Fig. 3(c), the unit's switches, S_1 & S_2, are turned off in this mode and the inductor current is pumped into the capacitors and charges them to a certain level defined by the load.

$$(\Delta V_{C_i}/\Delta t) = (I_{C_i}/C_i) \quad \Rightarrow \quad \Delta V_{C_i} = (I_{C_i}/C_i)\cdot \Delta t \tag{4}$$

A plasma phenomenon has been modeled by decreasing the load resistance from R_1 to R_2 through switch S_L which is demonstrated in Fig. 3(d). The required energy is delivered to the load from the voltage and current sources in this mode. The capacitor bank and the inductor are discharged subsequently according to the proportion of energy stored in them. Once the load supplying process is finished, the topology can switch from the supplying mode to the charging inductor mode with no concern.

III. CONTROL STRATEGY

Switches used in this power supply have two different functions. A single switch at the front side of topology, S_S, can charge the inductor at a certain level. A range of switches, S_1 & S_2, at the output of the topology either circulates the current in on state, or conducts it to the capacitors by being switched off. The switch used for modeling the plasma break down phenomena in the load, S_L, is controlled at a certain voltage level. As expected each sort of these switches is functionalized under a specific principle in order to meet assigned duties.

A flowchart shown in Fig. 4 describes the logic of decisions which generate control signals to charge the inductor and the capacitors.

A. Current source control

The first stage is charging the inductor through the front part of the circuit. Assuming the switches S_1, and S_2 are on, therefore the inductor can be charged when the switch S_S is turned on. The controller measures the inductor current and turns off the switch when the inductor current reaches I_{max}. In this case the energy stored in the inductor is $(1/2)L \cdot I_{\max}{}^2$ Whereas, S_S is turned on while the earlier load supplying cycle is finished and the stored energy is delivered to the load in that cycle. This will be detected for the system as soon as output voltage becomes less than a specific level, V_{min}. V_{min} is relevant to the load energy demand and determined by the programmer. The only concern which restricts V_{min} determination is diode's breakdown voltage, V_d.

$$V_{\min} \le V_d \tag{5}$$

To increase V_{min} level, it is possible to connect a number of low voltage diodes in series. In this way the flexibility of stopping load supply in higher voltages will be brought to this configuration as another advantage.

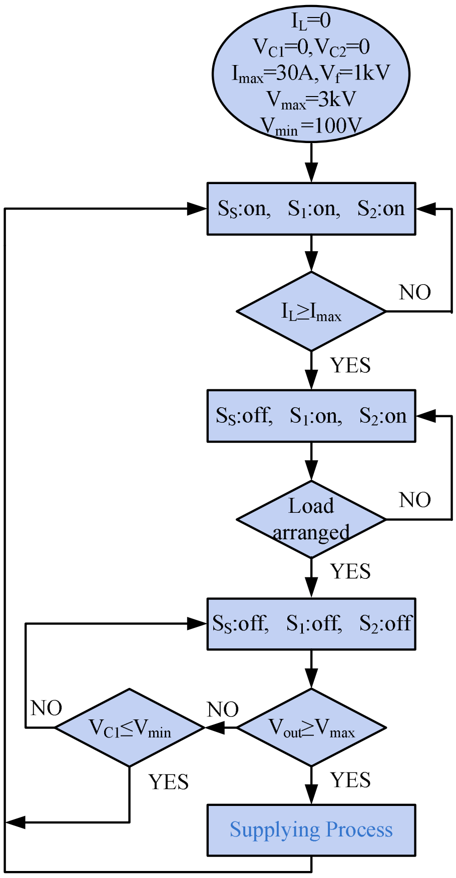


Figure 4. Flowchart of the control algorithm

B. *Voltage source control*

Simultaneous switching of capacitors is considered in this paper to demonstrate the performance and the capabilities of this topology. In this method all unit's switches will be turned off together after the inductor is fully charged. As a result, the inductor current will be pumped into all output capacitors and charges them at the same time. Each capacitor generates a specific dv/dt and voltage level regarding the capacitor amount. Assuming similar capacitors, the eventual voltage level will be shared among all capacitors equally. Pulsed power will be generated and applied to the load which discharges voltage and current sources subsequently. This trend will be repeated for the next pulse supplying cycles. The simulation results of this strategy are displayed in Fig. 6.

C. *Load modeling control*

Load switch, S_L, is turned on when the output voltage reaches to a specific voltage level. Therefore the resistivity of the load suddenly collapse by turning S_L on, in order to simulate a breakdown phenomenon. On the other hand, S_L becomes off while the reaction ends.

The current and voltage waveforms accompanied by switching signal patterns of circuit controlled with this principal are exhibited in Fig. 5.

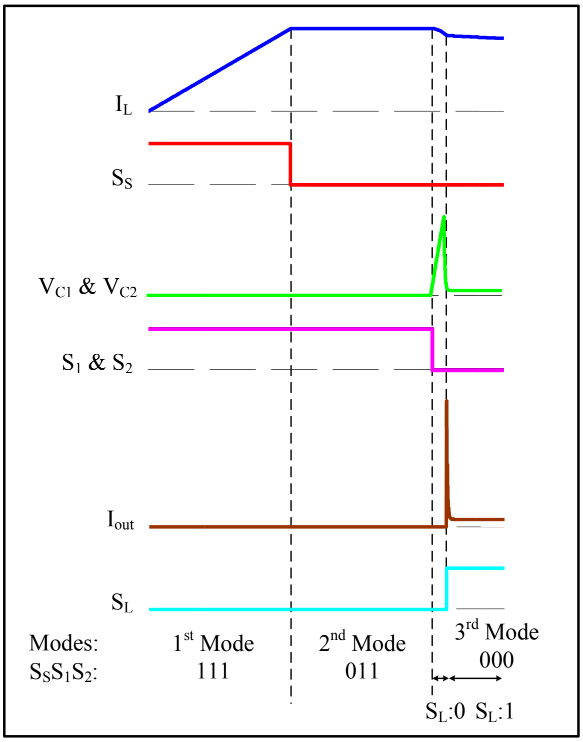


Figure 5. Current and voltage waveforms accompanied by relevant switching signals pattern

