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A Novel 1.6 kV High Voltage Low Current Step-up DC-DC Converter with Cockcroft-Walton Voltage Multiplier for Power Supply Modules

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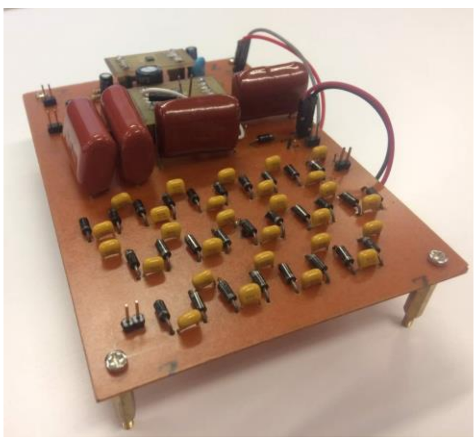
Graphical abstract



Abstract

A high dc voltage is commonly used in many process industries in testing, research laboratories and others. Currently, a high voltage dc is implemented using transformer. In this paper, a novel high voltage low current transformerless step-up dc-dc converter is presented. The proposed design consists of two step-up dc-dc converters with negative feedback signal and 15 stages of Cockcroft-Walton (C-W) voltage multiplier. The dc input voltage of 5 V triggers the first step-up dc-dc converter circuit to generate 30 V dc voltage and the second step-up dc-dc converter circuit boosts up to 100 V dc voltage. Further, diode-capacitor multiplier circuit is connected at the final stage to achieve 1.6 kV dc output voltages at 200 kHz switching frequency. The simulation results indicate that the proposed dc-dc converter can generate 1.548 kV dc voltage with a load current of 0.16 mA at 10 MΩ load resistor. Meanwhile, the experiment results show that the proposed dc-dc converter can generate 1.475 kV dc voltage with 80 % efficiency. The results validate both the simulation and experimental of the proposed high dc voltage power supply module.

Keywords: DC-DC converter, high voltage, power supply, low current, voltage multiplier

Abstrak

Voltan dc tinggi biasanya digunakan dalam banyak poses pengujian di industri, penyelidikan makmal dan lain-lain. Pada masa sekarang, voltan tinggi dicapai dengan menggunakan pengubah. Dalam kertas ini, arus rendah bervoltan tinggi pengubah dc-dc langkah naik baru tanpa pengubah dipersembahkan. Rekabentuk yang dicadangkan terdiri daripada dua pengubah dc-dc langkah naik dengan isyarat suap-balik negatif dan voltan gandaan Cockcroft-Walton (C-W) 15 peringkat. Isyarat masukan dc 5 V memicu litar pengubah dc-dc langkah naik pertaman untuk menjana dc voltan 30 V and pengubah dc-dc langkah naik kedua menggandakan voltan dc menjadi 100 V. Seterusnya, gandaan litar kapasitor-diod disambungkan pada peringkat akhir untuk mencapai voltan keluaran dc 1.6 kV pada frekuensi isyarat masukan 200 kHz. Keputusan simulasi menunjukkan pengubah dc-dc yang dicadangkan boleh menghasilkan 1.548 kV voltan dc dengan 0.16 mA arus beban pada peringtang beban 10 MΩ. Sementera itu, keputusan ujikaji menunjukkan pengubah dc-dc boleh menghasilkan dc voltan 1.475 kV dengan kecekapan 80 %. Kedua-dua keputusan simulasi dan ujikaji mengesahkan cadangan bekalan kuasa dc voltan tinggi.

Kata kunci: Pengubah dc-dc, voltan tinggi, bekalan kuasa, arus rendah, gandaan voltan

1.0 INTRODUCTION

High dc voltage is commonly used for the testing purposes and research work as the necessity of the high dc power is required [1–3]. Based on the other applications for the fuel cell energy systems and back-up system for interruptible power supplies, both of them require high step-up converter approach to increase the low input voltage to high output voltage [4–6]. Because of the greater usage of electrical equipment, there is a high demand for electrical energy generation [7–8]. In order to accomplish the high dc voltage requests, numerous efforts are taking place to determine a new method in generating high voltage where the value is higher than the supply voltage. The requirement for high voltage is achieved by implementing a transformer in conventional dc converters [9].

