POWER CONVERTER DESIGN FOR BIO-MIMETIC SOFT LENS BASED ON COCKCROFT MULTIPLIER CIRCUIT

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Abstract

The DC-DC converter steps up or steps down depending upon the application requirement. In soft robots, they are used to amplify the signal from milli-volts to several kilovolts. This allows soft robots to obtain diverse features. The current work describes the details of DC-DC converter based on the Cockcroft Walton Multiplier circuit which is developed to control the output voltage required to electrically potentially induce the actuation of dielectric elastomer films used in the bio-mimetic eye. Soft robots require careful manipulation of voltage and current signals. The input to converter is 12V Alternating Voltage whereas the output is 3.7kV. Dielectric elastomer films require voltages in several kilovolts for actuation. This converter is suitable for soft robot applications because of being low cost, lightweight and portability. In the study, a multiplier circuit is constructed based on the Cockcroft Walton generator.

Keywords: Electro-active (EA), dielectric elastomer (DE), Human Machine Interference (HMI), Switched Mode Power Supply (SMPS), Cockcroft Walton Multiplier (CWM)

I. Introduction

There has been a sudden interest in the soft robots possibly due to the functionalities they offer which don't come from rigid bodies. Electro-active polymers (EAP) are considered for achieving the goal of mimicking the artificial muscle. Some of the most investigated EAP is a dielectric elastomer (DE) whose toughness, strain, movement, weight, and power are similar to the muscle of a living creature [XXIII]. Many of the applications today's robots are not suited for will be replaced by soft
robots in the near future; that is because of the rigidness in their nature [XVIII]. Compared to conventional glass lenses, the soft lens made with Dielectric Elastomer shows much more superior performance. [I], [XIX], [XXI].

HMI between the brain and the soft lens requires the change of focal length. This change of focal length should perfectly mimic the eye. An electroactive dielectric elastomer film possesses a soft dielectric layer which is in the middle of a positive and negative plate. When the two metal plates are applied with electric potential, this dielectric elastomer film expands its surface area and its thickness is reduced through according to Maxwell stresses [XIII], [XI], [X].

High voltage DC-DC supply is required to actuate the DE-film as depicted in Figure .1 This Converter will amplify the low voltage signal needed to actuate the DE-film causing motion. The Cockcroft Walton multiplier is an extensively used multiplier circuit because of its simplicity, low cost and high voltage gain used for many applications like in Switched Mode Power Supply(SMPS) [XVII], [XX].

The portability is one of the important aspects looked upon when DC-DC converter is selected for soft robots; However, because of the existence of voltage in the order of several Kilovolts safety should be ensured probably from a shock. There should be a mechanism for quick discharge of high voltage too when the equipment isn't being used [V]. There are several documentations available for calculation values of ripple voltage, to control the voltage and stray capacitance [IV], [XIV], [XII]. Designing a circuit with such high voltage is a very difficult task. The Cockcroft Walton Multiplier Circuit has found out to be very handy in case of as laboratory voltage supply [III].

II. Literature Review

The Converter designed here is Cockcroft Walton Multiplier Circuit which has been used to actuate the soft lens made with Electroactive Polymer Film. In 1930, J. D. Cockcroft and E.T.S. Walton recommended an ambit to develop a high voltage circuit by adopting a Grienacher Voltage Doubler circuit to investigate positive ion emission from the hydrogen and other elements [XVI]. Following this work, they started working on the application of the Cockroft Walton Voltage Multiplier (CWM).
The multiplier circuit is connected to a 5-relay system which would be switch controlled with an Arduino or raspberry pi. The Arduino would open the relay system as instructed by the Electrooculography signal coming from the eye. The selected relay will conduct the actuated voltage to the DE-film connected to that relay i.e if the relay for the left side is enabled then the 4kV boosted voltage will charge the Dielectric Elastomer film on that the right side which would cause it to expand, as a right side would expand the left side of the lens would pull the lens causing the lens to move in the left direction. Similarly, for the right movement left Dielectric elastomer film will be actuated causing the lens to move in the right direction. Similar is the process for upward and downward movement. When the movement is performed, now the lens needs to go back to its center position for this purpose the actuated part is discharged using a high load or grounding the circuit through a final relay activated when a circuit needs to discharge, also controlled by Arduino [VI].

