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EUREKA CONVERTER: A MODIFIED BUCK CONVERTER

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Abstract
This paper presents a modified form of DC-DC Buck converter and elaborates its operation in continuous conduction mode. The proposed model is based on the original Buck converter topology with extra modifications. In relation, the elementary voltage transfer function and the accompanying proposed circuit equations are also worked out in this paper. Ripple factor and difference between actual and target voltage has been reduced. Performance analysis of the proposed design is also carried out in considerable depth.

INTRODUCTION

DC-DC converter is an electrical circuit used to convert direct current from one voltage level to another. Primarily used as an electric power converter, it is used in computers, photovoltaic systems and wind power generation units, but not just limited to such applications. Buck converter is a type of DC-DC converter. Output voltage of buck converter is less than or equal to the input voltage. Internal switching mechanism of such converters controls the current in order to vary the output voltage.

Buck converter due to its primitive modeling has many limitations. Such as, its efficiency decreases with an increase in the duty ratio [1]. Pointing towards the fact, that outputs from higher duty ratios are not feasible. Furthermore, it can only produce a single transfer function [2]. This limits it from having different current values for the same output voltage. Assuming a converter of having infinite number of transfer functions, consequently, we can get the same output voltage for higher duty ratios due to the variation in the transfer function, which was previously un-achievable due to the impracticality of a low duty cycle.

Discontinuous conduction mode for a Buck converter is governed by an inductor. Decreasing the size of the inductor below the minimum inductance required to keep the current in the inductor from falling to zero, L_{min} will automatically change the operation [2]. However, if a device requires an unchanged inductor value and discontinuous conduction mode at the same time, then this converter fails to comply with those parameters. These limitations can be rectified using a modified

Buck converter proposed in this paper as Eureka Converter. Multiple output converter having a central power supply with tight voltage regulation [3], have superseded single output converters due to the latter size and cost.
Periodic fluctuation in D.C peak to peak output voltage and voltage overshoots can be reduced by using a capacitor. A digitally tuned capacitor possesses the ability to regulate voltage electronically, thus creating a scenario for displaying different transient responses [4].
Buck converter in its continuous conduction state has a low power factor besides having an erratic transient response. Previously, many circuits have been developed for improvement of power factor and transient response [5]. Though inductors are essential components for designing converter, they dissipate a significant amount of heat causing a reduction in device efficiency. As a solution, an inductor-less step-down Dc-Dc converter has been proposed in [6] by using logic gates and flip-flops to realize the improvements in efficiency and noise reduction. Apart from that, a digital controlled algorithm for separating transient response and required output voltage has been developed in [7] with which a zero steady-state error can be achieved, which can help the controller to track load changes. Switching losses are a major flaw in Buck converter which reduces the efficiency. Introducing soft switching control with variable frequency can remedy this flaw [8]. The novelty of this device makes it a prime contender for modus operandi in the field of step-down DC-DC converters. Our proposed Eureka converter steps down the source voltage to a lower level, depending on the switch (S) duty cycle. It can be used as an alternative to Buck converter, having considerable improvements upon its predecessor. Buck converter, being capable in its own domain has certain limitations, which our proposed converter, addresses to a considerable extent in this paper.

1. Circuit Analysis

This section analyzes working of proposed Eureka Converter. Fig 1 shows the topology of Eureka converter. Here, only continuous conduction mode is considered.
This analysis assumes the following:

- Ideal components.
- Switching time is T, keeping the switch closed for time **DT** and open for **T-DT**.
- Capacitor is large, so that output voltage is kept constant.

Rate of change of inductor current in the circuit when switch is closed is equal to:

$$V - Vo = (L_1)\frac{di}{dt}, \quad (1)$$

Where V is the source voltage, V_o is the output voltage. L_1 and L_2 represent the inductors respectively. Fig 2 represents the circuit, when switch is closed. Rate of change of inductor current during the operation (switch closed) is formulated and integrated from **0** to **DT** in order to express it as:

$$\frac{(V-Vo)D}{(L_1)f} = i_{(switch\ closed)}, \quad (2)$$

Where D and f in (3), represents Duty ratio and switching frequency respectively.
Fig 3 shows the current path when Switch is open. Rate of change of inductor current when switch is open is expressed as:

$$-Vo = \frac{L_1 di}{dt} - \frac{L_2 di}{dt}, \quad (3)$$

Integrating equation (3) with respect to time from **DT** to **T**, we get the following equation:

$$-\frac{Vo(1-D)}{(L_1-L_2)f} = i_{(switch\ open)}. \quad (4)$$

Combining both formulas and equating to zero, we get the transfer function in terms of duty cycle.