By utilising AC source, the transformer shows a results of inefficiency of bulk and cost, then the problem of ripple voltage is unsolved. With the usage of the transformer, the turn large ratio inviting high current and voltage stresses with higher switching losses on the switches.On the other parts, the high voltage spikes on the main switch and high power dissipation of the converter occurs [4, 5, 10–12]. The use of the transformer will prevent the development of compact converter. Therefore, corporation between the transformer and a converter circuit has led to reducing of operating efficiency because of the leakage inductance as it resulted in high voltage stress. Because of this situation, the losses is increased in the case of higher dc voltage and also increases the operational cost [9].

The current-fed converter is one of the converter types which is integrated with a step-up transformer in [13–14] and coupled inductors are introduced in [15–16]. However, the energy stored in the leakage inductor can cause the voltage to spike on the main switch and the efficiency becomes worse. Another step-up converter by using switched capacitor and voltage-lift technique is used but these designs cause high charging current flows through the main switch and enhances the conduction losses [5, 11, 17–19]. In addition, the secondary side of the coupled inductor is implemented as a flyback converter then the leakage of the transfomer will make the active switch of the converter produces a high voltage stress [3, 20]. Referring to the other converter-based designs with a single and double-switch which have been explained in the current literature but the conversion ratio is not satisfied [6, 11, 21]. The matrix converter is a solution for AC-AC conversion but it is restricted because of the inherent limitation. In fact this conversion process has resulted in higher cost, larger size, energy loss and heavy in weight [12, 21–24].

However, the selection of the components is one aspect of the overall design that should not be taken for granted. Careful consideration of all component parameter is the only way to ensure both reliable and predictable circuit performances. In the cascaded multiplier circuit, the transformer is the bulkiest part of the high voltage dc power supply unit and most of the losses are associated with it. Therefore, no transformer will be used in the construction of the 1.6 kV dc output to supply low load current in this research thus, making it feasible to integrate the high voltage supply with other associated circuit on a single chip. For saving the volume of the transformer, a high-frequency switching technique in the advanced of C-W voltage multiplier circuits for smoothing the output ripple and regulating an output voltage is proposed. In this paper, cascaded commercial IC is introduced with C-W voltage multiplier circuit to accomplish the requirement of the desired voltage.

Commonly high voltage is required at the output side; therefore, voltage multiplier technique is a good alternative [2]. The Cockcroft-Walton is the most popular technique for voltage multiplier. The traditional Cockcroft-Walton voltage multiplier is very prevalent among high voltage applications where the circuit was discovered by Heinrich Greinacher in 1919 [1–2, 15–16]. The Cockcroft-Walton is a multiplier method which able to convert ac or pulsing dc electrical power from low into high dc voltage level [20]. Instead of using a transformer which can increase and decrease voltage, it also rectifies by using one of the approaches with the implementation of diode and capacitor [7, 18, 20] as in Figure 1. The output voltage is generated with a low input voltage where the load applied has high input impedance. Instead of that, the input voltage stability is not a major concern [2, 7, 24, 25]. The C-W voltage multiplier circuit is made by joining a ladder stage of diode-capacitor where each stage consisting of two combination components in series [4, 12, 17, 22, 23, 26]. The voltage multiplier circuit is classified based on the ratio of output voltage to input voltage which is known as a voltage doubler, tripler and quadrupler [4, 7, 24].