The graphic of the human eye has been shown in figure 1. The suggested multiplier output is connected to the lens at 4 traces. In this paper, the main focus has been given to the high voltage Dc supply. This paper is divided as follows, motivation is presented in section-II, section-III describes the design of power converter, and section-IV shows the simulation results between the usual selection and proposed selection scheme. In section-V conclusion is presented. In [XXII], the writer penned the superiority of CWM for portable devices so tackle the cost and overall packaging of equipment. According to him, the CWM can beneficial by allowing us to construct a device that is small in size. Whenever CWM is employed cost is less due to cheap
components being used. In the same work, the author presented a paper for the optimal utilization of the transient behavior of the circuit.

In [XXII], the Cockcroft-Walton voltage multiplier is used to converts a very low voltage signal i.e. an AC signal coming from the antenna is 100mV which is converted to 250mV DC signal using CWM. The 350mV generated at the output end of CWM Powers up another sub-system. With a frequency of 10MHz, the CWM can convert the input of 140mV AC to 350mV output DC. The transformer can be used to amplify the AC signal but with the cost of stepping down the current. Through manipulating windings, a suitable voltage can be obtained but core loss, saturation loss and current leakage loss and construction of transformer abstain us from using it. For a fixed and large load, voltage multiplier circuits are preferred [II]. In the Cockcroft Walton circuit, the output DC voltage depends upon the number of stages applied. In this work, the input to multiplier is taken from transformer 230V A.C.; and amplified to 3.7kV DC for actuation.

### III. Problem Statement

The DC high voltage is used mainly in the field of research work specially in soft robotics and in industrial work such as high DC voltage cables having a large relative capacitive load, for which high current is required to test with AC. For dielectric testing high voltages are needed to operate equipment at a power frequency of sinusoidal waveform instead of AC or DC for Dielectric materials, current in milli-amperes and voltage in several kilo-volts is needed. There are several applications of DC high voltage in electrical engineering and robotics such as Dielectric Elastomer technology recently developed. The Dielectric Elastomers are made with conductive carbon grease and Very High Bond tape and they mimic human muscles. Most of the recent research work related to the field of soft robotics shows that for actuation the Dielectric Elastomer film requires a high Voltage DC supply of 4kV to 5kV for charging the parallel plate capacitor formed by the Dielectric Elastomer film. The DC power supply required for the actuation of the Dielectric Elastomer film is very costly and is one of the major problems faced while working on the field of soft robotics. To resolve this issue a low-cost DC power supply of 4kV is designed which would resolve most of the power supply cost issues, which is easy to design and convert the power. This power supply is easy to use and reliable and can be used in all the relevant and related soft robotic projects requiring high DC voltage. The DC power supply will convert 12 V DC input to 4kV DC output by using a Cockcroft-Walton voltage multiplier circuit. The multiplier circuit converts the DC input by multiplying the input voltage with itself passing through the circuit as many times as the circuit requires. This multiplier circuit is using the 8th stage of the CWM circuit where each stage multiplies the stored voltage in the capacitor with itself. The voltage in the circuit keeps doubling until the 4kV voltage is achieved.

### IV. Power Converter

The figure shows the multi-stage Cockcroft-Walton multiplier circuit. The working principle is explained as follows:
A. Operation

According to [IX], The CW circuit will convert low AC/DC voltage to very high DC voltage using a network of diodes and capacitors. The Cockcroft-Walton multiplier circuit converts low AC or pulsating low DC voltage to high DC voltage as shown in the figure. It is made up of a voltage multiplier circuit where it resembles a ladder network. It's each step represents a combination of diodes and capacitors to generate a high voltage DC voltage supply. Normal transformers require heavy cores that convert the high or low input voltage to low or high output voltages by stepping down and stepping up the values respectively.

