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High Voltage Energy Harvesters

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Abstract

Green energy helps in reducing carbon emission from fossil fuel, harvesting energy from natural resources like wind to power consumer appliances. To date, many researches have been focusing on designing circuits that harvest energy from electromagnetic signals wirelessly. While it could be designed to be efficient, the generated power however is insufficient to drive large loads. Wind energy is highly available environmentally but development of small-scale energy harvesting apparatus aiming to extract significant power from miniature brushless fan has received limited attention. The aim of this chapter is to give audience an insight of different voltage multipliers used in energy harvester and knowledge on various circuit techniques to configure voltage multipliers for use in different high voltage applications. These include AC-DC converter, AC-AC converter and variable AC-DC converter.

Keywords: alternating current, capacitor, charge pump, circuit, generator, converter, diode

1. Introduction

Evolution of portable electronic devices over the past decades has led to surge in demand of batteries. The issues arise from using the batteries include maintenance cost, limited durability and associated environmental pollutions. Further, the size of battery becomes the bottleneck for miniaturization of electronic device. **Table 1** shows the severity of lead battery pollution in some developing regions due to unregulated and immature recycling process [1]. Renewable energy sources have become the viable solution to overcome the limitations of batteries. Although such type of energy sources from wind and hydropower have long existed, they are used mainly to power electrical appliances in streets and buildings with large turbines rated at hundreds of kW [2]. Solar energy is another attractive option due to its high availability. However, the cost of solar panel is high and the manufacturing process is associated with air pollution. RF energy harvester has become a hot research topic

Region	Number of sites affected	Impacted Population
South America	15	322,800
South Asia	10	287,000
Africa	8	154,000
Southeast Asia	34	123,500

Table 1. Ranking of lead pollution severity by region [1].

in recent decades with emergence of RFID technology. Nevertheless, it is only useful for low power applications [2] and is thus not relevant to the interest of this chapter. Other available ambient energy sources include thermal energy, mechanical vibration and human activities. Implementation of small scale wind energy harvester is possible by using miniature brushless fan as a AC generator. Wind energy harvester is chosen to be focus of the works in the chapter as it fits the goal of sustainable development to create intelligent, autonomous and eco-friendly systems. Practically, windy condition can be created when moving on a transport or resting under a blowing fan. A well-designed energy harvester circuit can enhance the power generation efficiency.

Practically, it is desirable to boost the output voltage of energy harvester by connecting it to a voltage converter. The most intuitive way of boosting the output voltage of energy harvester is using step-up transformer. However, additional rectifier circuit is needed to convert the secondary voltage of transformer into DC voltage. Further, the size and cost of the transformer is a concern for realizing miniature energy harvester. Switch capacitor circuits [3, 4] and boost converters [5–7] could be used to serve the same purpose. However, they require additional clock signals at the input and is thus not feasible for use in energy harvester. Meanwhile, diode capacitor based voltage multipliers [8–14] are more preferred to be used in energy harvester circuit due to its simplicity in circuit architecture and low cost. The works presented in this chapter focus on using miniature wind energy harvester to generate high voltage (>10 V) for powering portable devices at milliwatt level.

Three different architectures of energy harvesters are detailed in this chapter. This first wind energy harvester adopts Cockcroft-Walton voltage quadrupler and a 2.4 W brushless fan to achieve more than 17 V DC at output. The second energy harvester is a AC to AC converter that uses a self-powered inverting op-amp to achieve the purpose. Lastly, a variable DC voltage generator is presented. It is formed by connecting a voltage doubler to the output of self-powered op-amp. They are detailed in Section 3. In Section 2, various architectures of existing voltage multipliers are exploited and reviewed.

2. AC to DC converter

In this section, the fundamentals of the voltage multipliers are reviewed.

2.1. Villard voltage doubler

The most fundamental component of a voltage doubler is basically a voltage clamp which was invented by Paul Ulrich Villard [8]. As shown in **Figure 1(a)**, it consists of only a shunt diode and a series capacitor. During negative cycle of input voltage, diode D1 conducts and voltage across capacitor, V_c is charged to a value that is equivalent to peak amplitude of AC input voltage, V_p . In the next positive cycle, voltage seen at output terminal hit peak value of $2V_p$ as the capacitor now behaves as battery with DC potential of V_p . Overall, the resulted output voltage waveform is a similar copy of input AC voltage waveform but with DC level shifted from 0 to V_p . Nevertheless, voltage clamp cannot be used directly to power DC load due to unregulated output. Note that the analysis described above ignore the forward biasing voltage of diode, V_{D1} for ease of explanation. In practice, the maximum output voltage of diode voltage clamp is $2V_p - V_{D1}$. **Figure 1(b)** shows the comparison of input and output waveform.

2.2. Greinacher voltage doubler

Greinacher overcomes the deficiency of Villard voltage doubler by connecting an envelope detector in cascade with it at the output [9]. As shown in **Figure 2(a)**, the envelope detector consists of a series diode, D2 that steer current generated from voltage clamp into storage capacitor. This operation occurs at positive cycles of input voltage whereby diode D2 is forward biased and diode D1 is reverse biased or open-circuited. As shown in **Figure 2(b)**, the capacitor, C2 is charged up to $2(V_p - V_d)$ with voltage drops across diodes taking into consideration. During negative cycles, diode D2 acts as a potential barrier to ensure that only capacitor C1 is charged at that instance. With charging and discharging actions of storage capacitor, C2 across positive and negative operating cycles, the ripple content of voltage signal