For the case of ac system, high voltage is obtained by focusing on transformer usage where the output of the secondary will increase the voltage with decreasing current and more losses occurred. Besides, a transformer is not used in the case of dc system due to the constant current and flux which is not link primary to secondary. Therefore for stepping up the voltage, dc system is preferable [23, 30]. The rectification process is going through the rectifier grade diode and high value capacitor which causes heavy in weight. Referring to aforementioned above problems, the voltage multiplier circuit has obtained high voltage with low load current [21]. Referring to the circuit in the figure above, the voltage according to each stage is equal to the twice of input voltage and the output can tap the output from any stages and the same applied with multi-tapped transformer. With a complete circuit connection, dc output voltage is practically less than theoretical value. Besides, this implemented circuit has the advantages of compactness and cost-efficiency [17, 21,22, 28].

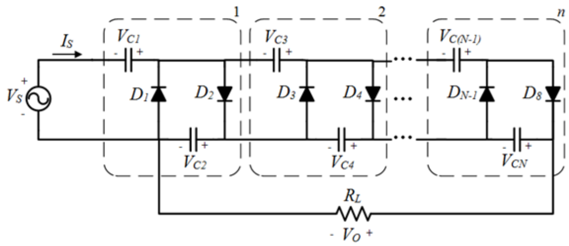


Figure 1 Conventional Cockcroft-Walton voltage multiplier [12]

Major shortcomings produced by the multiplier circuit are voltage drop and ripple voltage due to the ac impedance of the capacitors [10]. When focusing on the voltage multiplier circuit, high ripple voltage is generated when low frequency is applied in the range of 50 to 60 Hz [2, 4, 23, 26, 29]. By implementing a low frequency voltage source in the multiplier circuit, it can cause low response with the increase number of stages. The low frequency can be replaced with a merit of high frequency voltage source. With a concern of high-frequency switching technologies for instance high frequency pulse width modulated converters to be used for designing high frequency voltage source [2]. Besides, the switching frequency, load resistance and voltage multiplier capacitance are the key factors of producing high voltage pulse response time in high voltage power supply performance system for imaging quality in X-ray application [26].

2.0 METHODOLOGY

The block diagram of the propose dc-dc converter is shown in Figure 2. The input 5 V dc voltage is applied to the LT1618 step-up dc-dc converter to produce 30 V dc voltage. Furthermore, this value is employed as an input signal to the second stage of LT 8331 step-up dc-dc converter to produce 100 V dc voltage at 200 kHz switching frequency. The 100 V output voltage is amplified by using a C-W voltage multiplier circuit. The C-W voltage multiplier circuit consists of capacitor-diode pair at each stage. Every stage can generate 100 V dc. The main purpose of using two step-up dc-dc converters due to the specification input and output for each dc-dc converter circuit is different. The negative feedback function is used to regulate an output voltage in the controller circuits.
The last stage of the propose dc-dc converter is C-W voltage multiplier circuit. The C-W voltage multiplier circuit consists of capacitor-diode pair at each stage. Every stage can generate 100 V dc. By considering losses at every stage of C-W voltage multiplier circuit, 15 stages are required to generate 1.6 kV dc voltage.

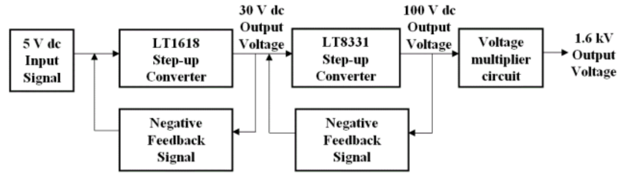


Figure 2 The proposed dc-dc converter with voltage multiplier block diagram

The complete circuit of dc-dc converter with 15 stages C-W voltage multiplier schematic is shown in Figure 3. The output from LT1618 circuit is connected to the LT8331 input terminal. Furthermore, the output voltage from LT8331 is connected with 15 stages capacitor-diode pair of C-W voltage multiplier circuit. The output is taken from OUT16 terminal to obtain approximately 1.6 kV dc voltage.

