A novel CDVM based high-voltage converter using low power solid-state switches and a tuned resonant circuit designed for pulsed power applications

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***Abstract*—A novel concept of producing high dc voltage for pulsed-power applications is proposed in this paper. The topology consists of an LC resonant circuit supplied through a tuned alternating waveform that is produced by an inverter. The control scheme is based on the detection of variations in the resonant frequency and adjustment of the switching signal patterns for the inverter to produce a square waveform with exactly the same frequencies. Therefore the capacitor voltage oscillates divergently with an increasing amplitude. A simple one-stage capacitor-diode voltage multiplier (CDVM) connected to the resonant capacitor then rectifies the alternating voltage and gives a dc level equal to twice the input voltage amplitude. The produced high voltage appears then in the form of high-voltage pulses across the load. A basic model is simulated by Simulink platform of MATLAB and the results are included in the paper.**

Keywords-Capacitor-diode voltage multiplier; High voltage power supply; LC Resonant Circuit; Pulsed Power; Tune

I. INTRODUCTION

Pulsed power is extensively utilized in a diverse range of applications these days. Due to this fast growing demand for pulsed power in industrial and environmental applications, the exigency for a more efficient and flexible pulse modulator is now receiving greater consideration. To date, different topologies and accumulation techniques have been considered to produce high voltage pulses with a high dv/dt. Marx Generators (MG) [1], Magnetic Pulse Compressors (MPC) [2], Pulse Forming Networks (PFN) [3], and Multistage Blumlein Lines (MBL) [4], each using a specific technique, are among those that are still favorable and being utilized for pulsed power applications. In the other cases, a high voltage dc modulator connected in series to a gas based switching device is also used for these purposes. The entire idea is as given in Fig. 1. Most proposals for high voltage supply to date have been based on either charging several energy storing components or using ac transformers [5, 6]. These methods however associated with inevitable drawbacks such as high initial cost, operation losses, and weight in addition to bulkiness and lack of efficiency.

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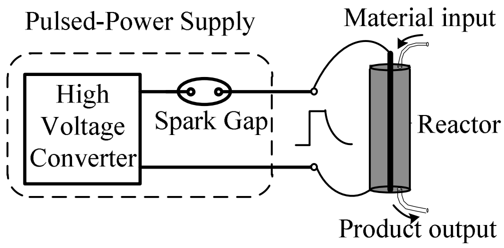

Figure 1. A pulsed-power supply scheme composed of a high voltage converter and a gas based switching module

Gas/Magnetic switching technologies (such as spark gap and hydrogen thyratron) have conventionally been used as switching devices in pulse modulator structures because of their high voltage ratings and considerably low rising times. However, they also suffer from serious drawbacks such as, low efficiency, reliability and repetition rate, and also short life span. Recently developed solid-state switching technology is an appropriate substitution for these switching devices due to the benefits they bring to the pulse supplies. Besides being compact, efficient, reasonable and reliable, and having a long life span, their high frequency switching skill allows repetitive operation of pulsed power supply. The main concerns in using solid-state transistors are the voltage rating and the rising time of available switches that, in some cases, cannot satisfy the application's requirements. However, there are several power electronics configurations and techniques that make solid-state utilization feasible for high voltage pulse generation [7, 8].

The proposed converter in this paper attempts to produce a dc high voltage level through low-power solid-state switching devices. To fulfill such an appeal, an LC resonant circuit is designated to be supplied by an H-bridge inverter comprised of four low-voltage Insulated Gate Bipolar Transistors (IGBT). The inverter switches are triggered in such a way that produces a voltage waveform with a frequency locked on the resonant frequency of the LC circuit. A simple one-stage Cockcroft-Walton CDVM circuit is also connected in cascade to the capacitor in the LC circuit in order to escalate the amplitude of voltage oscillation and to rectify the oscillating voltage to a dc

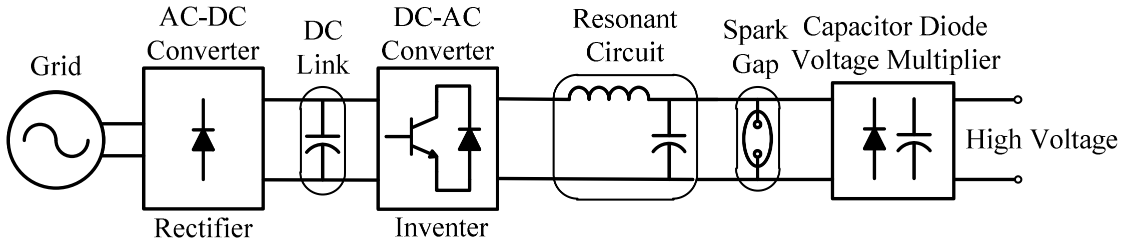

Figure 2. A block diagram of proposed high voltage converter

voltage level at the output of the converter. A lossy component is also connected to two sides of the capacitor of the LC circuit through a spark gap for protection purposes. A general block diagram of the proposed converter is given in Fig. 2.

