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A NOVEL HIGH VOLTAGE PULSED POWER SUPPLY BASED ON LOW VOLTAGE SWITCH-CAPACITOR UNITS

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Abstract

This paper presents a high voltage pulsed power system based on low voltage switch-capacitor units connected to a current source for several applications such as plasma systems. A buck-boost converter topology is used to utilize the current source and a series of low voltage switch-capacitor units is connected to the current source in order to provide high voltage with high voltage stress (dv/dt) as demanded by loads. This pulsed power converter is flexible in terms of energy control, in that the stored energy in the current source can be adjusted by changing the current magnitude to significantly improve the efficiency of various systems with different requirements. Output voltage magnitude and stress (dv/dt) can be controlled by a proper selection of components and control algorithm to turn on and off switching devices.

1 Introduction

Pulsed power converters became widespread industrially with increasing demands in applications such as ozonising, sterilizing, recycling, exploding, winery, medical and military applications [1,2]. Plasma systems are currently the most substantial application of pulsed power technology [3]. However, there are still specific issues which hinder the wide scale application of these systems. The main issue is power efficiency which can affect long term usage of pulsed power suppliers in industry.

Conventionally, voltage source topologies like Marx generators [4,5] are hired to supply pulsed power systems which are inflexible in controlling voltage levels and power delivery to the load.

Since plasma systems are naturally known as capacitive loads for power supply equipment, current source topologies are suitable candidates in terms of flexibility to supply these sorts of applications and improve efficiency. In respect to this issue, a dc-dc converter based on the buck-boost converters concept is designed to feed these loads. This topology aims to generate high voltage with a series of low-medium voltage switches. The novel idea in this proposal is employing a series of switch-capacitor units in order to provide high DC voltage with high voltage stress, dv/dt, considering plasma loads requirements. The modified version of this converter can generate high DC voltage levels in a few nanoseconds.

2 Topology and analyses

The proposed circuit diagram includes an AC-DC rectifier connected to a buck-boost converter as a current source as shown in Fig.1. An inductor connected to the DC source through a switch S_S acts as a current source. A controller is used to control the current through the inductor which adjusts the energy required by a load. A flywheel diode is used to provide a current loop for the inductor when the switch S_S is turned off. A series of switch-capacitor units connected in cascade to the current source generates high voltage level and stress and completes the topology.

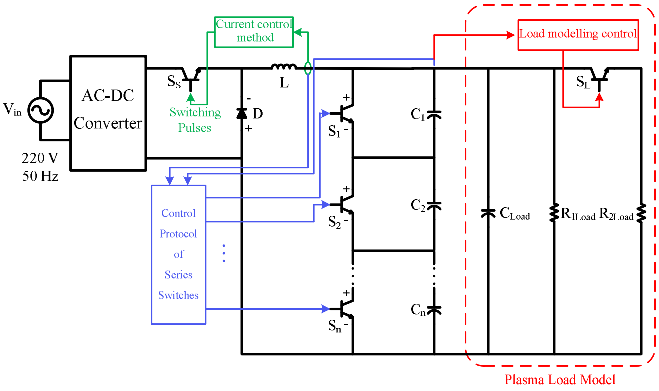

Figure 1: Plasma power supply configuration with multi switch-capacitor units

To analyse the pulsed power converter, we have considered two switch-capacitor units as shown in Fig. 2 and the analysis and simulations can be extended for n switch-capacitor units. There are also more simulations and analyses under different load conditions to verify the proposed topology and control. As the simulation results demonstrate, this power supply has the capability of generating pulsed power in an extensive range of amplitude and dv/dt.

The concept of this circuit is based on delivering the stored energy in the inductive and capacitive components to a load.

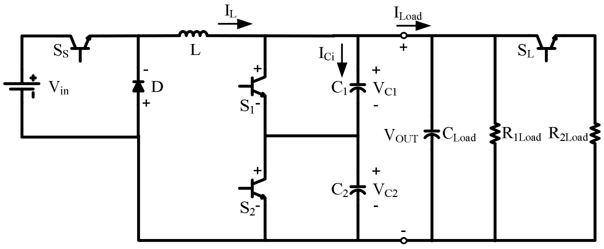

Figure 2: A simplified two switch-capacitor unit plasma power supply and the load model

To satisfy this condition, the inductor current should be pumped into the capacitor bank to charge the capacitors and create high voltage and high dv/dt across the load.