The selection of the components should be taken into account with the intention of an easier design in a dc-dc converter to ensure good circuit performance in overall circuits. For inductor selection, a fixed inductor L_1 with the value 10 µH is a good choice in LT1618 design with ferrite core types. This inductor has low copper-wire resistance and suitable in minimizing power loss. The capacitor is placed on V_{IN} pin and V_{OUT} terminal as shown in Figure 3 as a consequence of reducing the output ripple voltage. Electrolytic capacitor for C_1, C_2 and C_3 are used due to their best performance with moderate capacitance changes versus temperature and also suitable for general purposes. A switching diode D_1 with 1N4937 type is an ideal choice for this application due to its lower voltage drop and fast switching speed. The voltage rating for this selected diode is high as when the value does not exceed the output voltage. As for the current conduct when the switch is off, the supply current from D_1 is sufficient for most designs. The resistors R_1, R_2 and R_3 which are connected at the feedback pin are able to determine the output voltage for this controller by using Equation 1[32].

$$R_1 = (R_2 + R_3)\left(\frac{V_{out}}{1.263} - 1\right)$$
$$1.8Meg = (68K + 10K)\left(\frac{V_{out}}{1.263} - 1\right) \quad (1)$$
$$V_{out} = 30.41V$$

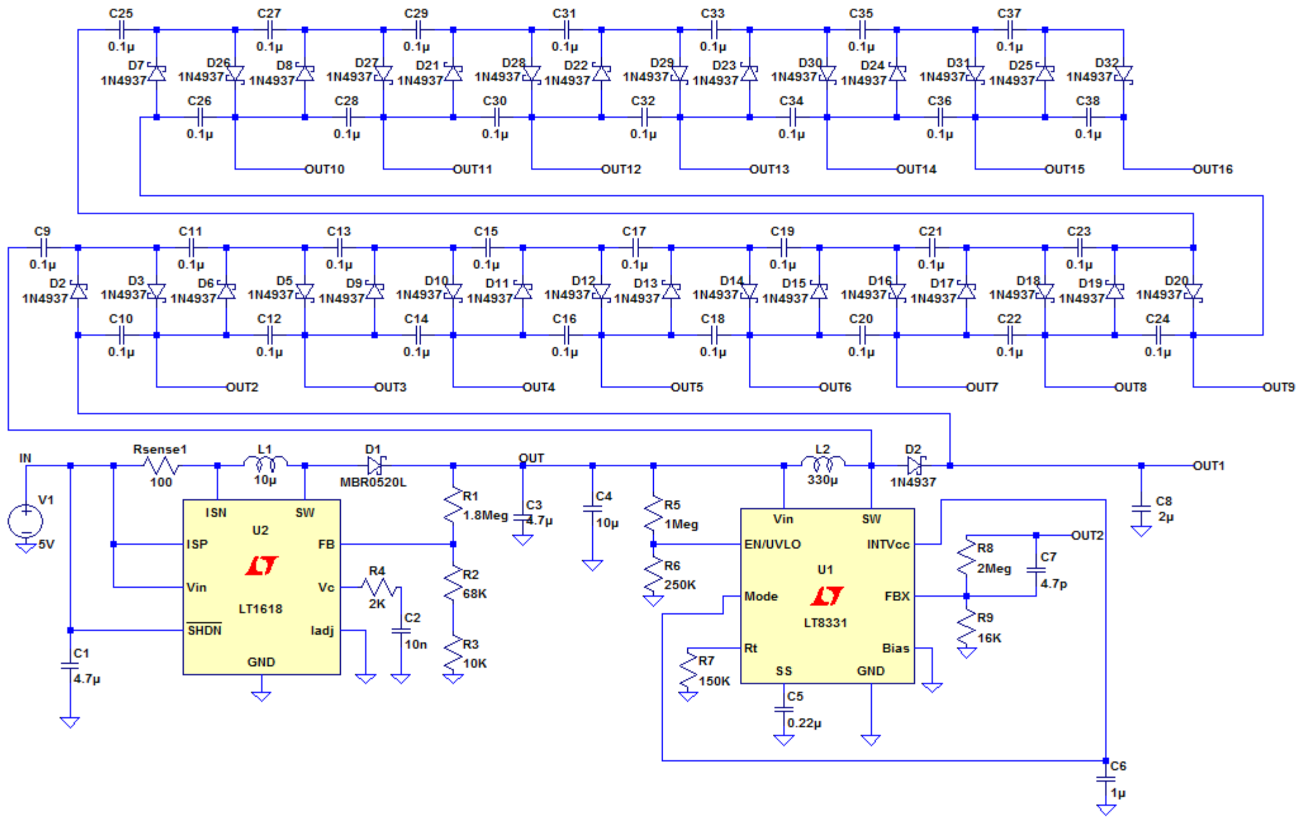


Figure 3 The schematic of dc-dc converter circuit with 15 stages C-W voltage multiplier