LC circuits are considered in resonant converters due to their inherent characteristic in reducing switching losses. Zero Crossing switching (ZCS) is a technique adopted in the inverters triggering process to minimize the switching losses. Triggering a device while either the voltage across or the current through it is zero keeps the switching losses at a minimum level. In addition to that, the resonant phenomenon in an LC circuit is also utilized in many high power applications including novel Marx topologies [9-12], high frequency distribution systems, dimmable electronic ballasts, and X-ray generation. However, induction-cooking appliances are the most widespread area in which the LC resonant circuits are utilized in high power applications.

Although a few former research studies have already considered the adjustment of frequencies in an LC circuit with a number of methods, tuning the supply frequency to the LC oscillation frequency and application of this in high voltage generation, have never been addressed in previous reports. The most significant contribution of this proposal is to utilize the zero impedance of an LC circuit, while being supplied through a tuned input waveform. According to this feature, increasing voltage amplitudes are anticipated to be achieved during the oscillations.

On the other hand, different CDVM arrangements are being used in microelectronics related configuration specifically in space applications. Being efficient, reliable and small in both size and weight are some of their advantages, however their capability in supplying a continuous dc level for high power applications has been criticized. Long transient time in their responses is another disadvantage of these circuits. It is also reported that CDVM configurations have already been utilized in high voltage applications [13].

II. Analysing the LC Resonant Circuit

A. An LC Circuit Supplied with a dc Voltage

As well known, resonance is the inherent behavior of inductive and capacitive components while connected to a dc electrical source, Fig. 3(a). There can be damping elements included in the resonant circuit. In such an LC circuit, the energy is exchanged between the source and the circuit in each half a cycle. A definite amount of energy is delivered to both the capacitor and the inductor in the first quarter of a resonant cycle.

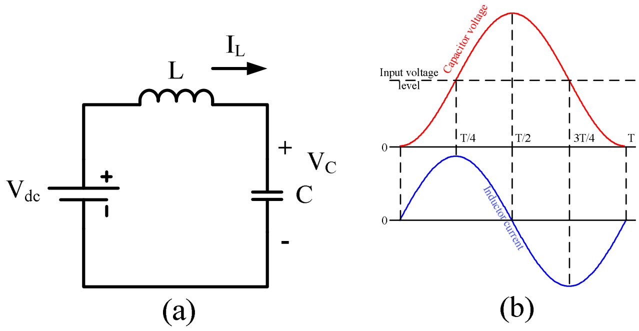

Figure 3. An LC resonant circuit with a dc supply, (b) Capacitor voltage and inductor current waveforms in the LC resonant circuit with a dc supply

The energy will then be exchanged between the inductor and the capacitor in the rest of the cycle. The capacitor voltage oscillates between twice the input voltage and zero levels, whereas the inductor current is a sinusoidal waveform with an average of zero Fig. 3(b). Both oscillations have similar frequency of (1).

$$f_r = \frac{1}{2\pi\sqrt{L \cdot C}} \tag{1}$$

B. An RLC Circuit Supplied with a Sinusoidal Voltage waveform

In case of an alternating sinusoidal input source, an LC circuit normally has the function of a filter; however there is always a resonant phenomenon with a similar frequency as (1) between the inductive and the capacitive components of the circuit. In this scenario, resonance is a condition in a series RLC circuit in which the capacitive and the inductive reactances are equal in magnitude. Therefore the equivalent impedance of the circuit has no imaginary part and is purely resistive.

$$X_L = X_C \quad \Rightarrow \quad \omega \cdot L = \frac{1}{\omega \cdot C} \tag{2}$$

In an RLC series circuit (as shown in Fig. 4) in which the inductor has relatively low internal resistance, it is possible to have a large voltage across the inductor, and an almost equally large voltage across the capacitor. Though, as the two are nearly 180° degrees out of phase, their voltages almost cancel, giving a total series voltage that is equivalent to the input voltage and quite smaller than individual voltages across the