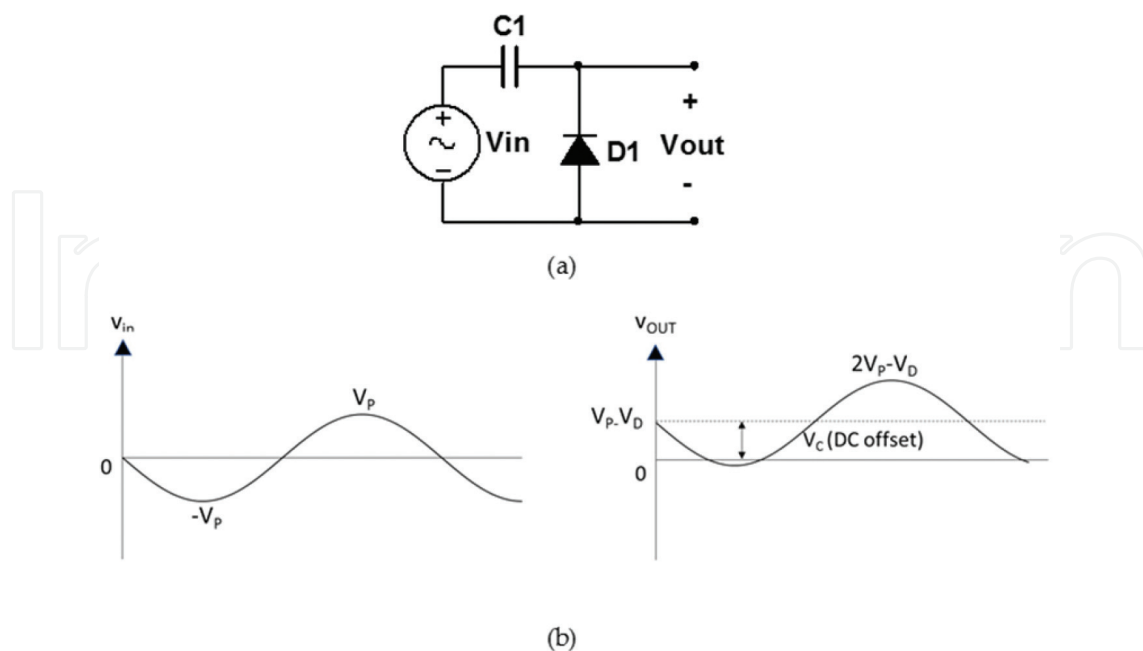


Figure 1. (a) Villard voltage doubler circuit and (b) its corresponding input/output waveform [8].

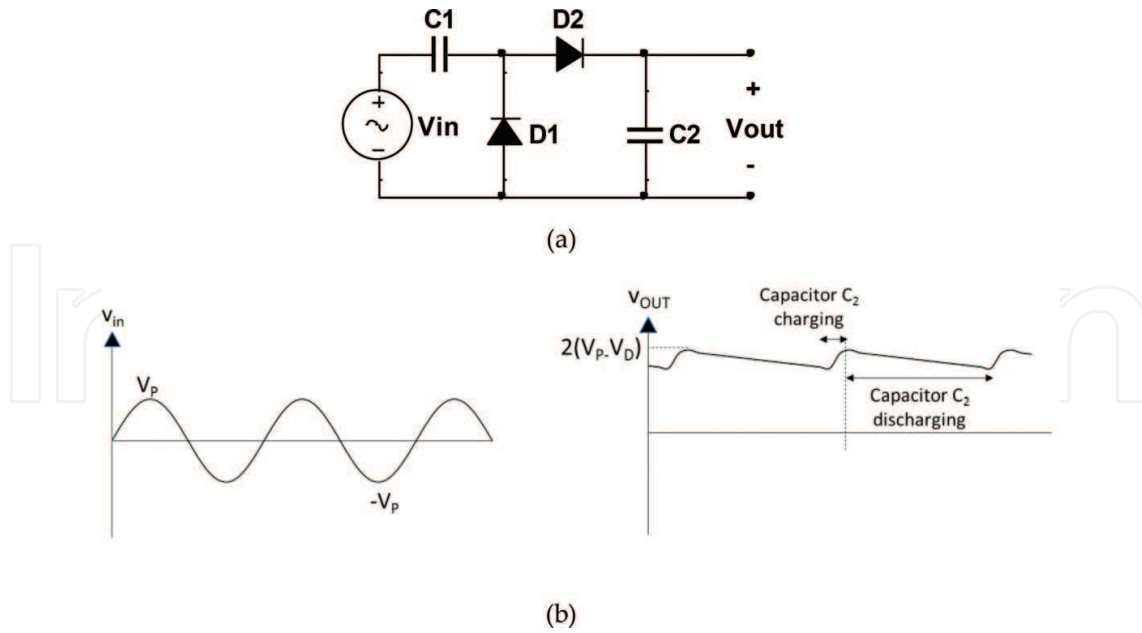


Figure 2. (a) Greinacher voltage doubler circuit and (b) it's corresponding input/output waveform.

at the output is greatly reduced or smoothed. Intuitively, the efficiency of the voltage doubler could be improved by choosing diodes that have low forward bias voltage.

2.3. Cockcroft-Walton voltage multiplier

In 1932, John Douglas Cockcroft and Ernest Thomas Sinton Walton developed a voltage multiplier for powering their particle accelerator [10]. The circuit architecture proposed is basically cascading stages of Greinacher voltage doubler and thus it is also known as Greinacher voltage multiplier. With the cascading connections described, the output voltage could be further boosted by arbitrary times higher but at the cost of reduction in current drivability. Also, the output impedance increases proportionally with the number of multiplying stages as more stage capacitances are connected in series. **Figure 3** illustrates the circuit architecture of Cockcroft-Walton voltage multiplier. Ideally, the n -cascading stage voltage doublers produces $2n$ times increased in output voltage.

In practice, the output voltage of Cockcroft-Walton voltage multiplier drops significantly from ideal prediction especially when the number of multiplying stages increases and significant loading current occurs at output. The regulation voltage, V_{Reg} which measures the drop in output voltage from ideal condition could be calculated as follows:

$$V_{Reg} = [I_{Load}(N^2 + 9N^2/4 + N/2)]/12fC \tag{1}$$

Where,

I_{Load} is the load current (Amps)

C is the stage capacitance (Farads)

f is the AC frequency (Hz)

N is the number of stages.

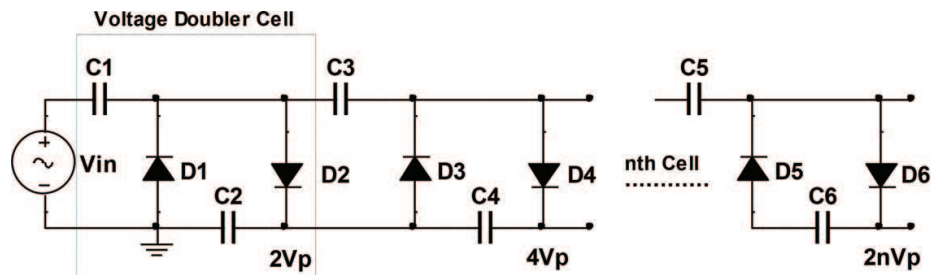


Figure 3. N-stage Cockcroft-Walton voltage multiplier circuit [10].

Hence, the DC output voltage could be written as:

$$V_{OUT} = N(V_P - V_D) - V_{Reg} = N(V_P - V_D) - [I_{Load}(N^2 + 9N^2/4 + N/2)]/12fC \quad (2)$$

Meanwhile, the ripple voltage at the output of voltage multiplier is given as:

$$V_{Rip} = [I_{Load}N(N + 1)]/2fC \quad (3)$$

Based on (1) and (2), the loading impact on output voltage could be minimized by increasing the values of stage capacitances and frequency of input AC voltage. The performance of Cockcroft-Walton voltage multiplier will further deteriorates if the stray capacitances at coupling nodes are significant fractions of stage capacitances. Therefore, it is not suitable for applying on monolithic integrated circuits.

2.4. Bridge voltage multiplier

So far, the voltage multiplier circuits discussed in previous sections are classified as half-wave type since voltage at output appear as single polarity (Positive or minus) with respect to ground of input source. Instead, voltage doubler can be implemented using bridge circuit (Delon circuit) whereby two peak detectors with opposite polarities are stacked in series and fed by a common AC source (Figure 4). Thus, the voltage tapped across the outputs of peak detectors is twice the amplitude of AC source ideally. The orientation of diode determines the polarity of peak detector output since it only conducts either half of the operating cycle. As compared to Greinacher voltage doubler, there is no voltage clamp needed in bridge type voltage doubler for achieving the same purpose.