LT8331 in Figure 3 uses a constant frequency PWM architecture that has been programmed to switch from 100 kHz to 500 kHz by implementing R_T pin connected to the ground. The 154 kΩ with an approximately 150 kΩ is chosen to generate circuit with 200 kHz switching frequency, f_{sw} by using Equation 2 with a resistor value in Table 1 [25]. The R_T value is calculated in kΩ while for switching frequency, f_{sw} in MHz. A ferrite core inductor L_2 with 330 µH has low copper wire resistance to minimize power losses. A selectable inductor has low losses at programmed switching frequency. The capacitor value from 4.7µF into 10µF electrolytic and a ceramic capacitor is enough to bypass LT8331 and easily handle ripple current. An input capacitor, C_4 combined with inductance track forms a high quality circuit. Low equivalent series resistance is used to minimize the output ripple voltage.

$$R_T = \frac{32.85}{f_{sw}} - 9.5 \tag{2}$$

Table 1 Preferable RT value for switching frequency, f_{sw} [27]

Switching Frequency, fsw (MHz)	R_T (kΩ)
0.1	324
0.2	154
0.3	100
0.4	73.2
0.45	63.4
0.5	56.2

The output capacitor value with the range of 10 µF to 47 µF is sufficient for most application. In order to make a voltage generates as required value, high performance tantalum capacitors are used which are connected with the OUT_1. An output performance is performed by varying feedback resistors R_8 and R_9 and applying Equation 3. Selectable component values are summarized as in Table 2.

$$\begin{aligned} R_8 &= R_9\left(\frac{V_{out2}}{1.6} - 1\right) \\ 2Meg &= 16K\left(\frac{V_{out2}}{1.6} - 1\right) \\ V_{out2} &= 201.6V \end{aligned} \tag{3}$$

Table 2 Components requirement for the simulation

Component Description	LT1618 Symbol	LT1618 Value / Part No.	LT8331 Symbol	LT8331 Value / Part No.
Resistor	R_{sense}, R_1, R_2, R_3, R_4	100 Ω, 1.8 MΩ, 68 kΩ, 10 kΩ, 2 kΩ	R_5, R_6, R_7, R_8, R_9	1 MΩ, 250 kΩ, 150 kΩ, 2 MΩ, 16 kΩ
Capacitor	C_1, C_2, C_3	4.7 µF, 10 nF, 4.7 µF	C_4, C_5, C_6, C_7, C_8	10 µF, 0.22 µF, 1 µF, 4.7 pF, 2 µF
Inductor	L_1	10 µH	L_2	330 µH
Diode	D_1	1N4937	D_2	1N4937

Before obtaining the required voltage value, an output voltage is connected to a voltage divider for the second controller circuit. The 5 V dc input voltage is supplied will supply to operate LT1618 and obtain a required output. Then an output voltage from LT8331 supplied voltage from LT1618 output generates a voltage multiplier circuit through all stages. The specification of the simulation is shown in Table 3 to meet the output requirement.

Table 3 System specification of the simulation

	LT1618	LT8331
Input Voltage, (V_{in})	5 V	30 V
Output Voltage,(V_{out})	30 V	100 V
Switching Frequency, (f_s)	1.4 MHz	200 kHz
Resistive Load, (R_{load})	400 Ω	2.2 kΩ

3.0 SIMULATION AND EXPERIMENT RESULTS

The simulation results of step-up dc-dc converter circuits are demonstrated in Figure 4. As can be seen, a 5 V input voltage is applied to LT1618 to produce 30.41 V output voltage. The output from LT1618 is connected to the input terminal of LT8331 to obtain 101.43 V.