Fig.2: Basic Cockcroft Walton Multiplier Circuit

Many stages required in the Cockcroft-Walton multiplier circuit where the input voltage is doubled at each stage. The output voltage at each consecutive stage is the double its previous stage value which is the peak to peak shifted and doubled value of the previous stage. Figure 2 shows the Cockcroft-Walton circuit for a single-stage which explains the basic circuit of the system where the next consecutive stages are a repetition of the same circuit for boosting the voltage to almost the double of the previous voltage. Here two capacitors are used with two diodes, upon next stage 4 capacitors and 4 diodes are used, similarly, the process would continue for the 8th stage. Figure 2 shows a Cockcroft-Walton circuit having three stages. Here when the input is negative the capacitor no.1 charges through diode 1 to its maximum voltage. When the transformer gives positive input then the previously charged capacitor and the input supply both combined charge the 2nd capacitor to double the input voltage i.e 2Vmax through diode no.2. Again, the process repeats for the second stage and the 2nd capacitor having double the voltage of the 1st capacitor, charges the 3rd capacitor so that its value is 4 times the input voltage i.e 4Vin. In the 3rd stage, the 4th capacitor is charged by the voltage output of the 2nd stage i.e 4Vin. After the 3rd stage, the voltage output is 8 times the input voltage i.e 8Vin. As shown in figure 4.

B. Converter Design

First, 5V DC input would be taken in as input, this input would be converted to 12V DC using a boost converter circuit, then this 12V DC would be converted 12V AC using an inverter circuit. This AC output of 12V would be stepped upto 230V A.C. output. This 230V A.C. is the $V_{rms}$ value showing the strength of the sine wave and the actual voltage value is taken is 325.27 volts shown in equation 1.

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Saad Hayat et al
of the capacitor is already selected having a value of 470uF which at each stage stores the charge provided by the input voltage and keeps doubling the voltage till the 8th stage. Each stage voltage is provided and controlled by using diodes, the diode used in this circuit are 1N40017. After the 8th stage, the multiplier circuit gives 4KV DC output shown in equation 2 which is the optimal voltage required to charge and actuate Dielectric Elastomer Film which also acts as a capacitor having the almost value of 445p.

Fig.3: Block diagram showing the power stages

Fig.4: The Cockcroft Walton Multiplier Circuit having three stages

Elastomer Film which also acts as a capacitor having an almost value of 445p. This is shown in 3 The CWM is designed using the equation;

\[ V_o = 2N V_i \]  

(1)

Where Vo is the output voltage, N is the total number of stages and Vi is the input voltage. Since the output of the transformer is 220Vrms or 370 peak voltage. This peak voltage is taken as Vi. So, a total of 8 stages are sufficient to produce an output of 4kV which is required to cause actuation.

The CW has a lot of disadvantages like the generation of pulsating input current, delay in response [VII]; There is the third disadvantage termed as "Sagging" as the stages are increased, the voltage begins to distort. The reason is the AC impedance...
shown by capacitors in lower stages. When supplying an output current in the order of ampere, the voltage ripple becomes directly proportional to a total number of stages of CWM [XXII]. To compensate these issues,

- By increasing the capacitance in the lower stages the sag can be reduced.
- By increasing the frequency of the input AC voltage and using a square wave AC input ripple is reduced.

CWM is used to generate high DC voltage for applications which require high DC voltage at relatively low current. [XX], [VIII].