Similarly, the half-wave Greinacher Voltage Doubler/Multiplier described in previous section could be extended to full-wave bridge configuration by stacking the negative version of it in series. Figure 5 illustrates the circuit schematic of full-wave Greinacher Voltage Doubler. The upper half version of the circuit is a positive voltage doubler whereby the lower half version is a negative voltage doubler. The resulted output voltage is double of those in half-wave version. Also, the voltage rating of stage capacitors (C3, C4) only need to be halved of those used in half-wave version for generating the same output voltage. As the ripple frequency of full-wave doubler is twice the supply frequency, it has lower ripple content than the half-wave voltage doubler. However, there is no common ground between the input and output.

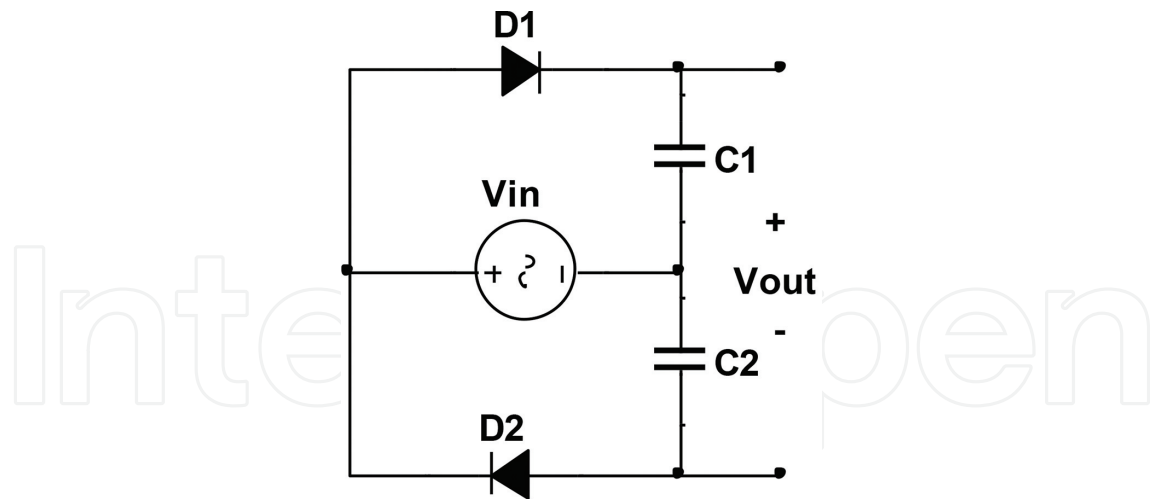


Figure 4. Delon bridge circuit.

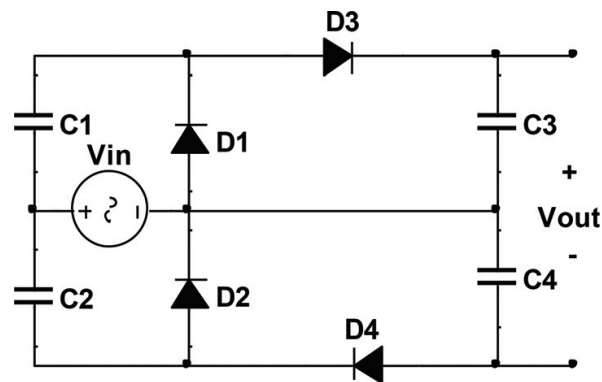


Figure 5. Full-wave Greinacher voltage doubler circuit.

2.5. Dickson charge pump

Dickson charge pump [11] was invented to overcome the deficiency of Cockcroft-Walton voltage multiplier in dealing with stray capacitances. **Figure 6** shows the schematic of Dickson charge pump circuit where the output stage is a peak detector to hold the multiplied voltage at final stage. Under this configuration, clock signals with orthogonal phases are fed separately into capacitive coupling nodes at odd and even stages of charge pump. As compared to Cockcroft-Walton voltage multiplier, the stage capacitances in Dickson charge pump are parallel connected instead of series connected. The main advantages of this configuration are that the stray capacitances have little impact on the performance of voltage multiplier even with relatively high value. Also, the current drive capability is not affected by the number of multiplying stages. However, it is not suitable for high voltage application since the output node alone need to withstand the multiplied voltage entirely. As a result, the voltage rating of output capacitor becomes the bottleneck of maximum output voltage achievable. In addition to that, the circuit is not feasible for energy harvesting applications since it requires extra feeding of two anti-phase clock signals to operate. The operation principle of Dickson charge pump circuit can be summarized as follows:

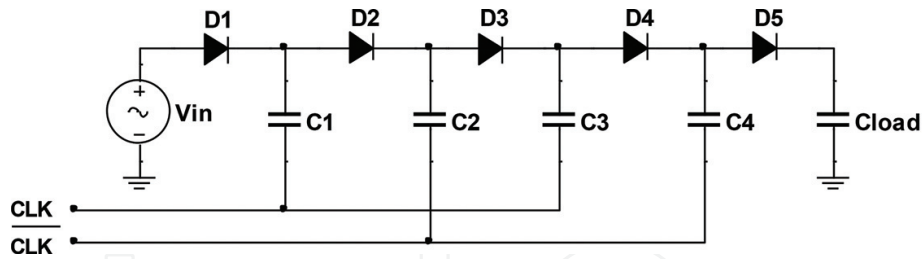


Figure 6. Dickson charge pump circuit.

1. During the zero cycle of the clock pulse, CLK , the first diode, $D1$ at the input stage will be forward biased and charge the stage capacitor, $C1$ to the peak DC input voltage (V_{in}).
2. As the clock signal, CLK goes high and \overline{CLK} goes low, the voltage appears at top plate of $C1$ is boosted by twice to $2V_{in}$. Under such circumstance, diode $D1$ becomes reverse biased whereas diode $D2$ becomes forward biased. Thus, current flows through $D2$ to charge capacitor, $C2$ for up to $2V_{in}$ assuming negligible voltage drops across diodes.
3. Similar operations described are repeated for next subsequent stages of charge pump voltage multiplier. The final output voltage stored in $C4$ is captured by a peak detector consisting of diode, $D5$ and load capacitor, C_{load} .