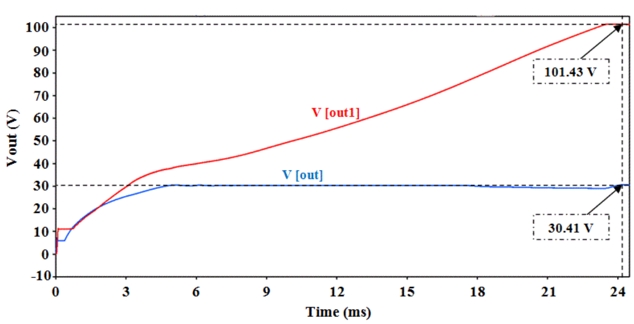


Figure 4 Results of output voltage performances from LT1618 and LT8331

Figure 5 shows the simulation results of C-W voltage multiplier circuit. The dc output voltage of 1.548 kV is obtained. The increment of 100 V at every stage can be seen clearly from the simulation results. The voltage drop occurs due to the power losses through the connection path of the multiplier stages. Furthermore, it also causes by capacitance due to the finite value of diode resistance and leakage current in the capacitance correspondingly. Based on the calculated value as given in [22], the ripple voltage value is about 0.96 V and the percentage of voltage drop is 3.25% are obtained. The voltage drop is considered low compared to the largest number of voltage multiplier stages that have been used. This is because the voltage drop and ripple voltage will increase as the load current and the number of stage increase.

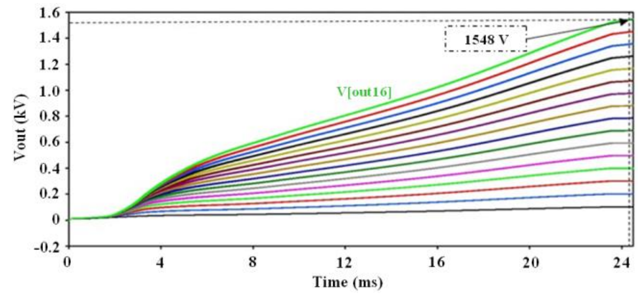


Figure 5 Simulation results of the voltage multiplier circuit

In designing high voltage power supply, the output current is considered low. High voltage power supply can gain variable output performances as the reference voltage in dc-dc converter circuit is varied. Figure 6 shows the simulated output power and the output current with a 10 MΩ load resistor. The output power of 0.25 W and the output current of 0.16 mA are obtained from the input voltage of 5 V and output voltage of 1.548 kV.

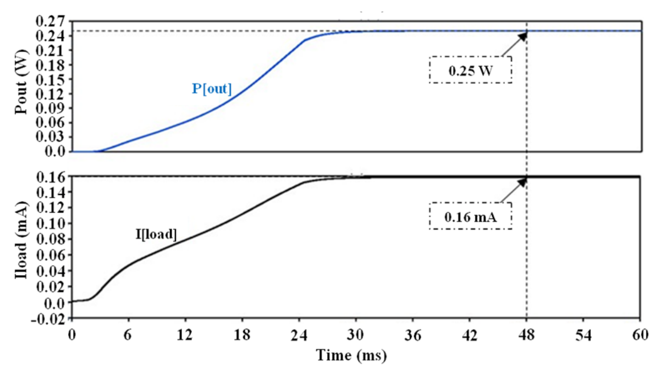


Figure 6 Cascaded converter with 15 stages C-W voltage multiplier power output and load current

Figure 7 shows the prototype of high voltage low current step up dc-dc converter on the printed circuit board (PCB). The dimension of the PCB is 10 cm x 14.5 cm. The experiment is setup by connecting the power supply to the input terminal and output voltage is measured by using digital multimeter as shown in Figure 8. In order to measure a high voltage, a modified high voltage probe is used which can measure up to 10 kV output voltage. The 5 V dc input voltage from laboratory dc power supply is converted to 1.475 kV as can be seen in multimeter screen.