The operation modes of this topology are shown in Fig.3. To control the inductor current, a current control block determines a duty cycle for the switch S_S located between the DC source and the inductor in order to charge the inductor at a specific current level. In this strategy, the desired amount of inductor current is selected as a limit to turn off S_S. The switching state in Fig.3(a) shows the inductor charging mode.

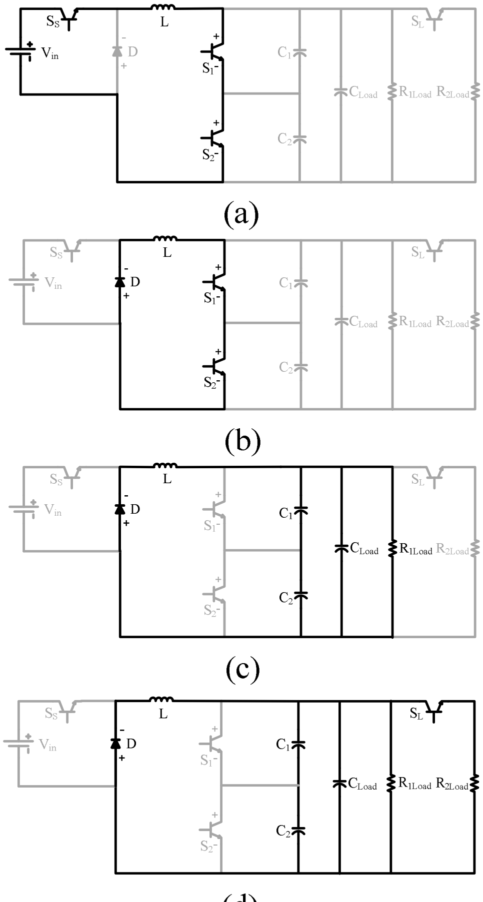

Figure 3: Switching states of the proposed power supply circuit (a)Current source, charging mode (b)Current source, discharging mode (c)Voltage source charging mode (d)Load supplying mode

There are arbitrary numbers of switch-capacitor units connected in series together and the whole unit, in parallel with the current source of the system which charges the capacitors. The number of these units is determined by the required output voltage. Take it into the account that when the inductor is charging through S_S all those switches should be closed otherwise there may be an undesired resonant between the inductor and the capacitors. As soon as the inductor current crosses a defined current limit, indicating the inductor is fully charged, S_S is switched off and the inductor current flows through the diode, D, as shown in Fig.3(b). The forward diode and switches voltages create a small negative voltage across the inductor which slightly discharges the inductor.

In the next switching mode, which is called capacitors charging mode and is shown in Fig.3(c), the switches, $S_1, \ldots, S_n$ get opened simultaneously to allow the inductor current to flow through the capacitors and charge them. This can create a high voltage across the capacitors particularly while the capacitors are selected in nanofarad ranges.

$$\frac{dV_{C_i}}{dt} = \frac{I_{C_i}}{C_i} \tag{1}$$

Since the capacitors are identical and the same current flows through all capacitors, there will be a similar voltage across each capacitor. Therefore, the summation of these voltages appears at the output of power supply.

$$V_{out} = n \cdot V_{C_i} \tag{2}$$

$$dV_{out} = n \cdot dV_{C_i} \tag{3}$$

Where n is the number of switch-capacitor units which can be extended to satisfy load demands. Having more units reduces the equivalent capacitance of capacitor bank in the output of the topology and with a fixed injected current there will be a higher voltage level and stress in the output of power supply.

$$C_{eq} = \frac{C_i}{n} \tag{4}$$

Based on heating and switching characteristics of the power switches in terms of internal resistivity of conducting and non-conducting modes, both sides of each capacitor are connected to the sides of each switch in order to provide voltage sharing over the switches.

Plasma reaction is resumed in respect to the stimulation of a high voltage over related material. But the key point is that, this high voltage should be induced with an extremely high voltage stress, dv/dt. Pumping stored current into the series of capacitors which have considerably low capacitances can fulfil the high voltage level and stress of the plasma creation requirements.