The CW is easy to set up however we have to be cautious with components parameters so that the circuit works in safe and prognosis behavior; Whenever a ladder network such as the one designed is considered the ripple factor and regulation need to be managed. The ripple factor denoted by $\delta V$ is provided as:

$$\text{Ripple factor} = \delta V = \frac{(I/fC)n(n + 1)}{2} \quad (2)$$

![CWM Circuit Diagram](image)

**Fig.5:** Circuit diagram for CWM for biomimetic soft lens

where $I$ is the load current in amps, $f$ is the frequency of input AC in Hz, $C$ is the capacitance in farads, $n$ is the number of capacitors and $2n$ is the number of stages;

So,

$$\text{Voltage drop} = \phi V = \frac{(I/fC)(2/3n^3 + n^2/2 - n/6)}{2} \quad (3)$$

The equation of voltage regulation and calculation of ripple percentage is given as:

1) Voltage regulation $= V/2nEm$
2) Percentage of the ripple $= \delta V /2nEm$

The equation (2) and (3) are taken from [XII]. Calculation of optimum no. of stages with minimum

$$\text{Voltage drop} = \sqrt{Emf (c/T)}.$$  

$E_m$ is the output from a single stage. In CWM the size of the capacitor matters, as it is in direct proportion with the input AC voltage frequency. At 50Hz AC input
frequency, the capacitance of the capacitor should be in between 1 microfarad to 200 microfarads. If the input AC frequency is 10Khz the capacitance should be from 0.02 microfarad to 0.06 microfarad.

V. Simulations

The simulation work has been done on Matlab Simulink Ver:2016a. Figure 5 shows the circuit schematic Table I shows the values of the components for all of the 8th stage Transformer input has been shown in figure 8 (A). The output of the transformer has been shown in Figure 6 (B). Figure 7 shows simulation output.

Table 1: Values of all the components used for simulation of CWM

| Components                | Notation | Value       |
|---------------------------|----------|-------------|
| Output Voltage            | \$V_o\$  | 4kV         |
| Diode                     | \$d_1\$ to \$d_{12}\$ | IN4007      |
| Capacitor                 | \$c_1\$ to \$c_{12}\$ | 470uF       |
| Frequency                 | \$f\$    | 60Hz        |
| Transformer input voltage | \$V_s\$  | 12V         |
| Transformer output voltage| \$V_i\$  | 330V        |
| Load                      | \$R\$    | 1MΩ         |

Fig.6: (A) Showing transformer input of 12 Volts AC. (B) Showing transformer input of 220V.
VI. Conclusion

Due to the close resemblance of soft robots with living organisms, they can move and adapt to their surroundings that's why they are replacing rigid robots that suffer from lack of the degree of freedom for their movement. These soft robots have got integrated actuators that perform a specific task. Different rating actuators are present in a single robot that makes a single power supply not reliable; There comes the DC-DC converter, if a DC-DC converter is safe, portable and cost-effective then it is ideal for application in a soft robot. Present work shows that the Dielectric Elastomer film in the Lens section, is divided into 5 different parts, each part is given separate 4KV DC power supply through a relay system. For the lens to move in one direction the other side of the lens is actuated causing the lens to move on the opposite side of actuation. By simply actuating one side of the lens we can perform many intricate movements of the lens. This actuation of Dielectric Elastomer Film is also placed on the top of the center part of the lens, where an annular layer of the Film is actuated causing the lens to change focus. This actuation can only be achieved with a 4-5 kV DC supply; Hence a low-cost DC power converter can be made for this technology by using the Cockcroft-Walton circuit having 220V AC supply coming from transformer and passing through six stages of the Cockcroft Walton circuit. This boosted voltage is the shifted voltage which is almost double the voltage of its previous stage but that is what is needed to charge Film as the Dielectric Elastomer is also a parallel plated capacitor having Very High Bond tape as dielectric material in the center. This actuated voltage would be later discharged through a very high lead when the lens needs to return to its previous position. shows a DC-DC converter realized using the Cockcroft Walton Multiplier which will enable the motion of a soft lens. A voltage in the order of several kilovolts is required to cause actuation in dielectric elastomer film which is mimicking the human eye muscle. The input and output voltage waveform of CWM has been shown in this paper. This output voltage is directly connected to a soft lens.

Fig.7: Output voltage of 8-stage Cockcroft Walton Multiplier
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