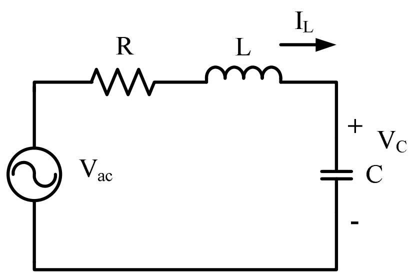

Figure 4. An RCL circuit with a sinusoidal input waveform

inductor L and the capacitor C. In order to get a high voltage oscillation across the capacitor, it is essential to tune the input supply frequency into the resonant frequency; otherwise the boost of voltage magnitude does not occur. This is one way to produce a large voltage oscillation with only a small voltage source. A considerable voltage can be achieved in this circuit for only a small voltage input from the power source. The energy stored in the large oscillations is gradually supplied by the ac source, and it is then exchanged between the capacitor and the inductor in each cycle.

C. An LC Circuit Supplied with a Squar Waveform Voltage

The circumstances for an RLC circuit with a square waveform input supply are quite similar to the one supplied by a sinusoidal waveform. In case of a tuned voltage supply, the capacitor voltage and the inductor current oscillate in such a way that the magnitudes of both are increased gradually. The resonance in a tuned mode results in divergent sort of oscillations of the voltage and the current. As can be seen in Fig. 6, the magnitudes of both are increased along with repetition of alternating voltage levels at the input. As given in Fig 5, the circuit supplied by a square waveform input has two modes; positive and negative half a cycles of supply. Fig. 6 also has a snap that highlights the first five cycles of the input voltage and circuit responses.

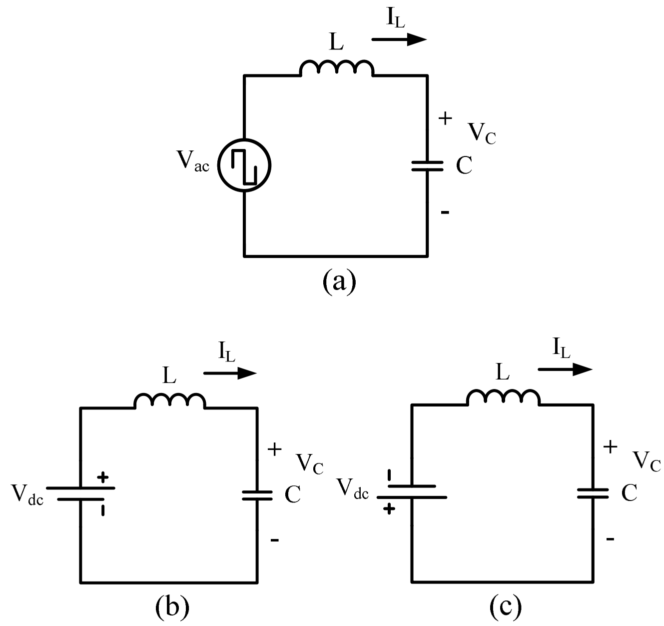

Figure 5. (a)A resonant LC circuit with square waveform supply, (b,c)Two modes of supply

As shown, the input voltage starts with a positive level that charges both the inductor and the capacitor until the voltage across the capacitor gets to the input voltage level. Then, the charging process from the source is stopped due to zero voltage difference across the inductor; however the capacitor still keeps charging due to the inductor current flow. Therefore the energy stored in the inductor is delivered to the capacitor and the capacitor is charged up to twice the input voltage whereas the inductor is out of charge and the current is zero. The resonance occurs in this mode based on (3) and (4). The ultimate voltage and current levels at the end of this mode (V_1 and I_1 at t_1, as given by (5) and (6)) are supposed as the initial values of the circuit for the next half a cycle.