The output voltage of Dickson charge pump for N multiplying stages could be expressed as follow:

$$V_{OUT} = N(V_P - V_D) \quad (4)$$

In order to improve the efficiency of Dickson charge pump, Schottky barrier diodes should be adopted due to its lower forward biasing voltage. However, such component is not readily available in CMOS technology. In such case, diode connected MOSFET [15–17] is more preferred due to its lower cost, wider availability and receives better support from Process Design Kits (PDKs). Figure 7 shows different version of Dickson charge pump circuit where conventional diodes are replaced by diode connected MOSFET. Nevertheless, the efficiency of such circuit is no better than those versions with Schottky barrier diodes due to its high threshold voltages and leakages. Although the threshold voltage of MOS transistor could be canceled using external biasing described in [17], the MOS transistor could not swing to “ON” state or “OFF” state fully. This resulted in high conduction resistance, leakage current, and thus lower efficiency. Active diode reviewed in next section presents a better alternative to conventional diode.

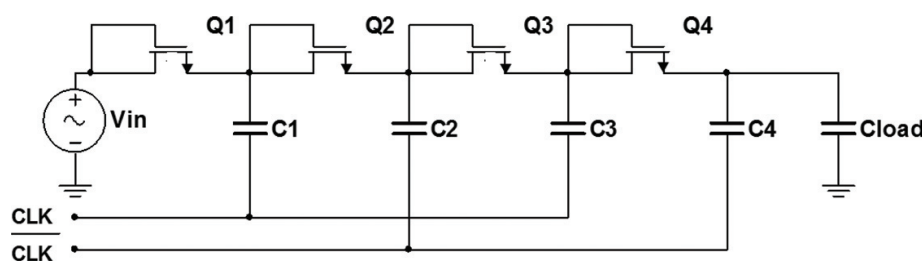


Figure 7. Dickson charge pump circuit based on diode connected MOSFETs.

2.6. Karthaus-Fischer cascade voltage multiplier

For applications where the clock signals are absent, the Dickson charge pump circuit described in previous section could be modified such that the anti-phase clock signals are replaced by input AC source and its corresponding ground connection. This resulted in much simplified circuit as shown in **Figure 8**. The circuit configuration described is also known as Karthaus-Fischer cascade voltage multiplier [12, 13]. It is interesting to note that the unit voltage doubler cell is resembled back to a Greinacher Voltage Doubler. As compared to Cockcroft-Walton voltage multiplier, the inputs of all multiplying stages are parallel connected whereas their outputs are fed into voltage clamp of next multiplying stage. In addition to that, all output peak detectors of multiplying stages share the same ground as input.

During the negative half cycle of the input sinusoidal signal, the pumping capacitors are pre-charged in parallel, and next positive half cycle charged pumping capacitors deliver current to the storage capacitors and output capacitor (CL) connected to the ground node. Input current from the received RF carrier enters to the diodes only half period of the signal in the half wave voltage multiplier.

Nevertheless, the modified Dickson charge pump is still associated with stringent requirement of capacitor ratings. Thus, another version of the charge pump is proposed in [14] whereby the output capacitances of multiplying stages are connected in series with each other instead (**Figure 9**). As a result, the minimum voltage rating required for each output capacitor is only twice of AC voltage amplitude at input. Such modifications also correspond to higher output impedances and thus implementation in full-wave configuration is recommended to reduce the impact of current loading.

2.7. Active diode based voltage multiplier

Active diode based charge pump [18–21] has been introduced lately as a good candidate for replacement of conventional diode in voltage multipliers. As shown in **Figure 10**, it is actually

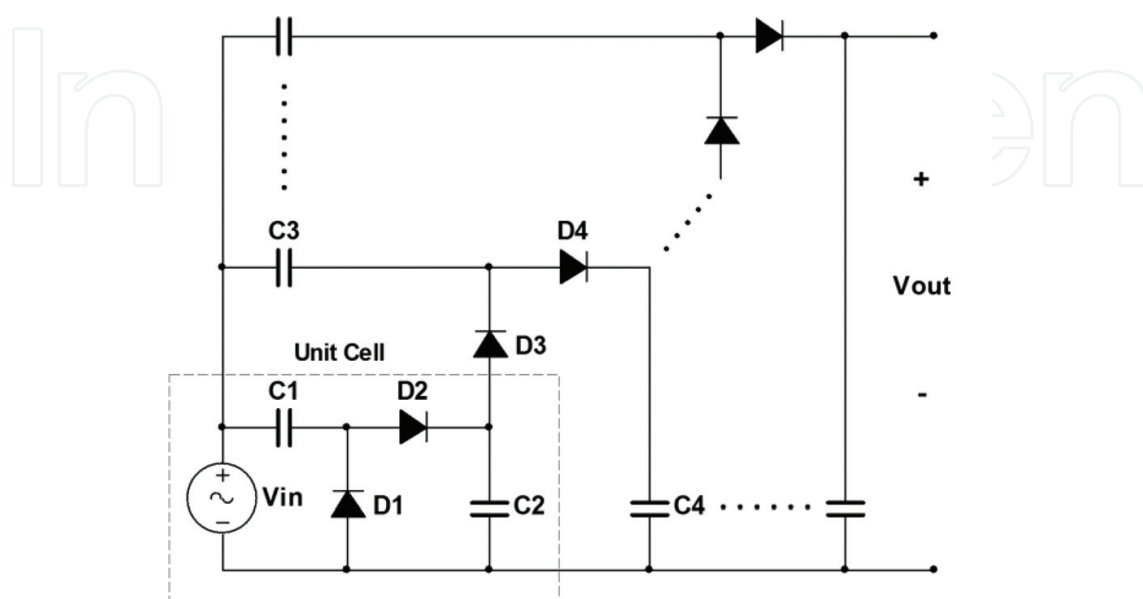


Figure 8. Karthaus-Fischer cascade voltage multiplier circuit.

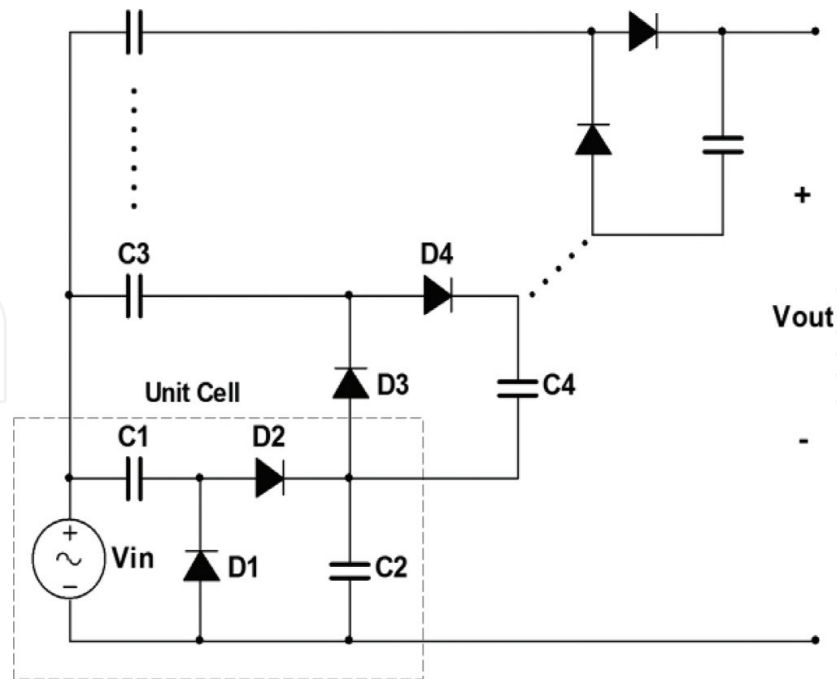


Figure 9. Modified Karthaus-Fischer cascade voltage multiplier circuit.

