Zabihi, Sasan and Zare, Firuz and Akiyama, Hidenori (2010) ***A high voltage power converter with a frequency and voltage controller.*** In: Proceedings of the 17th IEEE International Pulsed Power Conference (PPC09), June 28 -July 2 2009, Renaissance Mayflower Hotel, Washington, DC.

A HIGH VOLTAGE POWER CONVERTER WITH A FREQUENCY AND VOLTAGE CONTROLLER

Sasan Zabihi*, Firuz Zare*, Hidenori Akiyama†
**School of Electrical Engineering, Queensland University of Technology, GPO Box 2434, Brisbane, QLD, 4001, Australia. Emails: s.zabihi@qut.edu.au, f.zare@qut.edu.au*
†Kumamoto University, Japan

Abstract

A high voltage power converter is presented in this paper and is based on a Capacitor-Diode Voltage Multiplier (CDVM) supplied through an inverter. This power converter has the capabilities of generating variable high DC voltage with improved transient response. The simulation results which are presented in this paper verify that due to its fast transient response, this converter can be used as a high DC voltage source in many applications.

I. INTRODUCTION

CDVMs have been used widely in space and communication applications. Among them, the Cockcroft-Walton multiplier topology has a remarkable role in voltage promotion in microelectronics related configurations such as, radio frequency passive transponders [1], passive wireless microsensors [2] and battery-operated devices [3]. Three different configurations of these voltage multipliers, including simple N-stage schematic of both a Cockcroft-Walton voltage multiplier and a Dickson charge pump are depicted in Fig.1.

The advantages of CDVM in those applications are that they are of small size and weight and have high efficiency and reliability. The main disadvantages of CDVM in these cases include the delay between input and output and the non-negligible amount of capacitance needed, but this can be reduced within acceptable limits by increasing multipliers' operating frequency via an AC-AC converter placed in the input of multiplier [4]. In relation to radio frequencies in particular, Cockcroft-Walton multiplier is widely used to increase alternative voltage magnitudes to higher DC levels in regard to its stages. The simplicity of the circuit is the most remarkable benefit of it. Each stage consisting of a couple of diodes and capacitors escalates voltage one more time. Such stages function as a complementary extension of a single topology, adding voltage steps to the output value. Therefore, there is no necessity to use gate turning on switches or transistors and their relative circuits like control boards and stacks. It is obvious that these control blocks make the configuration heavier, more complex, expensive and less reliable. On the other hand, these circuits have the flexibility of being fed by any frequent input waveforms except those with a pulse shape. This means that there is no obligation to give them just sinusoidal waveforms. In respect to the nature of these circuits which is based on the peak detection, they are able to increase the voltage magnitude of any alternative waveforms, including sinusoidal, trapezoidal or even sinusoidal voltage waveforms with harmonics. However, the voltage stress (dv/dt) across the input should be controlled in order to control the leakage current through the capacitors.