IV. SIMULATION RESULTS AND ANALYSES

Several simulations at different conditions have been carried out to verify the validity of the proposed topology performance. The Input voltage level, the components size, the inductor current magnitude and the load breakdown resistivity are the parameters varied in an extensive rang to study the topology performance in different situations. The results presented in this paper belong to a simulation model with specifications addressed in Table I.

TABLE I. SPECIFICATIONS OF THE MODELED CIRCUIT

V_{in}	200V	**C_1**	10nF	**R_{1Load}**	10M Ω	**C_{Load}**	1nF
L	0.6mH	**C_2**	10nF	**R_{2Load}**	10 Ω	**f_S**	2kHz

In this case, the inductor is charged up to 30A and kept charged in this level for a while. Then S_1 and S_2 are switched off simultaneously and let the inductor current to be pumped into the capacitor bank. The inductor energy delivered to the capacitors is exchanged to the voltage form. The generated dv/dt is in proportion with the inductor current level and the equivalent capacitors size. With this respect, output DC link's voltage is charged up to 3kV, while each capacitor generates 1.5kV. This level of voltage accompanied by an appropriate slope, dv/dt, is critical for the modeled load and cause a breakdown phenomena in the load. Thus, load resistivity is markedly dropped and lets the load to consume the stored energy. Consequently, the capacitors are discharged in a considerably short time stint because of a very small time constant.

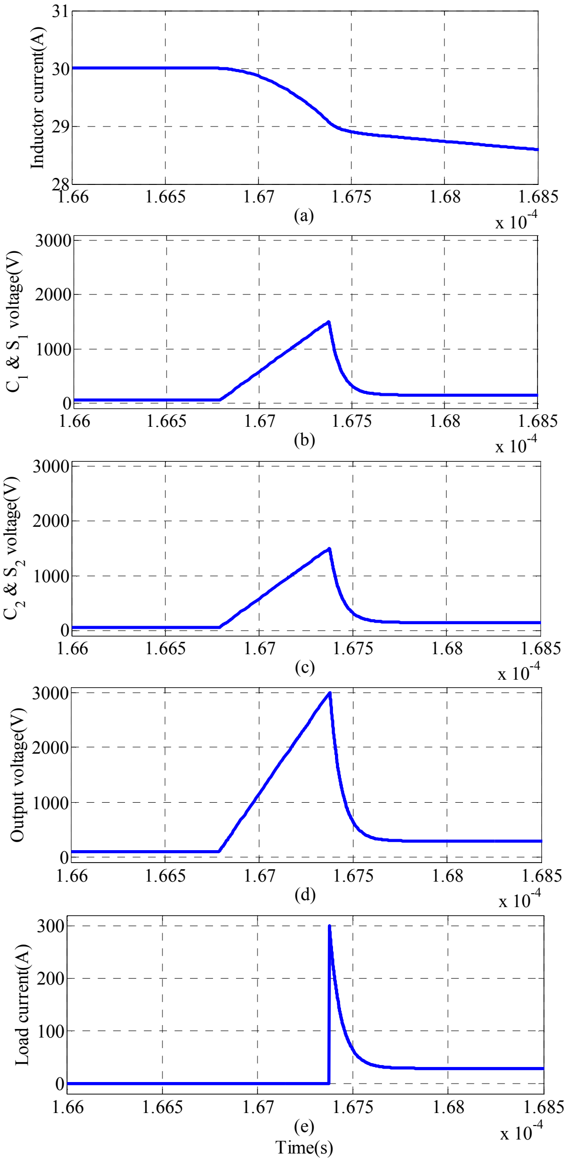


Figure 6. Power supply waveforms, (a) Inductor current (A), (b) C_1 & S_1 voltage (V), (c) C_2 & S_2 voltage (V), (d) Output voltage (V), (e) Load current (A)

$$\tau = R \cdot C \tag{6}$$

The capacitors are not fully discharged because the inductor still supplies the load with the current. This current magnitude times load resistivity creates a voltage across output capacitors during this period. The inductor is discharged afterwards because of a bigger time constant.

$$\tau = L/R \tag{7}$$

The remained voltage at the output also shared equally between two capacitors. This supplying process can be stopped at anytime and this moment is determined by the load demand for energy. The graphs exhibited in Fig. 6 demonstrate the inductor current, the capacitors and the output voltage and the load current for a pulse generation moment respectively.

V. CONCLUSION

This paper presents a current source based topology for pulsed power applications. A range of switch-diode-capacitors connected in series together and in cascade to the current source is responsible for generating high voltage and high dv/dt. The novel contribution in this configuration is hiring low-medium voltage switches to tolerate a high voltage. In addition, this topology has the flexibility of being easily adjusted for a wide range of pulsed power application. Having control over power delivery to the load is another advantage of this power supply, which makes it thoroughly efficient. The proposal topology's true performance is investigated through several simulation models and the acquired results confirm the validity of this model to accomplish all desired duties in an acceptable range.

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