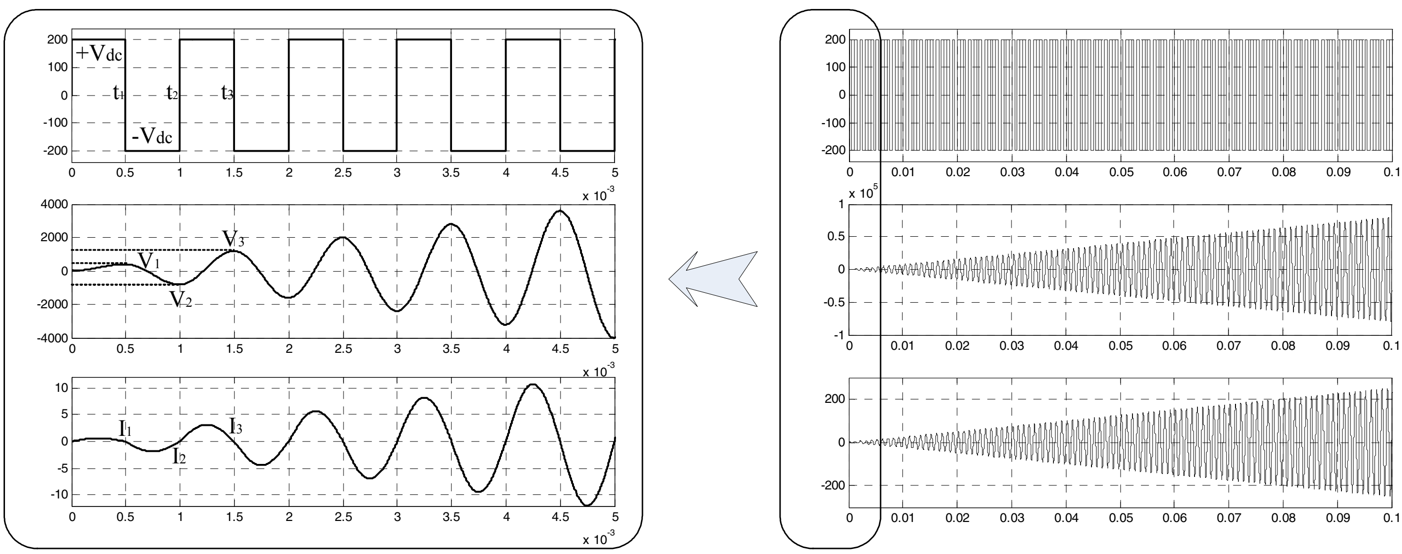

Figure 6. Both the capacitor voltage and the inductor current in an LC circuit supplied by a tuned input square waveform oscillate divergently

$$V_C(t) = V_{dc}(1-\cos\frac{t}{\sqrt{L\cdot C}}) \quad (3)$$

$$I_L(t) = \sqrt{\frac{C}{L}}\cdot V_{dc}\cdot(\sin\frac{t}{\sqrt{L\cdot C}}) \quad (4)$$

$$V_C(t_1) = V_{dc}(1-\cos\frac{t_1}{\sqrt{L\cdot C}}) = V_1 \qquad (t=t_1) \quad (5)$$

$$I_L(t_1) = V_{dc}\cdot\sqrt{\frac{C}{L}}\cdot\sin\frac{t_1}{\sqrt{L\cdot C}} = I_1 \qquad (t=t_1) \quad (6)$$

In the next half a cycle, when the input voltage is inversed and a negative voltage is applied to the LC circuit (Fig. 5(c)), the resultant of voltage across the inductor is the aggregation of the capacitor and the input voltages. That means a larger absolute voltage rather than the one in a continuous dc input supply, locates across the inductor and charges it to a higher level of current. Once the capacitor voltage becomes equivalent to the input voltage level, the energy flow from the source is ceased. At this stage the inductor is charged with an absolute current level higher than the level, it was charged in the first half a cycle. As a result, this current keeps circulating through the capacitor and charges it with a higher absolute voltage magnitude in comparison with the previous mode. This can be verified by considering the voltage and the current equations in this mode given in (7) and (8). The voltage and the current at the end of second half a cycle (V_2 and I_2 at t_2 as given by (9) and (10)) are the initial values of the next mode in which the input voltage gets back to the positive level (Fig. 5(b)). As described, the absolute value of voltage magnitude at the end of second mode is bigger than the one at the end of first mode.

$$V_C(t) = (V_1+V_{dc})\cdot\cos\frac{t}{\sqrt{L\cdot C}} + (I_1\cdot\sqrt{\frac{L}{C}})\cdot\sin\frac{t}{\sqrt{L\cdot C}} - V_{dc} \quad (7)$$

$$I_L(t) = -(V_1+V_{dc})\cdot\sqrt{\frac{C}{L}}\cdot\sin\frac{t}{\sqrt{L\cdot C}} + I_1\cdot\cos\frac{t}{\sqrt{L\cdot C}} \quad (8)$$

$$\begin{aligned} V_C(t_2) &= (V_1+V_{dc})\cdot\cos\frac{t_2}{\sqrt{L\cdot C}} \\ &+ (I_1\cdot\sqrt{\frac{L}{C}})\cdot\sin\frac{t_2}{\sqrt{L\cdot C}} - V_{dc} = V_2 \qquad (t=t_2) \end{aligned} \quad (9)$$

$$\begin{aligned} I_L(t_2) &= -(V_1+V_{dc})\cdot\sqrt{\frac{C}{L}}\cdot\sin\frac{t_2}{\sqrt{L\cdot C}} \\ &+ I_1\cdot\cos\frac{t_2}{\sqrt{L\cdot C}} = I_2 \qquad (t=t_2) \end{aligned} \quad (10)$$