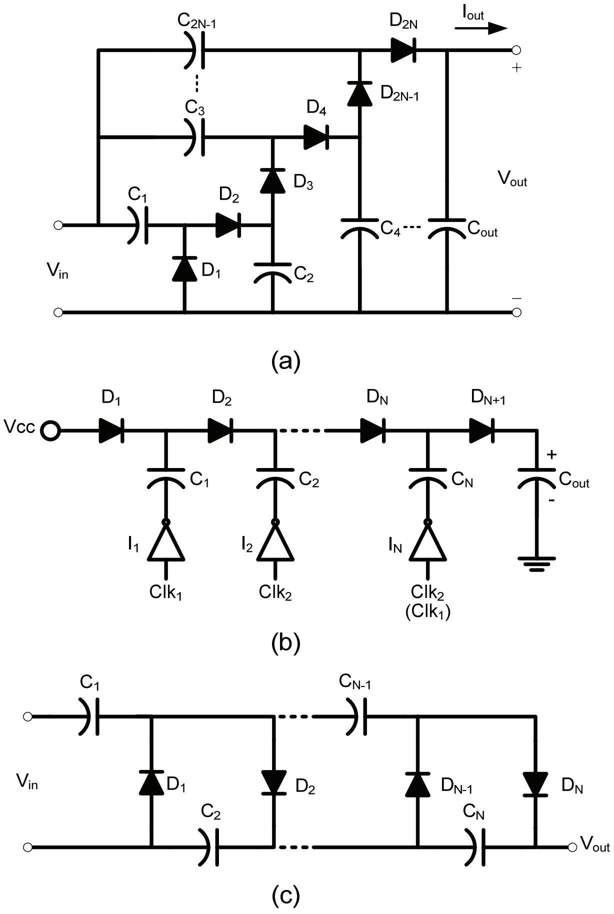


Figure 1. Capacitor-Diode Voltage Multipliers (CDVM) (a). N-stage Cockcroft-Walton Voltage Multiplier (b). N-stage Dickson charge pump (c). Another N-stage CDVM

$$i_c = C\frac{dv}{dt} \qquad (1)$$

These specifications support the idea of utilizing these multipliers for pulsed power applications.

Of all high voltage applications, pulsed power generators are the ones which demand novel configurations, including topologies and control strategies to improve the performance flexibility and power efficiency of these systems. In pulsed power applications, providing a high level of DC voltage is challenging.

In this research work, several simulations have been carried out using Matlab/Simulink and Pspice in order to analyse steady state and transient performance of the converter at different load conditions and validate the control algorithms. As can be seen in Fig.2, we considered a one-stage Cockcroft-Walton multiplier in this paper and presented all the simulation results for it. It is apparent that these simulation results and analyses can be developed for multi stage multipliers regarding few modifications.

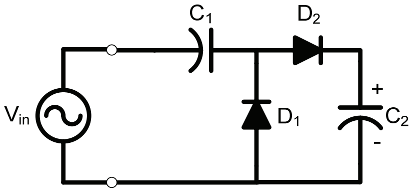


Figure 2. One-stage Cockcroft-Walton voltage multiplier

II. Transient

As mentioned, due to the load demands in pulsed power applications, it is absolutely crucial to supply load with a flexible DC voltage with a fast response time in order to improve the quality of the output voltage. Firstly, a one-stage voltage multiplier is connected to the grid and supplied by a conventional sinusoidal voltage waveform, 200V and 50Hz. As can be seen in Fig. 3(a), for the condition of identical capacitors, it takes 8 cycles (.16s) for the output voltage to get twice of the input voltage magnitude from zero at the beginning of the simulation and this period may either increase or decrease according to the capacitor's proportions. For example; if C_1 is ten times C_2, (C_1=10C_2=10 mF), the transient time will markedly decrease to (3 cycles, .05s) as shown in Fig. 3(b).

The voltage across capacitor C_2 is:

$$V_{C_2}(i) = \frac{2C_1}{C_1+C_2}V_{SM} + \frac{C_2}{C_1+C_2}V_{C_2}(i-1) \qquad \text{for} \qquad i>1,$$

$$V_{C_2}(1) = \frac{C_1}{C_1+C_2}V_{SM} \qquad (2)$$

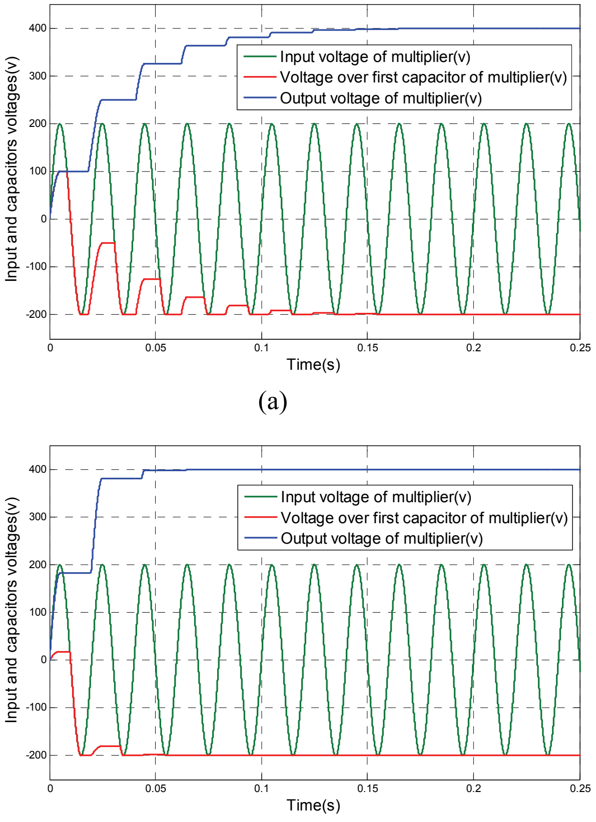
Where (i) represents the number of each cycle.