$$i_{(switch\ closed)} + i_{(switch\ open)} = 0, \quad (5)$$

$$\frac{(V-V_o)D}{L_1 f} - \frac{V_o(1-D)}{(L_1-L_2)f} = 0, \quad (6)$$

Rearranging the equation, the transfer function is expressed as:

$$\frac{V_0}{V} = \frac{D/L_1}{D/L_1+(1-D)/L_1-L_2}. \quad (7)$$

Equation (7) represents the output to input voltage relationship. Changing values of inductor $L1$ and $L2$

will in turn change the voltage transfer function in (8). Different "$L1/L2$" ratio can develop a unique equation.

Fig. 4 represents different **G(D)** functions, where **G(D)** = V_o/V for a range of duty cycle. Comparison between voltage transfer function of Buck and Eureka converter states that output for low duty cycle for the former is not feasible due to Mosfet impracticality, thus, using different transfer function of Eureka converter can give the same output for a high duty cycle. Negative polarity curves are not possible due to the circuit topology and diode positioning, however, magnitude is realizable.

Keep the ratio $L_1 = 2L_2$, the output to input voltage relationship is expressed as:

$$\frac{V_0}{V} = \frac{D}{2-D}. \quad (8)$$

Fig 5 is the graphical representation of the preceding equation. Comparing to the relationship for output voltage of Buck converter $V_o = V * D$, the values are leading in terms of duty cycle in comparison with Buck converter.

Changing the ratio to $L_2 = 2 * L_1$, the relationship is equal to:

$$\frac{V_o}{V} = \frac{D}{2D-1}. \quad (9)$$

Curve in Fig 6 represents the voltage transfer function. It is steeper compared to previous graphs. However, it is not possible to implement all the feature in simulation, as negative polarity is not possible in Eureka converter due to the positioning of the diode. Output voltage is undefined for limit duty cycle equal to 0.5.

Fig 6 expresses equation (10) in a graphical format.

Lastly, the inductor value is changed to $L_1 = 3 * L_2$, the transfer function is expressed as:

$$\frac{V_o}{V} = \frac{2D}{(3-D)}. \quad (11)$$

The equation can be expressed graphically in Fig 7. The curve is clearly trying to imitating the voltage transfer function of Buck converter.

Equation (1), (2) and (3) are three of the infinite iteration of equation (7). When $L_1 = 2 * L_2$, the output to input relationship converges to a value equal to 1 slowest in comparison to the other voltage transfer functions.

The transfer function of the proposed converter is Flexible in regards to different value of duty ratio that can be obtained for the same output. Apart from that, different current values can be extracted from these equations for the same output, confirming the hypothesis for current multiplier. The hypothesis is realized in the following graph.

Fig 7 represents current values for same output voltage (5 volts), blue curve represent the current across load from equation (8), while orange represents equation (11). Upon inspection, it is clear that as the inductor ratio increase, transient response becomes volatile.

Equations, which are of vital importance, must be formulated to fully understand Eureka converter inner working. First of all, maximum and minimum inductor current is deduced by the following method.

$$I_{L2} = I_R + I_c, \quad (12)$$

As the charge across the capacitor dissipates across the resistor, thus:

$$I_{L2} = \frac{V_o}{R}, \quad (13)$$

$$I_{L2} = I_R, \quad (14)$$

$$I_{Lmax} = I_{L2} + \frac{di_{(Switch\ closed)}}{2}, \quad (15)$$

$$I_{Lmax} = \frac{V_o}{R} + \frac{(V-V_o)D}{2(L_1)f} \quad (16)$$

$$I_{Lmin} = I_{L2} - \frac{di_{(Switch\ closed)}}{2}, \quad (17)$$

$$I_{Lmin} = \frac{V_o}{R} - \frac{(V-V_o)D}{2(L_1)f}. \quad (18)$$

The equation for minimum inductance is expressed as:

$$(L_{1min} - L_{2min}) = \frac{-(1-D)R}{2f}, \quad (19)$$

$$L_{1min} = \frac{V - V_o(DR)}{2V_o f} \quad (20)$$

Furthermore, ripple which is residual period fluctuation of DC-DC peak value of voltage, has to be calculated via ripple factor to get a thorough picture of the output voltage. Using Fig 8, we can deduce the equation for ripple factor. Graphical analysis can create an approximate formula for the charge on the capacitor.