Plasma applications are known as nonlinear resistive-capacitive loads. To simulate plasma behaviour for the pulsed power supply, a simple resistive-capacitive model with a switch has been chosen to show a high and low resistivity of load R_{1Load} & R_{2Load}, in different physical situations. R_{1Load} , in Mega Ohms range represents the load resistivity before a resumption of plasma reaction in order to model the load's leakage current. R_{2Load} in the range of a few ohms represents the load resistivity in the period of plasma reaction. This load model is highlighted in Fig. 1 and Fig. 3(d). In a real condition, the resistivity of load substantially drops and based on the proposed model, the load current is supplied by the voltage and current sources.

It should be noted that the capacitors should get fully discharged to avoid probable short circuits in the switch-capacitor units and resonant between the inductor and the capacitor bank. Based on this control algorithm, series switches should be opened when the load is ready and closed when the capacitors are fully discharged. Even when capacitors get fully discharged the flowing current to the load creates a voltage over capacitors which may cause a short circuit at the time of closing unit switches. There are several ways to either prevent or damp this phenomenon such as putting either reverse blocking components, extra inductive or other damping elements in the short circuit loop.

Since there is a possibility of not delivering the whole capacitor's energy to the load, and unit switches closing for current recovery, there should be an appropriate number of damper components like resistors or inductors, located in the switch-capacitor units to prevent the probable rush currents which is due to making charged capacitors short circuit by closing units switches.

3 Simulation results

According to the above equations, it can be deduced that a higher current can generate a higher dv/dt across the capacitors. Fig. 4 illustrates the results extracted from the simulation of the circuit operating in the mode shown in Fig.3(c). In this figure, the voltage and current stresses of circuit with two different inductors (L_1 & L_2) and current levels (I_{L1} & I_{L2}) are depicted.

To have a same stored energy in the both inductors, for $L_2 = n \cdot L_1$, the inductor current should be adjusted as:

$$I_{L2} = \frac{1}{\sqrt{n}} \cdot I_{L1} \tag{5}$$

Since,

$$\frac{1}{2}L_1 \cdot {I_{L1}}^2 = \frac{1}{2}L_2 \cdot {I_{L2}}^2 \tag{6}$$

In this example L_1 and L_2 are 1 & 9 mH, respectively and consequently $I_{L2} = 3I_{L1}$ in order to have the same energy stored in the inductors, L_1 and L_2. As it can be seen in Fig. 4(a) & (c), the inductors currents are controlled at 45 A and 15 A for I_{L1} and I_{L2}, respectively.

Ultimately, the voltage level of the capacitor is based on the stored energy in the inductor.

$$V_{out} = \sqrt{\frac{L}{C_{eq}}} \cdot I_L \tag{7}$$

There are same stored energies in the inductors for both cases. Therefore, the final values of the voltages are similar and reach the level of 18kV. However, dv/dts vary regarding the inductors current levels. In the first case, the inductor current is set to 45 A which creates a 4.5 V/ns voltage stress across the capacitors while in the second case, the inductor current (15A) causes the output voltage to rise with 1.5V/ns slope.

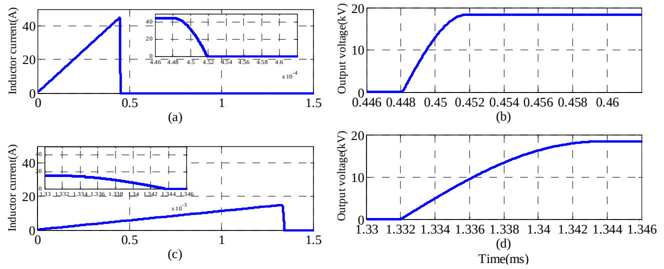

Figure 4: dv/dt s generated by different inductors with the similar inductive energy, (a) current of 1mH inductor (b) output voltage of 1mH inductor, (c) current of 9mH inductor, (d) output voltage of 9mH inductor.

To show how this power supply circuit works, and verify the validity and accuracy of foreseen circuit analyses which comes latter, a 10 Ω load is assumed as a resistivity of the load in the plasma reaction period and results are presented for the power supply feeding two loads with different demanded energies. . In the first mode, the load necessitates high amounts of stored energy so the power supply delivers most of the stored energies in the inductor and the capacitors to the load in one inductor discharging cycle.