For the specific situation when (C_1=C_2), the former equation could be simplified as:

$$V_{C_2}(i) = V_{SM} + \frac{V_{C_2}(i-1)}{2} \qquad \text{for} \qquad i>1, \qquad (C_1 = C_2)$$

$$V_{C_2}(1) = \frac{V_{SM}}{2} \qquad (C_1 = C_2) \qquad (3)$$

Hereby, we are able to recognize the number of cycles, taking in each transient for the output voltage to get the ultimate value. Hence, in regard to input frequency, the length of time each transient takes can be almost predictable.

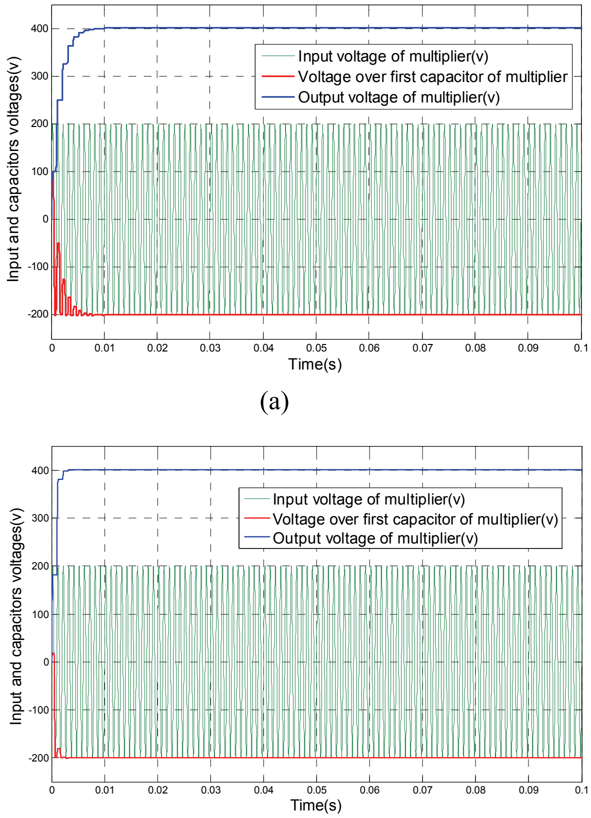


(a)

(b)

Figure 3. Voltage transient of multiplier with 50 Hz input frequency (a). Identical capacitors (b). Different capacitors

Another concept which may be considered a solution for decreasing transient time is supplying the multiplier with a high frequency power supply. As shown in Fig 4, the transient times of the multiplier with identical and different capacitors are reduced to 10 and 3 ms respectively when the multiplier is supplied by a 1kHz input waveform. Since the grid frequency is always constant (50 or 60 Hz), a frequency converter in the input of the multiplier is required to improve the transient response of the system. When feeding the multiplier with a higher frequency, each cycle lasts for a shorter time and as a result, the whole transient time will be decreased.



(a)

(b)

Figure 4. Voltage transient of multiplier with 1KHz input frequency (a). Identical capacitors (b).Different capacitors

III. Adjustable output voltage level

There are many demands for different voltage levels based on the various applications. A power supply with a capability of providing adjustable voltage magnitude is highly sought-after equipment.