The voltage and the current variations in the third mode are according to equations given by (11) and (12). The voltage located across inductor at the beginning of this mode is the summation of the input voltage and the voltage across the capacitor which is accordingly larger than the one which used to be at previous mode. That is why the inductor gets more charge rather than earlier modes and consequently charges the capacitor with more energy.

$$V_C(t) = (V_2-V_{dc})\cdot\cos\frac{t}{\sqrt{L\cdot C}} + (I_2\cdot\sqrt{\frac{L}{C}})\cdot\sin\frac{t}{\sqrt{L\cdot C}} + V_{dc} \quad (11)$$

$$I_L(t) = -(V_2-V_{dc})\cdot\sqrt{\frac{C}{L}}\cdot\sin\frac{t}{\sqrt{L\cdot C}} + I_2\cdot\cos\frac{t}{\sqrt{L\cdot C}} \quad (12)$$

D. The LC Circuit Response in Presence of a Damping Component and in Case of Inappropriate Tuning

The upward trend is kept going for both the voltage and the current in this circuit, unless a consuming component would be added to the circuit. In this case a transient mode will be followed by a steady state as shown in Fig. 7(a). The growing trends of voltage and current in the transient mode will be settled due to a restriction imposed by the resistance. That is how the growth of the voltage and the current can be controlled; however existence of a lossy component is undesirable in power supply topologies. On the other hand, if the input frequency is not tuned into the resonant frequency the voltage and the current amplitudes will be modulated which is not also desirable in this case. The divergence trend of the voltage oscillations in an LC circuit supplied through a tuned alternating input supply is an inherent feature of this combination utilized in this proposal to achieve a high voltage modulator for pulsed power purposes.

III. Rectifying Oscillations through a Voltage Multiplier

The high voltage oscillations across the capacitor has already been used for a number of applications such as X-ray beams generation, heating stoves and blasts; however it is not suitable in its current form for the applications appealing high voltage stress in addition to a high voltage level. In order to impose such a high voltage with an appropriate dv/dt across the load, a high voltage modulator can produce desired voltage level. This voltage can then be applied to the load through a spark gap switch that provides associated voltage stress for a prosperous reaction process.

There are a number of solutions to convert the high voltage sinusoidal waveform to a voltage with mono-polarity variation. One is using a full-bridge diode rectifier to rectify the alternating waveform and take advantage of rectified sinusoidal high voltage oscillations; however the descending trend of voltage in each half a cycle does not occur as expected at the rectifier output due to lack of a consuming load connected to the rectifier. Consequently the output capacitor gets a step charge in each half a cycle.