$$|Q| = \frac{V_o(1-D)}{(L_1-L_2)f^2}, \quad (21)$$

$$|Q| = C \triangleq V_o, \quad (22)$$

$$C \triangleq V_o = \frac{V_o(1-D)}{(L_1-L_2)f^2}, \quad (23)$$

$$\triangleq \frac{V_o}{V_o} = \frac{(1-D)}{(L_1-L_2)Cf^2}. \quad (24)$$

Fig 10 represents the nearly similar, albeit overlapping curves of capacitor currents across the output voltage. Upon inspection, the area covered by Buck waveform (purple) is greater than Eureka converter (blue).

Comparing both the graphs, the Eureka steady state has a small rate of change of current in contrast with Buck converter, although having a volatile transient phase for the former.

2. Performance Analysis

This section will compare both the converters and rate their abilities to perform their intended action. Fig 1.5 displays the capacitor current across C_2, dissecting the graph, the ripple factor across Eureka converter is nearly same as that of Buck converter. The ripple factor is nearly equal to that of Buck due to the reason of having the same components across the output side and the current graph for I_{L2} is nearly identical.

The comparison between the output voltages of different converter realizes the error between the target and real voltage. Comparing the output voltage waveform for both converters, there is a difference of 0.1 volts from the target value of 3.3 volts for the proposed converter and 0.6 volts for Buck converter. Apart from that, transient response for Eureka is much better in comparison with Buck converter. Moreover, duty ratio is 50 percent for the proposed converter and 33.33 for Buck converter, making it ideal for Mosfet switching.

Fig 4.2 represents the output voltage of both the converter

For a target output of 1.42 volts, shown in Fig 14, error for Buck is high, reinforcing the fact that low duty cycle outputs are not feasible for this primitive circuit.

For a target voltage of 7.5 volts, Buck converter output is equal to 4.6 volts, while eureka converter gives out 8.5 volts across the resistor. The accuracy of the latter is comparatively better, decreasing the error between target and achieved voltage. The values do not change with increase or decrease in frequency.

Fig 15 represents the output voltage for a target value of 7.5 volts. Buck converter is relatively better in terms of producing error, while reaching the required voltage. However, overshooting of voltage in boosting range has a negative impact in comparison with the proposed converter whose transient is not as erratic. To achieve the required value for the proposed converter, the inductor values must be increased keeping the ratio unchanged, while keeping the duty ratio constant.

Proposed converter is less prone to harmonics, in comparison with Buck converter. Apart from that, Buck converter has a single transfer function, increasing the duty ratio decreases its efficiency. This has been remedied in the proposed converter by introducing an inductor ratio in equation (8). Change in Vo/V relationship will create a new set of duty ratio for getting the same output voltage as was in the case of Buck converter, considering the transfer function when $L_2 = 2*L_1$. decreasing ripple even further, a capacitor and inductor in parallel is used at the source side. This will create a gate, by which conduction mode can be governed while keeping the function intact. Discontinous conduction mode is not explored as not being in the scope of this paper.

3. Conclusion

Modified converter has been proposed to overcome the limitations of Buck converter to a certain extent. Accuracy and efficiency has been improved, while future works include introducing multiple outputs for different iterations of the Proposed converter. in addition, High efficiency and bidirectional Dc-Dc conversion are hot commodity in field of power converters. Thus, the proposed converter can be designed according to [9] [10] to enhance its utility. Experimental results show the applicability of the novel device. Raw data is used as a test bench for future improvement and practical experimentation of Eureka converter.