The multiplier's output voltage is generated based on the input voltage and the number of multiplier stages.

In regard to Eq.4, for variable voltage magnitude, there are two options: either changing multiplier stages or the multiplier's input voltage. Alternative stages is not reasonable due to the complexities of installation and control method while it just gives the flexibility of ascending voltage related to the number of stages times the input voltage magnitude. On the other hand, as indicated in Fig. 6, a variable input voltage results in variable voltages in the output. It is not possible to change the input voltage since a constant voltage is supplied by grid and we have no control on it unless an AC-AC converter is placed between the source and multiplier and the multiplier is supplied through it.

$$V_{out} = n \cdot V_{in} \tag{4}$$

As indicated in Fig. 5, this converter consists of an AC-DC converter to provide an adjustable DC voltage, while the input power factor is controlled. The second converter is a DC-AC inverter which generates AC voltage with variable magnitude and frequency. In this new configuration, these two converters are connected in cascade, supplying an AC-DC voltage multiplier. The first converter consists of a diode rectifier with a boost converter which improves the input power factor and reduces low order harmonics. The controller changes the DC voltage based on the reference voltage to generate a high voltage at the output of the voltage multiplier. The second converter is an inverter which generates an AC voltage with a variable frequency. In a traditional diode capacitor voltage multiplier, the output voltage depends on the number of capacitors and diodes and input voltage magnitude. As the grid voltage is constant (220 V), it is not possible to change the output voltage easily. While in this topology, the output DC voltage of the first converter is controlled. In addition, the output AC voltage of the inverter can be adjusted in order to have variable voltage magnitude and frequency in the output.

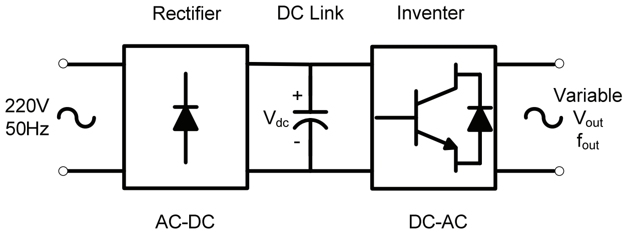


Figure 5. An AC-DC-AC converter

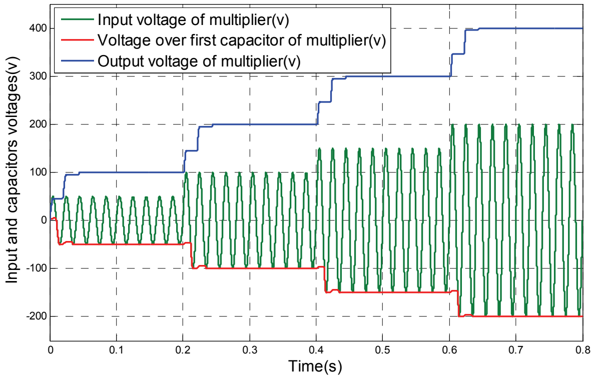


Figure 6. Variable input voltage results in variable voltages in the output

IV: Feeding CDVM through an inverter

Inverters are power-switch based pieces of equipment which convert DC voltage to AC voltage. A control strategy decides the frequent sequence of opening and closing of switches considering desired output. A schematic configuration of a single phase inverter utilized in this work is presented in Fig. 7. There are also various

PWM techniques providing control signals for these switches, such as bipolar and unipolar modulations. An inverter controlled under unipolar modulation gives the capability of having variable voltage amplitude in the multiplier input and subsequently in the multiplier output. It is the most striking advantage of an inverter switched with unipolar control method.