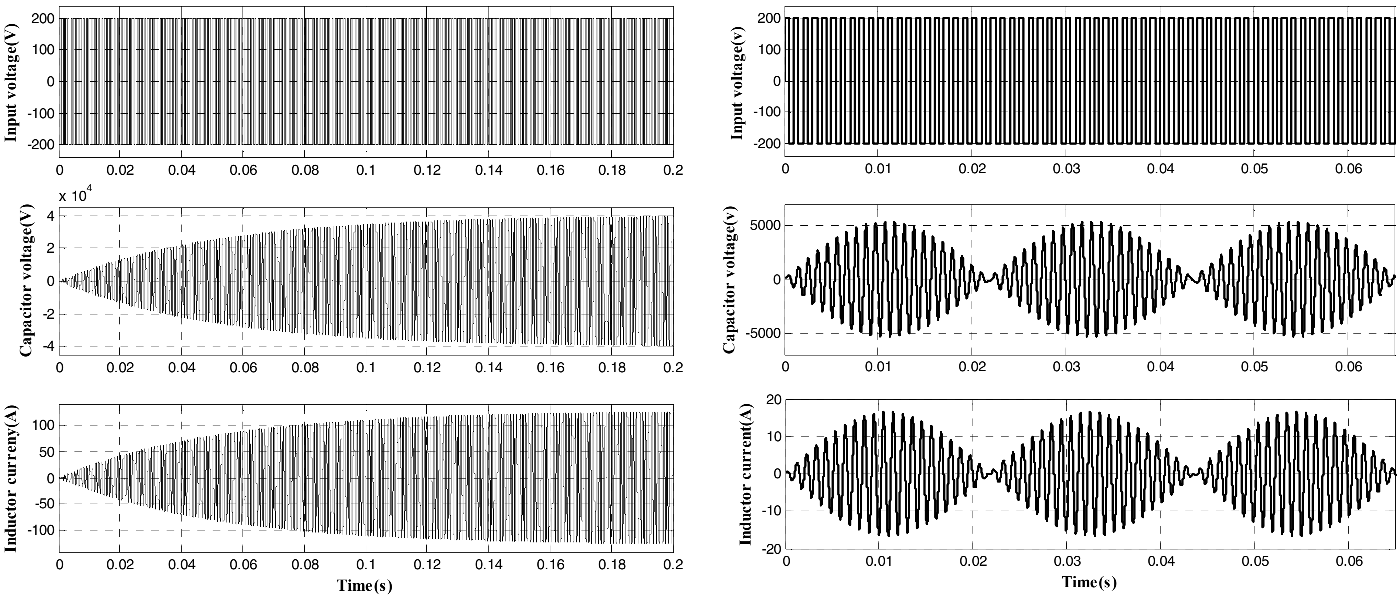

Figure 7. (a) The voltage and the current oscillations tend to the steady states by connecting a damping component into the LC circuit. (b) The oscillations amplitudes are modulated in case the input frequency is not identical to the resonant frequency.

Considering the fact that discharging both capacitors energy by the load instead of the resonant inductor in each pulse supply cycle, resets the resonant process, it does not seem to be an appropriate solution for this purpose. In this case, the amplitude of resonating voltage cannot be kept at its high level and there will be an interrupt in high voltage supply. Due to the transient period of the LC circuit, it takes a few half a cycles of resonance for the output voltage to get back to its former level. As a result, the pulse supply frequency is not as demanded by the applications.

As another solution, replacement of the rectifier by a voltage multiplier can be considered. A capacitor-diode voltage multiplier operating with an alternating input supply can exploit benefits of high voltage oscillation in an LC tuned resonant circuit. In addition to multiplying the rectified oscillation amplitude, it can provide a safety margin for the LC resonating energy, eliminate the transient period between pulse cycles and increase the frequency of produced pulses.

Different arrangements have been developed for capacitor-diode voltage multipliers to date. A simple one-stage Cockcroft-Walton multiplier shown in Fig. 8 is used in this structure that is capable of producing a dc voltage level equal to twice the input voltage magnitude. Since the converter produces high voltage dc levels at its output, it is necessary to have diode stacks including few series-connected diodes as the blocking components in the CDVM structure in order to properly accomplish the insulation functions. Thereby, the high voltage located across each stack will be shared by the diodes and each diode will withstand an equal share of voltage.

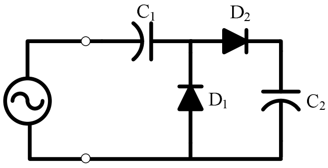

Figure 8. A one-stage Cockcroft-Walton capacitor-diode voltage multiplier

IV. CONTROL STRATEGY AND DESIGN SPECIFICATIONS

As shown in Fig. 9, the equivalent circuit of the multiplier varies with respect to forward and reverse bias modes of diodes D_1 and D_2. Considering spark gap connection modes, a load that normally has a variable characteristic is connected to this equivalent circuit when D_1 and D_2 are reverse and forward biased respectively (Fig. 9(b)). The variation of CDVM equivalent circuit due to variable operation modes has influence on the resonant frequency of the LC circuit. Since the CDVM is connected in cascade with the capacitor of the LC circuit, such a variation in its equivalent characteristics can change the equivalent capacitive characteristic of the capacitor in the LC circuit.

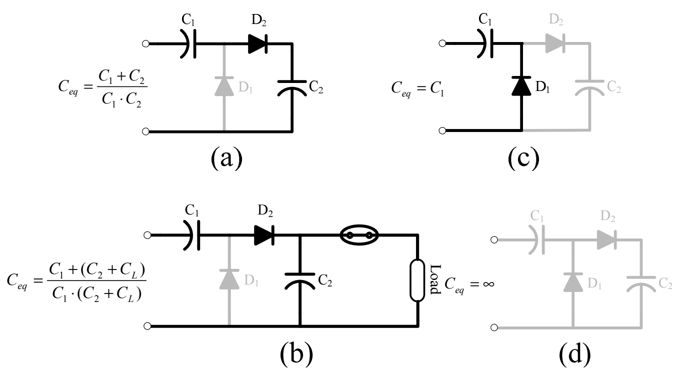

Figure 9. Different states of CDVM circuit due to the forward and the reverse bias modes of diodes, D_1 and D_2 (a) D_1: off and D_2: on, (b) D_1: off, D_2: on, and the spark gap conducts (c) D_1: on and D_2: off, (d) D_1: off and D_2: off.