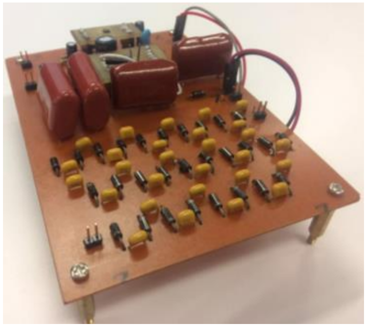


Figure 7 The prototype of high voltage low current step up dc-dc converter

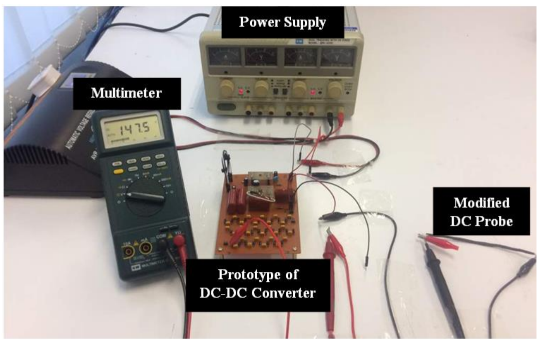


Figure 8 Measurement set-up of the proposed dc-dc converter

The measurement efficiency of the proposed dc-dc converter is depicted in Figure 9. The maximum efficiency of 97.49% is obtained with output power of 2.48 W at 1.6 kV output voltage. Besides, the full-load efficiency is approximately equivalent to 80.25% when the output power is 0.26 W as shown in Figure 9 with the same output voltage of 1.6 kV.

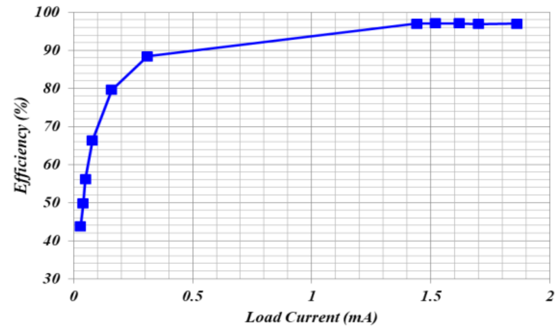


Figure 9 Measurement efficiency of dc-dc converter

The lower efficiency occurs at the lower value of input voltage because of the higher conducting loss attended by higher input current. Instead of that, the decrement of the efficiency value for the full-load or higher load condition is caused by the conducting loss of the diode and capacitor.

Table 4 presents the comparison of the performances of the previously reported transformer less dc-dc converter and this work. Based on the results that have been summarized on Table 4, the proposed design generates low output power and low current as compare to others. The advantage of the proposed design is low output power. The proposed design is suitable for high voltage low current power supply module applications.

Table 4 Comparison performance with previous research

References	[19]	[27]	This work
Input Voltage (V)	100	75	5
Output Voltage (V)	1150	1400	1600
Load Current (mA)	11.5	14	0.16
Output Power (W)	13.2	19.6	0.25
Topology	Capacitor-Switch Voltage Multiplier	DC-to-DC Converters and Capacitor-diode Voltage Multipliers	Step up DC-DC converter with C-W voltage multiplier

4.0 CONCLUSION

In this paper, high voltage and low current step-up dc-dc converter with 15 stages C-W voltage multiplier is proposed. Two step-up dc-dc converters are used to boost up 5 V input voltage to 100 V dc. Furthermore, 15 stages C-W voltage multiplier is employed to generate 100 V at each stage to produce high voltage of 1.6 kV. By comparing with the conventional transformer-based converters, the advantages of the proposed design are simplicity and a compact design. The simulation results and a laboratory prototype are presented to verify the performance. The experiment results explicitly validate the simulation results. For further improvement, the number of stages should be minimized in order to keep reducing the voltage drop value and ripple voltage.

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