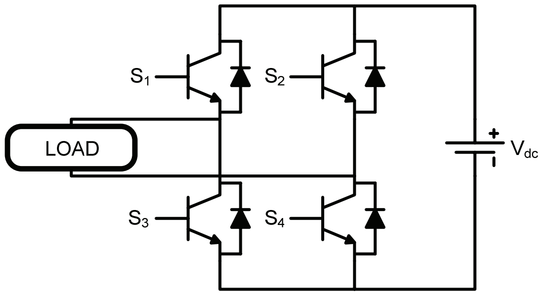


Figure 7. Schematic of full bridge (two-leg) inverter

A brief review of unipolar method control reveals how variable voltage is available in the output of an inverter. In the unipolar modulation control method of the inverter, the output voltage has three voltage levels of $-V_{dc}$ & 0 & $+V_{dc}$ while in the bipolar modulation, there are just two voltage levels, $-V_{dc}$ & $+V_{dc}$. Fig. 8 demonstrates one cycle of output waveforms for both modulation methods.

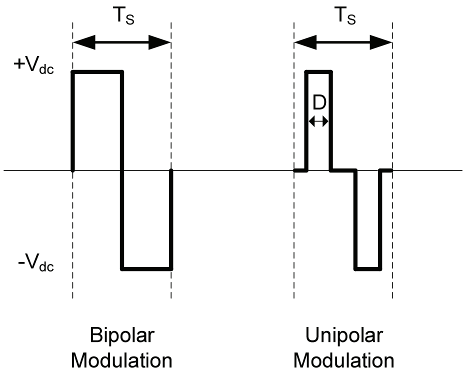


Figure 8. Bipolar and unipolar modulations output waveforms

In both cases, changing T_S gives variation of frequency f_S in the output. In bipolar mode, changing the average of the output cycles is possible by changing duty cycles, while in unipolar mode, the variation of duty cycles not only gives different output averages, but also leads to the change of the rms value of the output voltage. This eventually ends in having variable voltage magnitudes in the output of the filter.

The output voltage of the inverter cannot be given to the multiplier directly, since high dv/dt s of this pulsed shape waveform may cause inrush currents in the multiplier's capacitors. It is therefore necessary to reduce voltage stress (dv/dt). An LC filter located at the output of the inverter eliminates high frequency harmonics and delivers high quality voltage which has variable amplitude with respect to the variation of duty cycles. Fig. 9 shows simulation results for duty cycles of .05, .5 and .95, while output frequency is 50Hz.

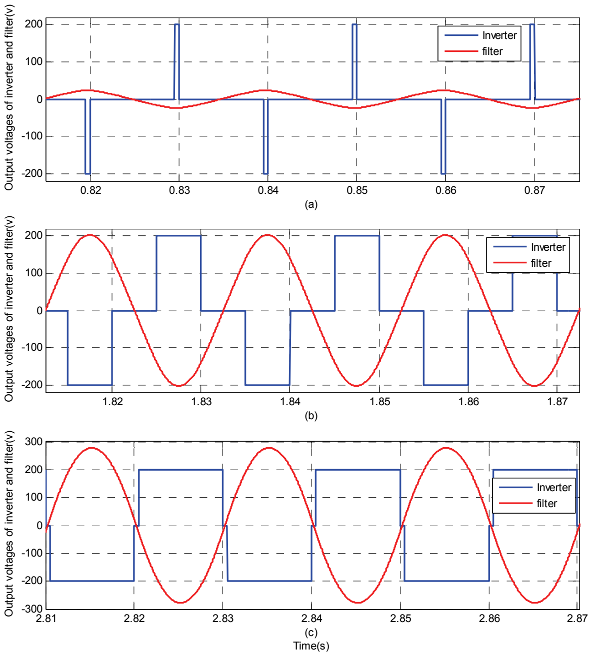


Figure 9. Output voltage of inverter and filter for duty cycles of (a). 0.05 (b). 0.5 (c). 0.95

The specifications of the simulated circuit are listed in Table I.

Table 1. Circuit specifications

Multipliers capacitors	1e-3 F
Inverter's DC voltage	200 v
Frequency of output voltage	1KHz

In Fig. 11(a), it is demonstrated that we can get different voltage magnitude in the output of the filter and multiplier with variations in duty cycles of switching in unipolar modulation. In this model, the duty cycle of switching changes from .1 to .9 and gives several voltage levels in the output. Inverter output voltage in Fig. 11(b) illustrates the unipolar control method's skill in providing the multiplier with variable voltage levels (duty cycles of .1 & .5 & .9). Load connections and their influence on system reply are shown in Fig. 11(c).