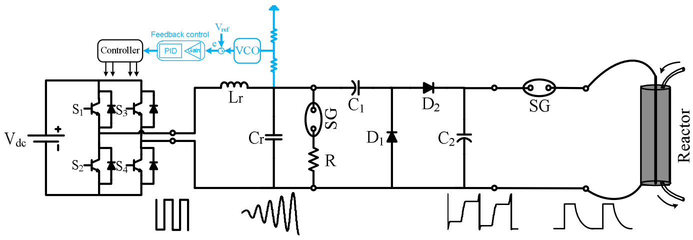

Figure 10. The circuit diagram of proposed converter

Therefore, resonant frequency of the LC circuit is variable due to the significance of changes in the equivalent C. In addition to this, the inherent toleration of either the inductor or the capacitor ends to another variation in resonant frequency of the LC circuit. As a result, the input frequency should also keep changing continuously according to the resonant frequency variation in order to keep the system permanently tuned.

A feedback loop is therefore required to deliver the detected resonant frequency to the micro-controller and to permit the controller to follow the error signal and produce triggering signal patterns for adjustment purposes. The produced square waveform frequency is then expected to stick to the resonant frequency and to follow its variations. A Voltage Controlled Oscillator (VCO) can be a useful module in the feedback to properly extract the frequency of the oscillations. However due to significance of voltage magnitude across the capacitor, a voltage divider is needed to insecure the measurement process. As given in Fig. 10, the feedback control enables the inverter to produce a waveform that is locked to the oscillation frequency of the LC circuit. As a result of that, the LC circuit is supplied by a tuned square waveform at its input. Therefore the amplitude of voltage oscillation across the capacitor is increased gradually. The CDVM then multiplies the voltage magnitude by a factor of two and produces a high voltage dc level at its output. That is how the whole high voltage dc converter operates with no more need to an ac transformation process. In order to protect the system particularly from instability modes, a series connected resistor-spark gap unit is connected across the capacitor of the LC circuit. The boundary voltage level of this spark gap is two third of the one located at the output of the converter. The entire pulsed-power supply configuration is as given in Fig. 10.

V. Simulation Results

With respect to the design specifications and components sizing, a basic model inspired by the idea of pulse production is simulated in Matlab. The simulated model's specifications are given in Table I. Once the voltage level across the output spark gap module exceeds the breakdown limit, the breakdown phenomenon takes place in the internal gas and the devise allows the voltage to be appeared across the load by conducting the current. The gas breakdown in the spark gap occurs in a fraction of micro-second and consequently a pulse shape voltage with a considerable dv/dt appears across the reactor that causes a semi-breakdown phenomenon to be taken place in the material. This reaction accompanies by a marked drop in resistivity of the load which discharges the energy stored at the output capacitor. This instant is indicated by the circles in Fig. 11.

TABLE I. Simulated Circuit Model Specifications

V_{dc}	L_r	C_r	C_1 & C_2	f_r & f_{inv}
200v	50.65mH	500nF	50nF	1kHz

As demonstrated in this figure, after a transient mode at the beginning of system, the pulse supply process is commenced and followed by repetitive conductions of the spark gap. Although both capacitors of the CDVM, C_1 and C_2, are discharged while supplying the load, the resonant capacitor C_r keeps its charge and follows the exchange process with no interrupt. It causes a fast recharging process for C_1 and C_2 and another load energizing cycle to be followed with a minimum possible recovery time. As can be seen in the simulation result, the average transient of supply cycles is almost two and half a cycles of the LC resonant circuit. In this specific model, while the resonant frequency is around 1 kHz, the repetition rate by which the converter can energize a load with a pulse train is almost 400 Hz; whereas by decreasing the LC component sizes and subsequently increasing the resonant frequency, the converter capability in supplying pulses with a higher repetition rate can be guaranteed. However, the smaller LC components are the smaller energy can be delivered to the load in each cycle. As can be seen through Fig. 12, the magnitudes of current oscillations in resonant circuit can be kept in lower levels by an appropriate selection of the capacitors and the inductor in this circuit. As evident by (4), the proportion of the capacitor and the inductor sizes can define the magnitude of current oscillations. Consequently, a large inductor connected to a small capacitor can ensure a limited magnitude of current.

The voltages across and the currents through all semiconductor devices utilized in this design, including the inverter switches and the multiplier diodes are given in Fig. 13. The voltages across the inverter switches refer to the inverter's dc link voltage which is 200v in this case. The currents through inverter switches are also restricted in low ranges.