The relevant simulation results are displayed in Fig.6. In the second mode, which may happen in some cases, the load demand for the energy is less and the power supply can deliver the stored energy in the inductor to the load several times through each inductor discharging cycle. These results are also shown in Fig. 6.

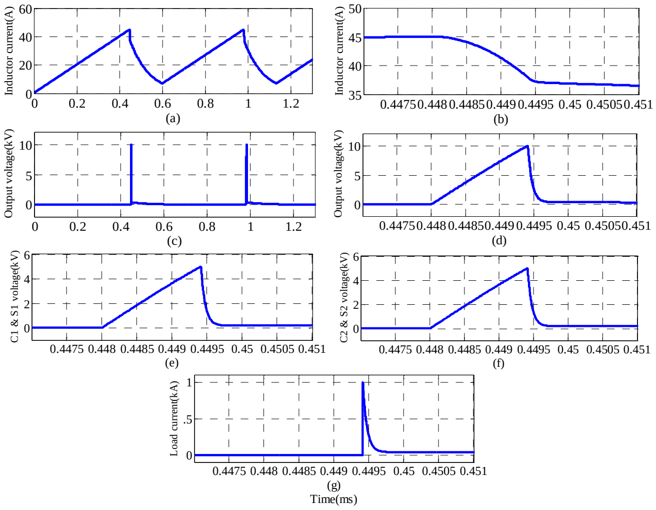

Figure 5: Output voltages and currents of power supply, in case of delivering inductive energy to the load in mono resonant, (a) & (b) Inductor current (A), (c) & (d) Output voltage (kV), (e) C_1& S_1 voltage (kV), (f) C_2 & S_2 voltage (kV), (V), (g) Load current (kA)

As can be seen in Fig.6 (c) & (d), the plasma resumes at 10kV voltage while each capacitor provides half of this voltage level shown in Fig.6 (e) & (f). At the plasma reaction period, the load discharges capacitors firstly and then the inductor energy will be delivered to the load with a bigger time constant. The load voltage created by inductor current which is remained voltage across capacitors after discharging is balanced identically. These results remove all concerns in regard of capacitor's voltage sharing issues. In the second example which may happens in some cases while the stored energy in inductor is more than requested energy by a load, each plasma reaction just will be fed by stored energy in capacitors and inductor current supplies several reaction in each discharging cycle. Hence this power supply has the capability of supplying loads with less energy demands.

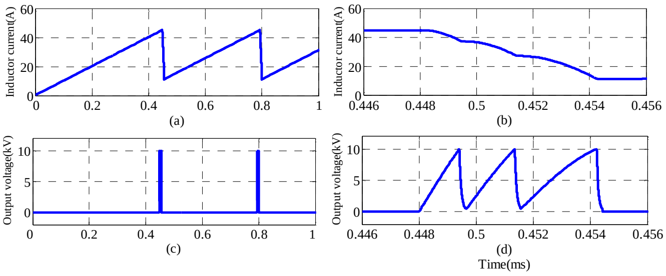

Figure 6: Output voltages and currents of power supply, in case of delivering inductive energy to the load in multi resonant, (a) & (b) Inductor current (A), (c) & (d) Output voltage (kV)

The results shown in Fig. 4 can also be beneficial for the analyses of power supply operation in the case of a lack of plasma reaction and energy delivering. As anticipated, the inductor energy will be entirely delivered to the capacitor bank and charge it. If this energy is not depleted the system will face a major trouble. For example, when the series switches get closed while there is a 20kV voltage across them. In this status, an external load should be connected to the power supply to discharge the stored energy.

4 Components determination and energy discussion

Efficiency is the main concern when designing a power supply for plasma applications. In this topology having least energy losses is considered in addition to the flexibility of the equipment which needs to be adjusted for a diversity of pulsed power applications. The inductive and capacitive components (L & C_i), should be selected appropriately in order to both satisfy load requirements and avoid energy wasting. As the output voltage level and stress and delivered energy are defined by load, the elements sizes can be determined with regard to those parameters.