Plasma generators have been recognized as one and probably the most significant customers of pulsed power technology.

In plasma applications, to have the most efficient reaction supplying, the system's input and output energy should be almost equivalent, which means equal power exchange.

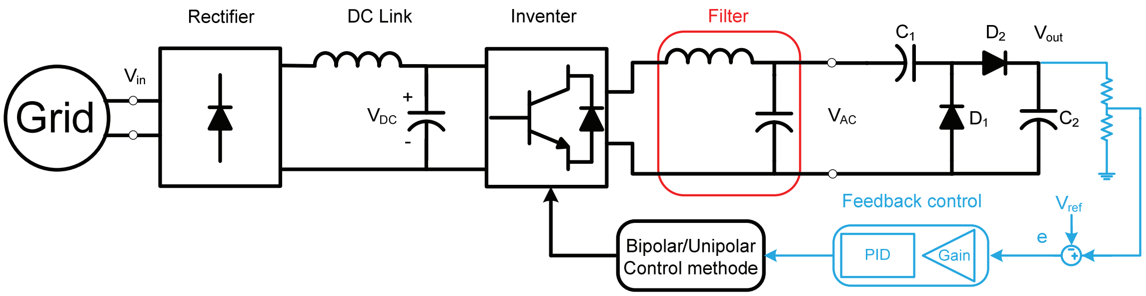


Figure 10. An inverter supplying multiplier with variable frequency and amplitude

$$E_{in} = E_{out} + E_{Loss} \qquad P_{in} = P_{out} + P_{Loss} \tag{5}$$

The difference between E_{in} & E_{out}, which is known as energy loss, should be minimized as low as possible. However, it could not be totally omitted due to switching and delivery losses.

As is known in an inverter-multiplier DC power supply, the output capacitor is responsible for delivering the output energy to the load. So the output energy can be defined as

$$E_{out} = \frac{1}{2}C(V_{\max}^2 - V_{\min}^2) \tag{6}$$

Whereas $V_{\max}$ and $V_{\min}$ are load voltages.

While the energy absorbed by load is defined as:

$$E_{Load} = (t_{on}).(P_{Load}) = (T_s.D).(\frac{\overline{V}_R^2}{R}) \tag{7}$$

Providing $\overline{V}_R = \frac{V_{\max} + V_{\min}}{2}$ and $\Delta V = V_{\max} - V_{\min}$,

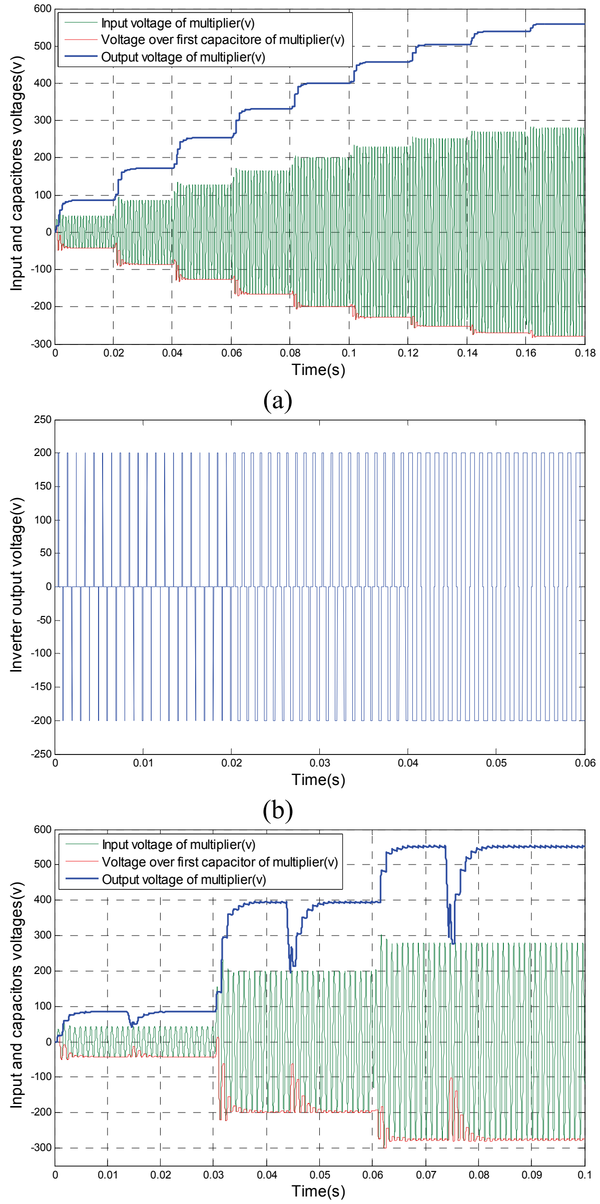
The load duty cycle could be defined as:

$$t_{on} = R.C\frac{\Delta V}{\overline{V}_R} \tag{8}$$

The application of the close loop control technique to this inverter-multiplier unit improves the accuracy, response time and quality of the output voltage.

Fig. 10 illustrates the entire concept of inverter utilization in multiplier feeding including control strategies.

The multiplier response to a square shaped input waveform in addition to the capacitor's current are demonstrated in Fig.12 (a & b). Thus the dv/dt of the inverter output voltage required to be less sharper. It can be observed in Fig. 13 (a & b) that how the current flowing through capacitor drops when the input voltage deforms to a trapezoidal waveform for less dv/dt. A first order low pass LC filter can either satisfy this aim or even detect fundamental components of input voltage, based on its appointed cut off frequency. Since having trapezoidal waveform in the output does not give the flexibility of supplying multiplier with variable voltage magnitude it is preferred to extract the fundamental components of input voltage via an appropriate filter. However, taking this into account when the frequency of inverter output is changed,



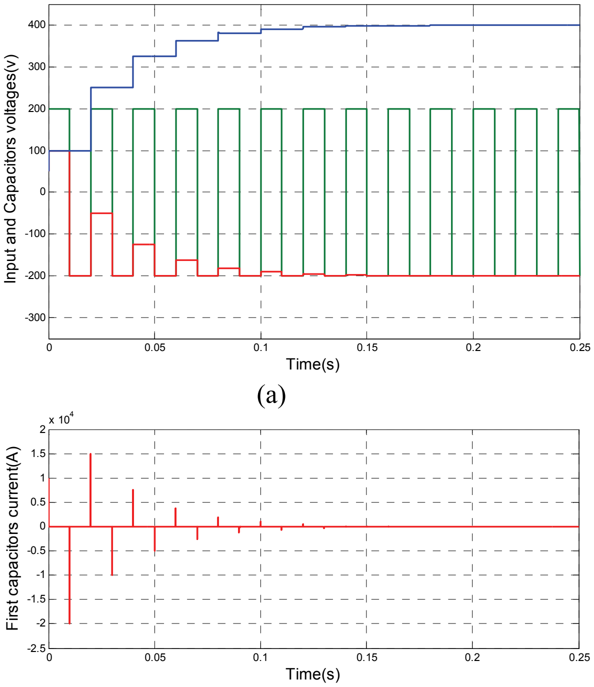
(a)

(b)

(c)

Figure 11. (a). Variable output voltage provided by an inverter under unipolar control method. (b). Inverter's output waveform with duty cycles of .1 & .5 & .9. (c). Load connections and voltage rehabilitation capability