a comparator controlled active switch which turns on or off depending on the potential difference between anode and cathode terminal. When the voltage at anode terminal is greater than cathode terminal, the comparator output becomes low. As a result, the PMOS transistor connected to the comparator output is turned on and the entire circuit acts like a forward biased diode. The opposite happens when the voltage potential of cathode is greater than anode. It behaves like an ideal diode since only very small voltage difference at the comparator input is needed to trigger the active diode for operation in the desired state. Further, the conduction resistance of the ohmic CMOS switch is small while the reverse current is negligible due to high output impedance of PMOS switch. Thus, it has great advantages of driving low voltage input due to high sensitivity. Several types of voltage multipliers have been reported using active diodes. These include Delon, Dickson and off-chip Cockcroft–Walton types of voltage multipliers. Nevertheless, additional power supply is required for the comparator circuits and the power efficiency degrades with increases in input voltage due to more dominance of conduction loss in transistor switch.

3. Energy harvester circuit

In this section, three small scale wind energy harvester circuits based on voltage multipliers are implemented for different types of applications. Cockcroft-Walton voltage multiplier scheme is adopted for all cases since it is more suitable for generating high voltage with less stringent demand on voltage ratings of capacitors. Also, it is more compact than the conventional transformer used for power generation. The voltage multipliers are designed using discrete components instead of integrated circuits to avoid the complex issues of stray capacitances. They are described in three separate sub-sections below.

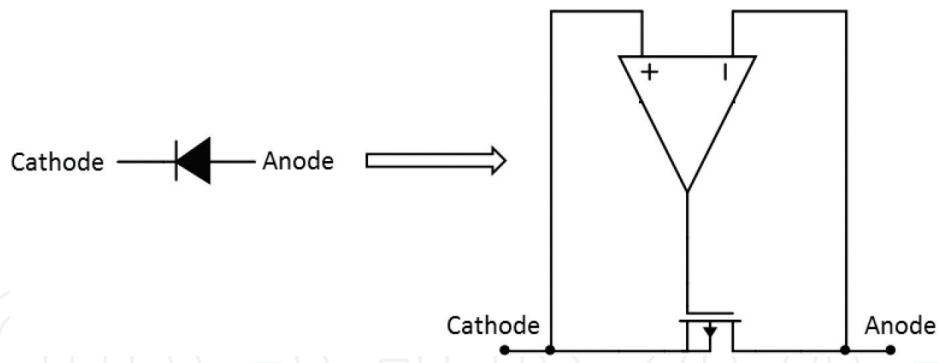


Figure 10. Active diode circuit.

3.1. Quadruppler voltage generator

A small-scale wind energy harvester circuit using voltage quadruppler is presented. As shown in **Figure 11**, it consists of two stages of Cockcroft-Walton voltage doubler that work as AC to DC booster. Schottky diodes, 1N5817 are used in the circuit given its low forward biasing voltage (≈ 0.3 V for current, $I_d < 0.1$ A). This is essential to keep the efficiency of voltage quadruppler as high as possible. A miniature brushless fan is used in the reverse way as AC generator by removing its commutator circuit. The current rating of the fan is chosen to be high (0.2 A) for better powering of voltage quadruppler. It generates around 3.5 V AC rms voltage at 80 Hz. Meanwhile, the values of stage capacitances (220 μ F) are optimized based on frequency of brushless fan (around 50 Hz) when rotating at fan speed. Choosing lower capacitances will enable the voltage multiplier circuit charge up faster to maximum DC voltage but at the cost of lower current drivability. Charging rate becomes slow when much higher capacitances are used and resulted in lower output DC voltage. The load devices used for this demonstration are LEDs. Therefore, voltage regulation issue is less concern since LEDs need very low current (in the order of μ As) to turn on or produce illuminations. The output of the voltage quadruppler is a

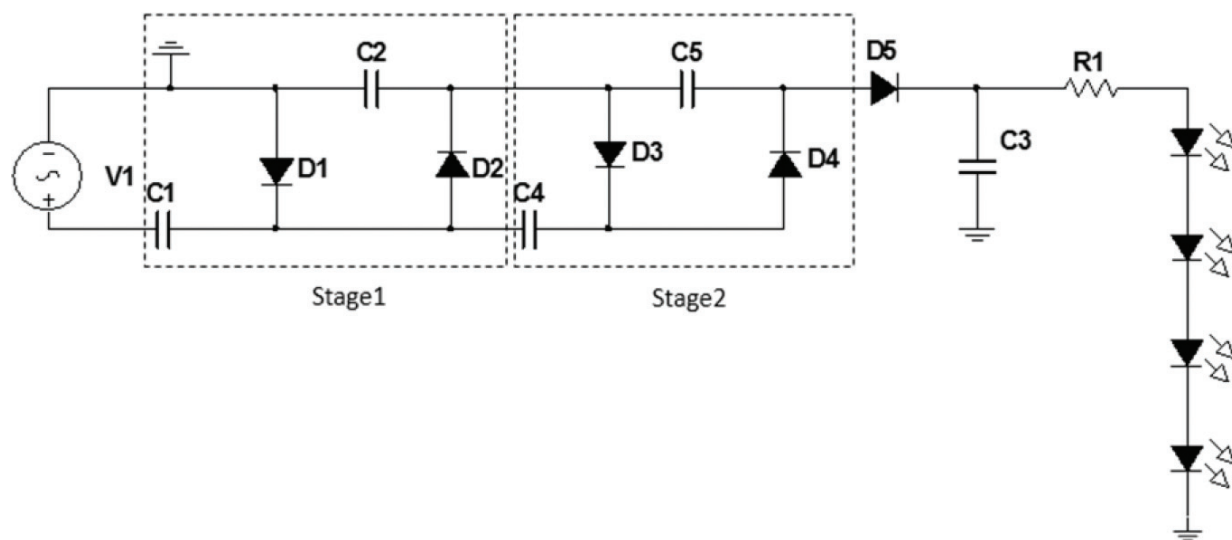


Figure 11. Quadruppler voltage generator circuit.

peak detector that consists of diode, D5 and capacitor, C3. The capacitance value of C3 is chosen to be large since it is used as a battery to power the loads at the absence of AC input voltage. as well as filtering of ripples.

The operation principle of a single voltage doubler stage could be described as follows. During the negative half cycle of the AC voltage source, diode D1 will be forward biased and charge capacitor C1 to the maximum voltage amplitude of the AC source. In the next positive half cycle, diode D1 will become reverse biased and act as a potential barrier to block current from flowing through it. Meanwhile, diode D2 will be forward biased, charging capacitor C2 to twice the maximum voltage amplitude of the source. The same operation repeats at the second voltage doubler which boost output DC voltage to four times of input signal amplitude.