The output equivalent capacitor, C_{eq}, should be at least ten times of the load capacitance to prevent any loading problem. On the other hand the equivalent capacitance needs to be as small as possible to generate voltage stress and level demanded by the load.

$$C_{eq} = 10C_{Load} \tag{8}$$

If the capacitors, C_i, are supposed identical:

$$C_i = 10n \cdot C_{Load} \tag{9}$$

n is determined by the switches voltage stability and demanded output voltage.

Assigning the correct value to the inductor current is the next step which can create the anticipated dv/dt, for the load.

$$I_L = (C_{eq} + C_{Load})\frac{dV_{out}}{dt} \tag{10}$$

In the last stage, the demanded energy stored in the inductor defines the inductance value.

$$\frac{1}{2}LI_L{}^2 = E_{Load} \tag{11}$$

Finally, the recovery time for inductive and capacitive components and the frequency of pulsed power generated by the power supply can be determined as follows:

$$T_{r\_L} = \frac{L \cdot I_L}{V_{in}} \tag{12}$$

$$T_{r\_C} = \frac{(C_{eq}+C_{Load}) \cdot V_{out}}{I_L} \tag{13}$$

$$T_{r\_LC} = \frac{L \cdot I_L{}^2 + (C_{eq}+C_{Load}) \cdot V_{out} \cdot V_{in}}{V_{in} \cdot I_L} \tag{14}$$

The frequency of load supply with pulsed power relies significantly on the load features and requirements but cannot be more than the recovery frequency of the power supply.

$$f_{s\_max} < f_{r\_LC} \tag{15}$$

The inductor current in a load supplying cycle is shown in Fig. 7 with detailed time periods.

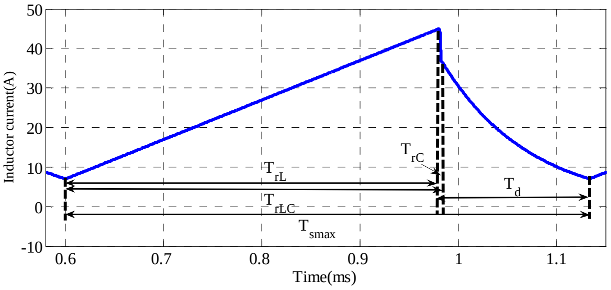

Figure 7: Times monitoring in a load supplying cycle

Regarding above determinations, a model has been designed in Matlab/SIMULINK environment to analyse the performance of the proposed circuit. The detailed specifications of circuit are available in Table I.

V_{in}	200V	R_{D_i}	1Ω	R_{1Load}	1nF	C_{Load}	10Ω
L	1mH	C_i	10nF	R_{2Load}	10MΩ	f_s	2kHz

Table I: Specifications of the modelled circuit

These results indicate how the topology decreases the energy losses and improves power efficiency. In the first strategy, the current source and the units switches, S_S & $S_1, \ldots, S_n$, get closed when the inductor still delivers 10 A to the load. This means 100 volt still exists across the 10Ω load which is named as $V_{off-out}$. Closing switches results in discharging output capacitors through unit loops and loses energy. This energy loss for a delivery cycle can be estimated as:

$$E_{Loss} = \frac{1}{2}C_{eq}V_{off-out}{}^2 = 0.5 \times 6 \times 10^{-9} \times 100^2 = 30\mu j$$

While the total stored energy in the inductor is:

$$E_{Total} = \frac{1}{2}LI_L{}^2 = 0.5 \times 1 \times 10^{-3} \times 45^2 = 1012.5mj$$

Regarding the calculation and analyses, in this strategy for example, the energy losses are almost less than 0.003% of the total stored energy in the inductor. This loss is negligible in comparison with the delivered energy to the load so, the efficiency could be considered more than 99.997%.

5 Conclusions

This paper proposed a new topology based on switch-capacitor units in series to generate high voltage level and stress for pulsed power applications. The general concept of this pulsed power supply is based on a current source topology connected to a series of low-medium voltage switch-capacitor units which considerably improves the efficiency of plasma systems. Simulations have been carried out to validate the proposed topology and control. The simulation results show that there is no restrict for the generation of higher voltage levels and stresses by increasing the number of the switch-capacitor units.

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