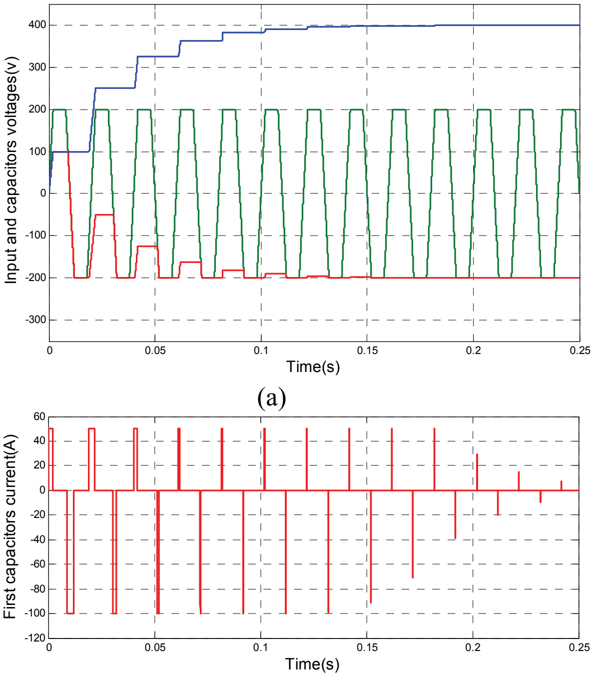
the filter's elements should be differed to adapt the cut of frequency to the new conditions. It reveals that a digital filter and a control system need to be installed to provide such adaptability. However, this brings complexity to the system.



(a)

(b)

Figure 12. (a). Multiplier voltages (b). Multiplier's first capacitor current with pulse shape input waveforms



(a)

(b)

Figure 13. (a). Multiplier voltages (b). Multiplier's first capacitor current with trapezoidal input waveforms

On the other hand, feeding the multiplier with only a high frequency does not incur such complexity, while it raises switching losses. A feedback control for the system may considerably decrease the switching losses as well as increase the system's accuracy.

V. SUMMARY

This paper presents a combination of couple of previously known converters releasing a useful configuration in high voltage with a number of the advantages in various applications. Based on the variation of inverter duty cycles, adjustable DC voltage level in the output have been found to be achievable. The transient time is drastically shortened due to high frequency input voltage. Furthermore, the efficiency of the system will be greatly improved by a feedback control. The validity of the proposed system has been verified regarding acquired simulation results.

VI. REFERENCES

[1]. C. Chen, M. Baghaeinejad and L. R. Zheng, "Design and Implementation of a High Efficient Power Converter for self-powered UHF RFID Applications," Proceedings of HDP'06.

[2]. F. Yuan and N. Soltani, "Design Techniques for Power Harvesting of Passive Wireless Microsensors," 51st Midwest Symposium on Circuits and Systems, 2008. MWSCAS 2008, 10-13 Aug. 2008 pp. 289 – 293.

[3]. D. F. Spencer, R. Aryaeinejad and E. L. Reber, "Using the Cockroft-Walton Voltage Multiplier Design in Handheld Devices," Nuclear Science Symposium Conference Record, 2001 IEEE vol. 2, 4-10 Nov. 2001 pp. 746 – 749.

[4]. L. Malesani and Roberto Piovan, "Theoretical Performance of the Capacitor-Diode Voltage Multiplier Fed by a Current Source," IEEE Trans. Power Electronics, vol. 8, no. 2, Apr. 1993.

[5]. T. Heeren, J. F. Kolb, S. Xiao, K. H. Schoenbach and H. Akiyama, "Pulsed Power Generators and Delivery Devices for Bioelectrical Applications," Twenty-Seventh International Power Modulator Symposium, 2006. 14-18 May. 2006 pp. 486 – 489.

[6]. D. Wang, T. Namihira, K. Fujiya, S. Katsuki and H. Akiyama, "The Reactor Design for Diesel Exhaust Control Usinga Magnetic Pulse Compressor," IEEE Trans. Plasma Science, vol. 32, no. 5, Oct. 2004.

[7]. T. Namihira, S. Tsukamoto, D. Wang, S. Katsuki, R. Hakam, H. Akiyama, Y. Uchida and M. Koike, "Improvement of NO removal efficiency using short-width pulse power," IEEE Trans. Plasma Science, vol. 28, no. 2, pp. 434–442, Apr. 2000.