Due to large capacitance of C3, it took around 2 min to charge it fully. The DC output voltage generated under no load condition is around 17 V and 15.5 V with load connected. It matches the calculation in (2) which takes into consideration of voltage drop across diodes. As demonstrated in **Figure 12**, it can light up six blue LEDs for more than 7 min given the high capacity of storage capacitor, C3.

3.2. Self-powered AC voltage booster

In the section, a self-powered AC voltage booster is presented for driving high AC voltage load instead of DC load discussed in previous section. Basically, the circuit comprises of a multi-stage Cockcroft-Walton voltage multiplier and an op-amp, LM324N. Here, the output of the voltage quadruppler is used as a DC supply for powering the op-amp. As compared to [18–21], the op-amp is used as an inverting amplifier and not an active diode. The op-amp requires higher supply voltage to increase the operating range of output voltage when used as an amplifier. Meanwhile, the AC voltage generated from brushless fan is used as an input source for both op-amp and voltage quadruppler. The resistance ratio, $R1/R2$ can be used to adjust amplification factor of input AC signal injected. Nevertheless, the maximum dynamic range of the output voltage swing is governed by the DC supply from voltage multiplier. Therefore, it is desirable to have larger number of stages of voltage doublers to achieve higher amplification and output voltage swing. Note that the loading current of op-amp will deteriorate the maximum output

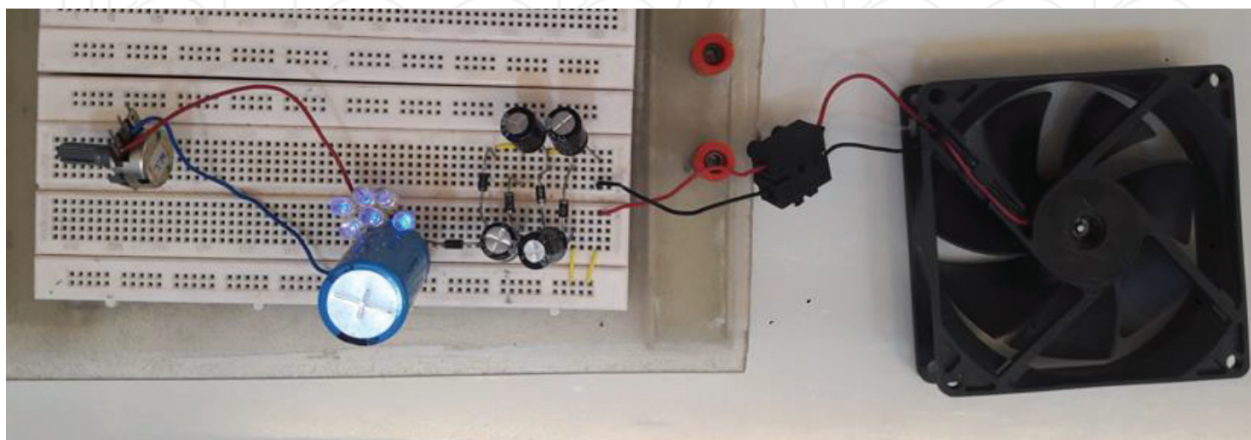


Figure 12. Demo photo of wind energy harvester using voltage quadruppler.

voltage achievable as discussed in Section 2.3. The shunt capacitor, C3 with large value helps improving the current drivability by reducing the output impedance. It also helps providing stable DC power supply voltage to op-amp by smoothing the ripples. **Figure 13** shows the schematic of proposed AC voltage booster using three-stage Cockcroft-Walton voltage doubler.

The functionality of the circuit is evaluated using MULTISIM software. As shown in **Figure 14**, the output AC voltage (Amplitude of 3 V) is twice of input AC source (Amplitude of 1.5 V) for resistance ratio, $R1/R2$ of op-amp set as 2. There is no distortion in the output as the DC power supply to the op-amp is well above the output voltage swing (6.96 V). Note that the input and output AC voltage are out of phase with each other since inverting op-amp is used in this case.

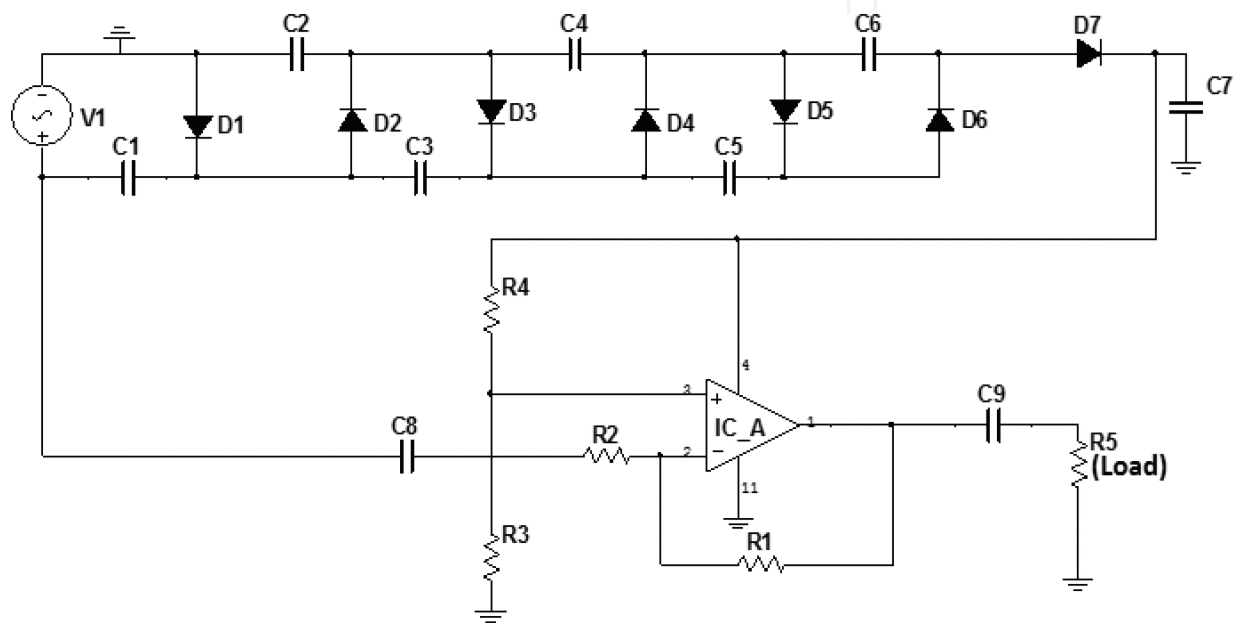


Figure 13. AC voltage booster circuit.