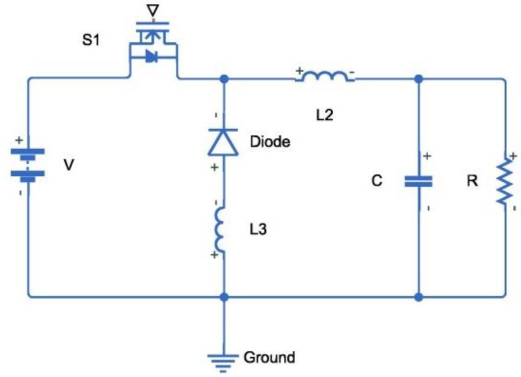

Fig. 1. Eureka Converter

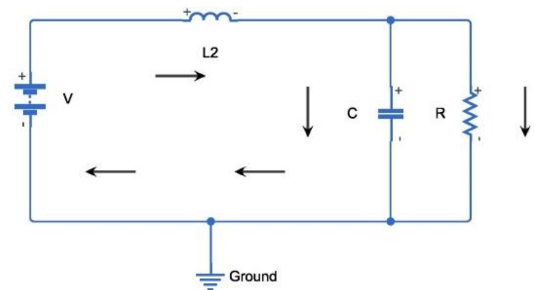

Fig. 2. Current path when Switch is closed.

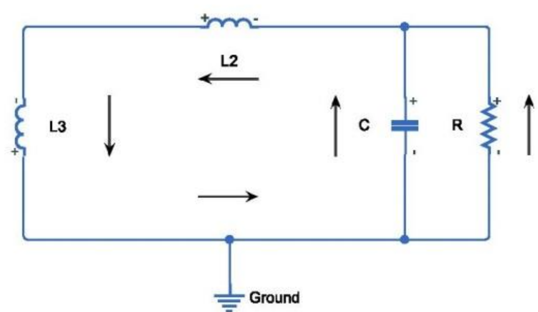

Fig. 3. Current path when Switch is open.

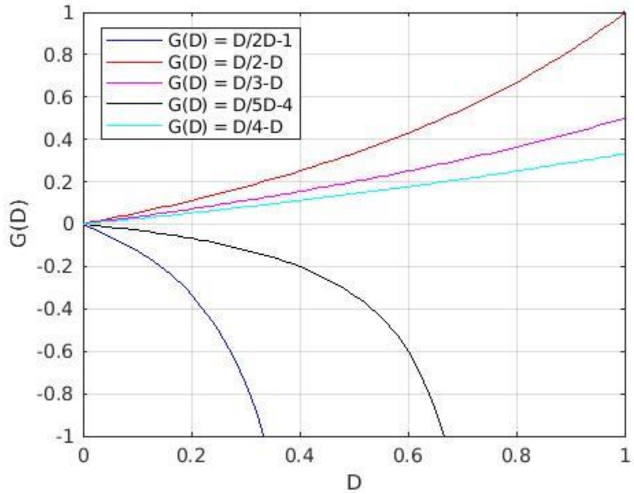

Fig. 4. Different iterations of (**7**) *in graphical format.*

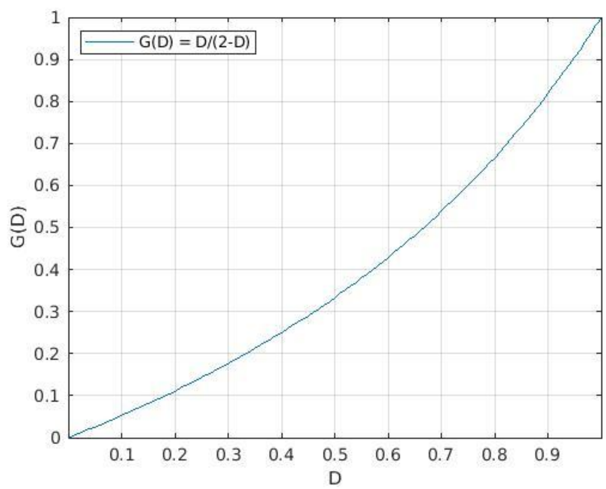

Fig. 5. Line representing equation (**8**).