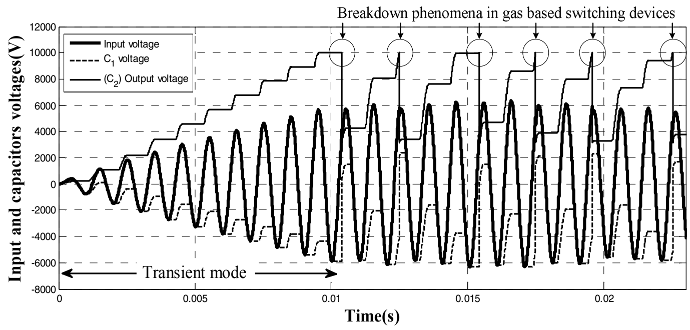

Figure 11. The input and the capacitors voltage waveforms in the CDVM circuit

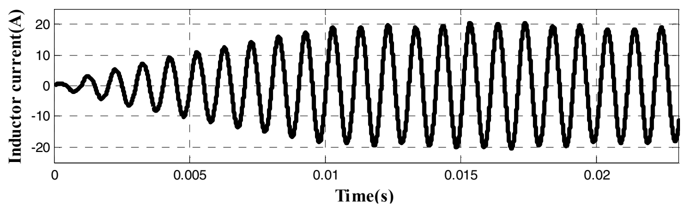

Figure 12. The Inductor current in the resonant circuit

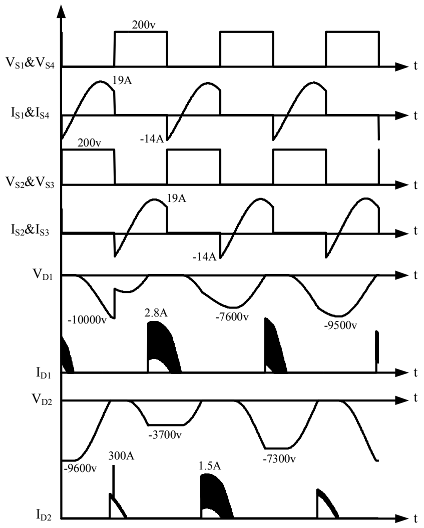

Figure 13. The voltage and the currents across and through the semiconductor switching and blocking devices

VI. DESIGN ADVANTAGES

In comparison with available technologies, this topology has significant contributions. As evident by the paper, no ac transformation is required in this converter. Therefore a remarkable saving can be expected in the initial cost, in addition to a substantial reduction in volume, weight and the operation losses of whole system. Furthermore, low power rating solid-state switching devices are utilized in this design that reduces the initial costs and operation losses. This also prevents the necessity of connecting several semiconductor switches in series and triggering them synchronously. The proposal is therefore introduced as a highly efficient power supply for pulsed power applications. It is also evident that this modulator can supply pulses with a few hundreds of kilo hertz repetition rate, even though the repetition rate is a function of the inductor and the capacitor sizes and cannot be adjusted during operation of the converter. Moreover, direct connection of power source and the load is avoided through an advanced design. That is a significantly beneficial property of a pulsed-power supply to thwart extra power losses in case of probable arc phenomenon in the load side. The load is basically supplied by the energy stored in the capacitors of CDVM. Therefore the energy in the LC circuit is kept permanently exchanging while a certain amount of it is conveyed to C_1 and C_2 in order to charge them after a pulse supply cycle. As a result, the efficiency of whole supply process can be considered higher than resembling systems under entirely similar circumstances.

VII. CONCLUSION

A high voltage solid-state based converter is proposed in this paper that takes advantage of the divergent oscillations in a tuned resonant circuit. The amplitude of voltage oscillations then is doubled by the means of a one-stage voltage multiplier to not only achieve a higher dc voltage level, but also prevent the load to be directly connected to the resonant circuit capacitor. A feedback loop using a VCO, adjusts the frequency of an inverter produced voltage waveform with the resonant frequency of the LC circuit. Frequency variations due to the conduction modes of CDVM diodes are compensated through this feedback loop. An LC circuit supplied by a tuned input voltage behaves like a zero impedance circuit and ensures the gradual increase of the voltage and the current oscillations magnitudes. The converter is designed to be used as a high-voltage source for pulsed-power applications. Therefore, the high voltage level converted by the CDVM, locates across a spark gap switch connected to the output of the converter and stimulates its contained gas. A conductive spark gas conveys the high voltage with a substantial dv/dt to the reactor and excites the material to react by a deformation reaction.

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