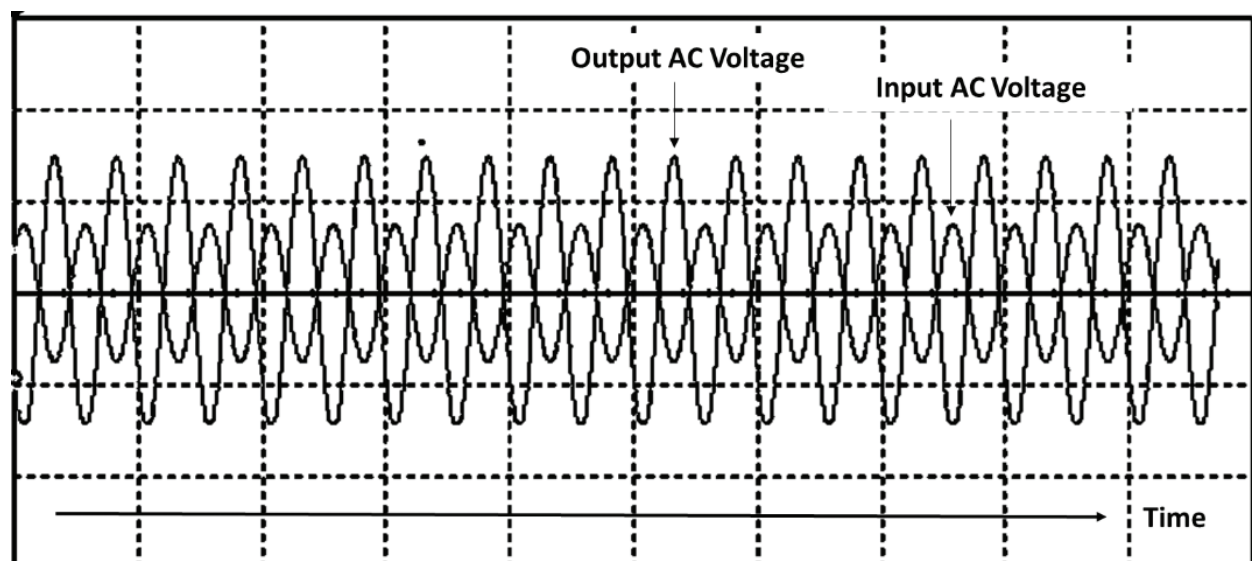


Figure 14. Simulated input and output voltage waveform of AC-AC converter.

Another version of the circuit (**Figure 15**) is implemented practically using only two stages of voltage doubler (voltage quadrupler) to power the op-amp. A function generator is used as the input of AC source instead for the purpose of analysis. The values of stage capacitances ($100\ \mu\text{F}$) and storage capacitance ($1000\ \mu\text{F}$) are chosen based on consideration on the load drivability of function generator. Meanwhile, the potential divider R3 and R4 act as the DC biasing circuit that determine the operating point of inverting op-amp. The biasing point is chosen to be at the midpoint of supply DC voltage to maximize the dynamic range of output voltage. Here, the impact of resistance ratio, $R1/R2$ on output AC voltage is studied experimentally. As shown in **Figure 16**, the output AC voltage increases proportionally with the resistance ratio, $R1/R2$ and saturates as the output voltage swing hits its supply limit. Note that the output AC voltage displayed is normalized with respect to those at unity resistance ratio ($R1/R2 = 1$). The maximum output voltage achievable using voltage quadruppler is around 1.5 times the input AC source. The result is within expectation since only one stage of voltage quadruppler is used to power the op-amp as compared to three stage voltage doublers described in previous simulation analysis.

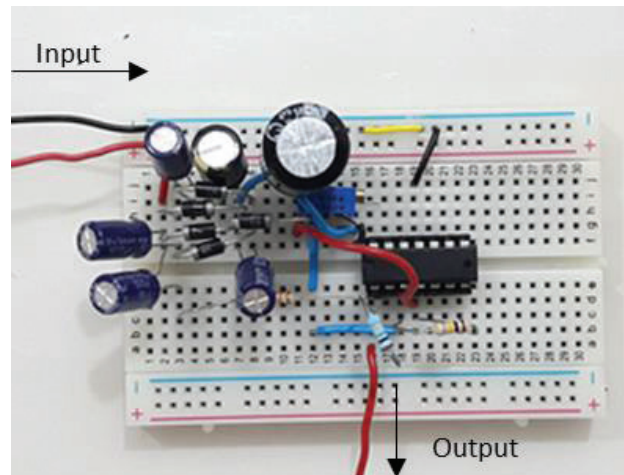


Figure 15. Circuit photo of AC voltage booster.

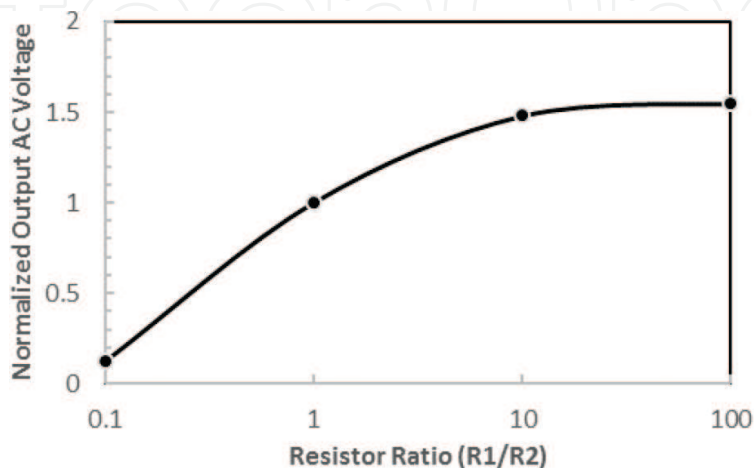


Figure 16. Measured output AC voltage with normalization.

3.3. Variable DC voltage generator

In actual applications, it is desirable to have variable DC power supply to meet the needs for different types of load devices. The conventional voltage quadruppler could be modified further using self-powered op-amp to provide varying supply DC voltage at output. **Figure 17** shows the circuit schematic of variable DC voltage generator. It is similar to AC voltage multiplier circuit presented in **Figure 13** with an exception that additional voltage multiplier stage is attached to the output of op-amp. The circuit works by using the resistance ratio of inverting op-amp to vary the output of connected voltage multiplier. The base voltage of the variable power supply could be further boosted up by tapping the ground connection of voltage multiplier at op-amp output to its own DC power supply node.