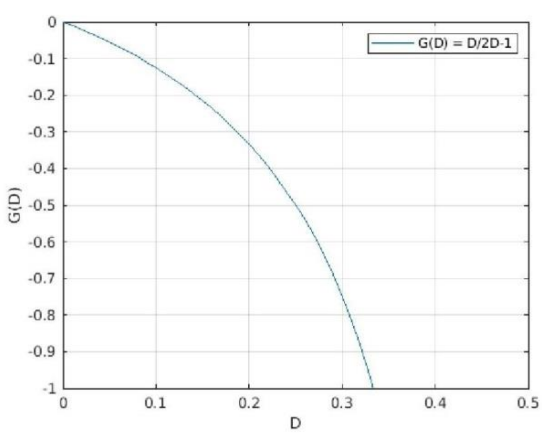

Fig. 6. Equation (**9**) *represented graphically.*

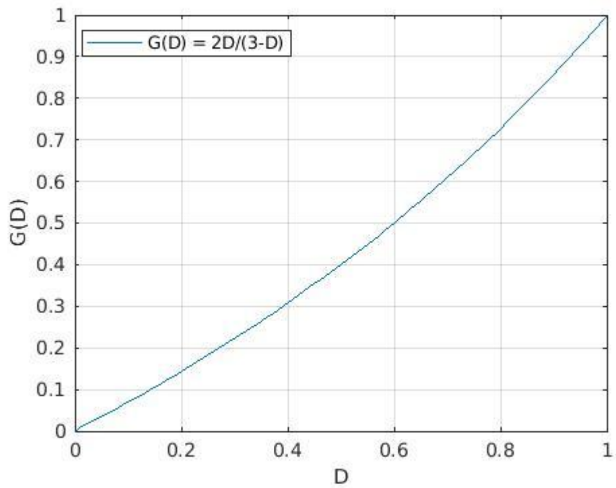

Fig. 7. $G(D)$ for equation (11).

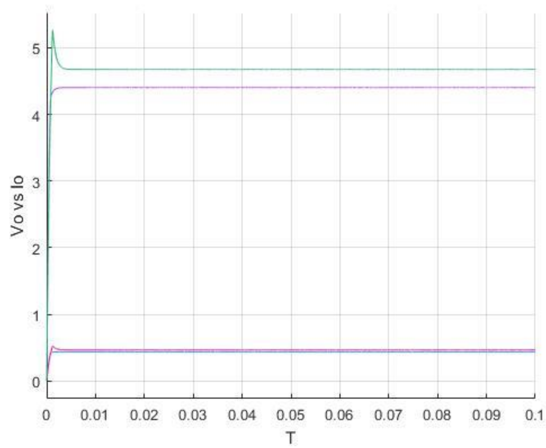

Fig. 8. Different current values for same output

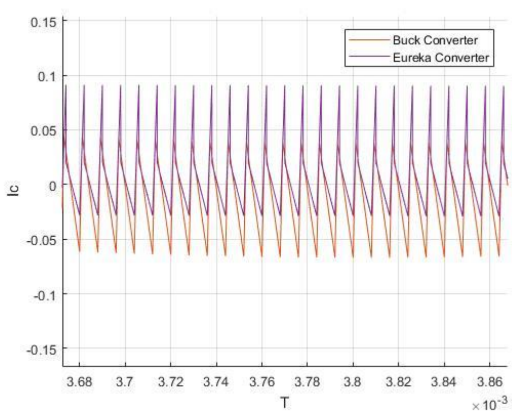

Fig. 9. (Zoomed) I_{L2} is represented to reinforce the thesis of the same waveform as that of Buck converter.

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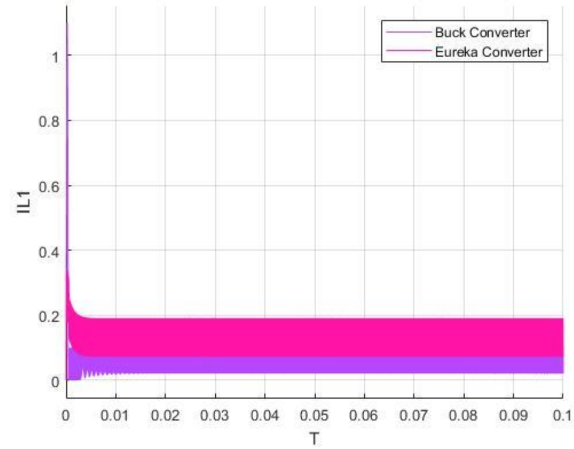

Fig. 10. I_{L2} for Eureka (blue) and Buck converter (brown).

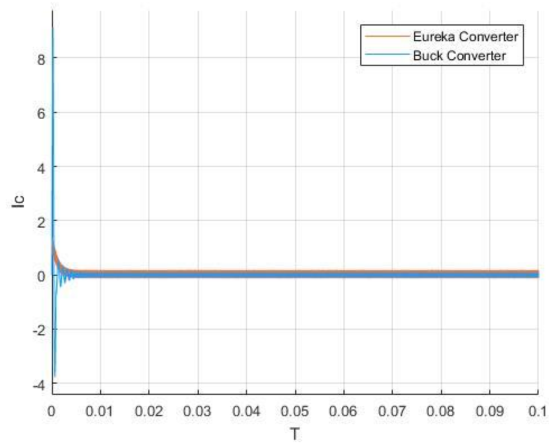

Fig. 11. Capacitors Current for Buck and Eureka converter.

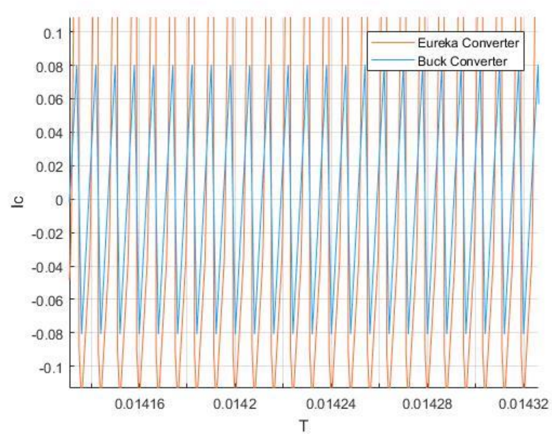

Fig. 12. Zoomed in section of Fig. 11.

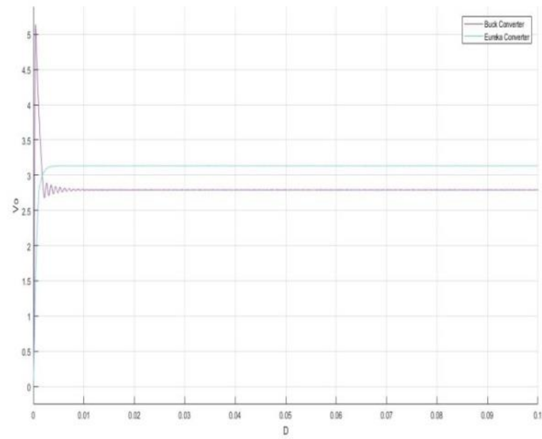

Fig. 13. V_o waveforms for Buck and Eureka converter.

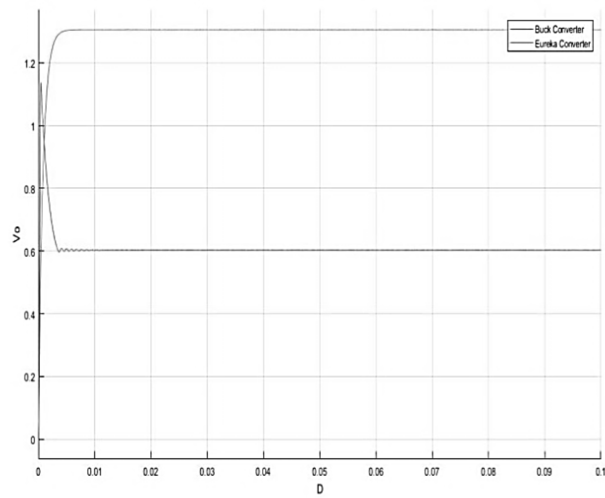

Fig. 14. V_o for Buck and Eureka converter for a target voltage of 1.42 volts.

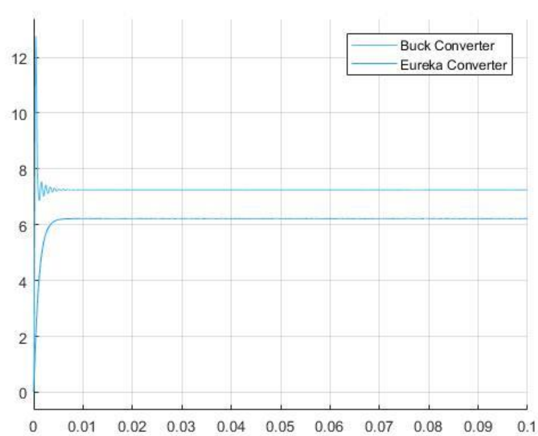

Fig. 15. V_o for a target voltage of 7.5 volts.

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