Circuit analysis is performed to evaluate the useful range of resistance ratio to be used for producing maximum variation of output voltage. The value of output voltage is normalized with respect to DC power supply from two stages of voltage quadruppler. As shown in

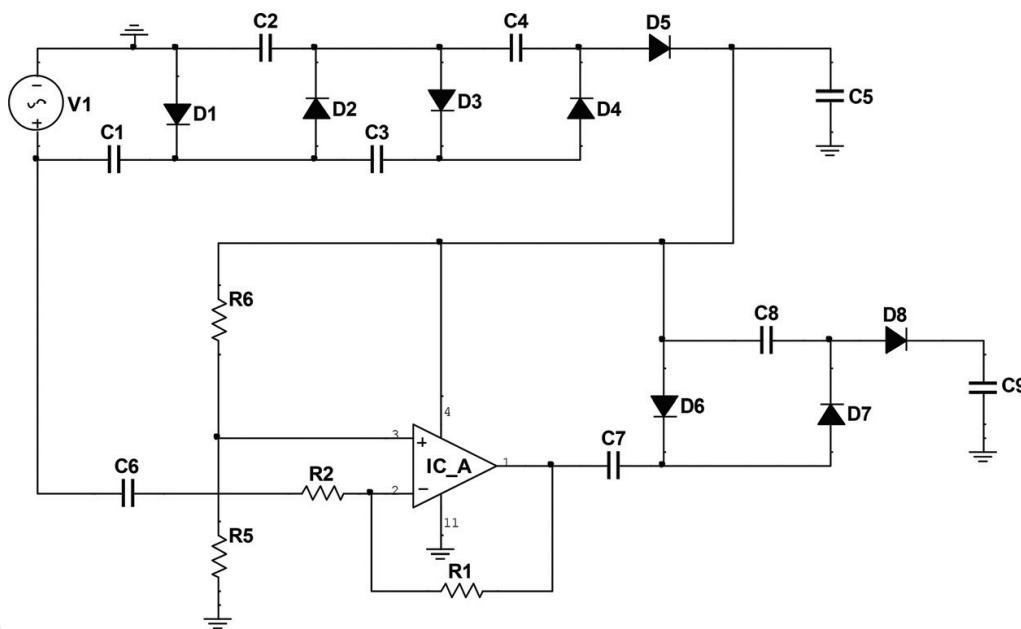


Figure 17. Variable DC voltage generator.

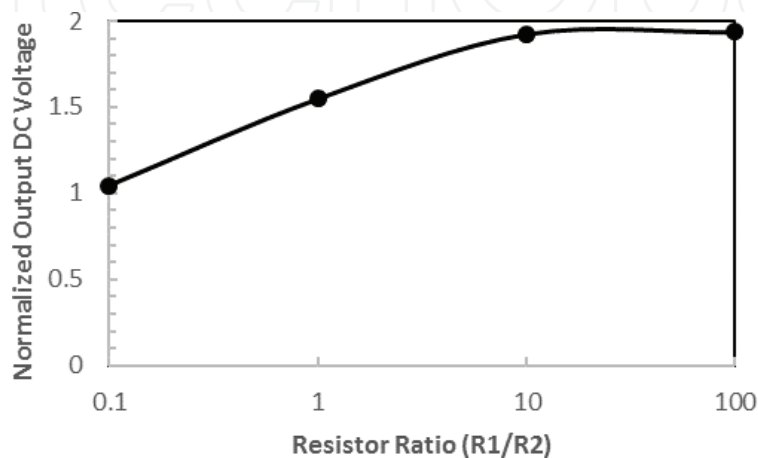


Figure 18. Simulated output DC voltage (normalized) versus resistor ratios of inverting op-amp.

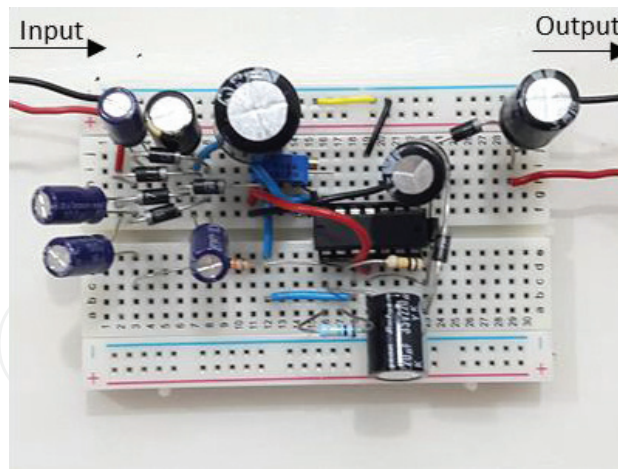


Figure 19. Circuit photo of variable voltage generator.

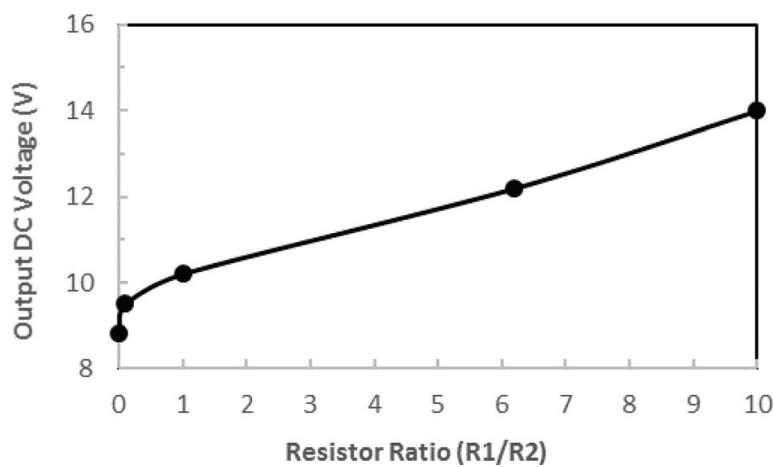


Figure 20. Measured output DC voltage versus resistor ratios of inverting op-amp.

Figure 18, the output DC voltage vary from DC power supply of op-amp to around 1.9 times of it. The useful range of resistance ratio to produce linear variation of output voltage is between 0 and 10 V for this case. Wider tuning range of output DC voltage is possible by cascading more numbers of voltage doublers at the output of inverting op-amp.

As shown in Figure 19, the circuit is implemented on a breadboard using discrete capacitors, resistors and an op-amp. It is similar to the version shown in Figure 15 with an exception that a voltage doubler is connected to the output of op-amp to evaluate its functionality. Figure 20 shows the variation of output DC voltage across different resistor ratios, $R1/R2$ of inverting op-amp. The output voltage of the circuit spans from 8.8 to 14 V. This shows that the circuit indeed functions as a variable DC voltage generator.

4. Conclusion

This chapter presents a miniature wind based energy harvester that is designed based on two stages of Cockcroft-Walton voltage doublers. The harvester circuit can generate 17 V DC voltage and light up six series connected blue LEDs for over 7 min when the source is

disconnected. Such circuit can also be used directly for battery charging and power other high voltage device under windy environment. An AC voltage doubler based on self-powered inverting op-amp is also presented. It is attractive for use to replace transformer given its miniature size. Besides that, it could be extended for wireless charging application since boosted AC voltage can be transmitted wirelessly and provide more charging power than those harvest directly from RF signal. The self-powered inverting op-amp circuit could be transformed into variable DC voltage generator when a voltage multiplier is attached to its output. It can vary by 90% of op-amp supply voltage when a voltage doubler is connected at the output. By doing so, the circuit allows flexibility to powered electronic devices of different supply voltage requirements through harvesting energy from wind.

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