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Comparison of electronic load using linear regulator and boost converter

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ABSTRACT

Direct current (DC) electronic load is useful equipment for testing the electrical system. It can emulate various load at a high rating. The electronic load requires a power converter to operate and a linear regulator is a common option. Nonetheless, it is hard to control due to the temperature variation. This paper proposed a DC electronic load using the boost converter. The proposed electronic load operates in the continuous current mode and control using the integral controller. The electronic load using the boost converter is compared with the electronic load using the linear regulator. The results show that the boost converter able to operate as an electronic load with an error lower than 0.5% and response time lower than 13 ms.

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1. INTRODUCTION

An electronic load is an equipment that can emulate the load. The advantages of using the electronic load are the load can be changed easily and has a high rating. It is a piece of useful equipment in testing electrical system like a battery [1], photovoltaic [2], generator [3], [4], or motor [5] at various load condition. The electronic load is also being used as the dump load to maintain the power quality of an electrical system [3], [6]. The curve tracing of photovoltage (PV) uses the electronic load to determine the degradation level of the PV panel [7]. The electronic load is also being used in surge protection [8]. These examples show that the electronic load is useful in various sector. A commercial electronic load can cost around 500 USD for a 200 W rating and can reach up to 18000 USD for a 6kW rating. Nevertheless, there are some researches available to build an electronic load at a lower cost.

Commonly, the linear regulator is preferred in the direct current (DC) electronic load [1], [9]-[11]. The metal-oxide-semiconductor field-effect transistor (MOSFET) and insulated-gate bipolar transistor (IGBT) is used to emulate the load. This is done by varying the voltage across the gate-source terminal of the MOSFET and the voltage across the gate-emitter terminal of the IGBT. Since the voltage required to control these power switch change with temperature, a closed-loop controller is needed to ensure the electronic load is able to maintain its operation. It also requires a complicated voltage-controlled gate drive. The control becomes more complicated since most of the power dissipation occurs at the power switch that results in high-temperature variation. To overcome this problem, the power switch needs to operate in the saturation

and cut-off regions. This can be achieved by using the load switching method [12]-[15]. Nevertheless, this method requires multiple power switches or resistances, which complicates the control process and this requires closed-loop control.

Since both linear regulator and load switching method requires closed-loop control, a controller is needed. The proportional-integral (PI) controller is commonly used to control the electronic load [1], [12], [16, [17]. There is also the user of the fuzzy logic controller to improves the performance of the electronic load using the PI controller [17]. The proportional-integral-derivative (PID) neural network controller has also been introduced to control the electronic load [18]. Another controller used in the electronic load is the quasi-proportional-resonance controller [19]. These controllers are implemented using an analogue circuit [8], [10] or digital platforms like Arduino [1], [9] or other microcontrollers [12], [16].

The design of the controller and its implementation for the linear regulator and load switching method for the electronic load is complicated. An electronic load with a power converter that can easily be controlled is preferred. The boost converter is one of the switched-mode power supply (SMPS) that can easily be controlled and it is not severely affected by the temperature changes [18]. Nonetheless, this converter is rarely used in the electronic load. Currently, the electronic load using the boost converter does not focus on the passive component design and the control is based on the current-controlled system [20], [21]. The passive component design is important to ensure the electronic load operate properly and within an acceptable ripple. Since the electronic load can receive the current source, the electronic load with the current-controlled system may not work properly. Besides a proper design of electronic load using the boost converter, the comparison between this electronic load with the electronic load using the linear regulator is incomplete in term of accuracy and transient response [13].

This paper presents the design of the DC electronic load using the boost converter. The boost converter is expected to operate in the continuous current mode with the voltage and current ripple below 1%. The results are compared with the electronic load using the linear regulator. Since the linear regulator requires a closed-loop controller, the integral controller is chosen. For a fair comparison, the linear regulator using the boost converter also use the integral controller. The integral controller for both electronic loads is based on resistive feedback to ensure the electronic load is able to work with voltage and current sources. The next section discusses the design of the electronic loads using the linear regulator and boost converter. The next section shows the results and discussions. The last section concludes the result of the comparison.

2. DESIGN OF ELECTRONIC LOAD

The DC electronic load consist of several parts. The simple closed-loop DC electronic load is shown in Figure 1. When a DC power source is connected to a DC electronic load, the voltage and current sensors measure the input voltage and current (V_i and I_i), respectively. The V_i is divided by I_i to obtain the input resistance, R_i, based on Ohm's Law. The R_i is compared with the reference resistance, R_{ref}, which are set by the user. The R_i is positive and the R_{ref} is negative since the increase in control input to the power converter results in the reduction of emulated R_i. The error produced by comparing the R_i with the R_{ref} is fed into an integral controller. Based on the error, the integral controller adjusts the control input for the power converter. The power converter adjusts the operation according to the control input. The process continues until the R_i is equal to R_{ref}. There are two power converters used for the DC electronic load, which are the linear regulator and boost converter.

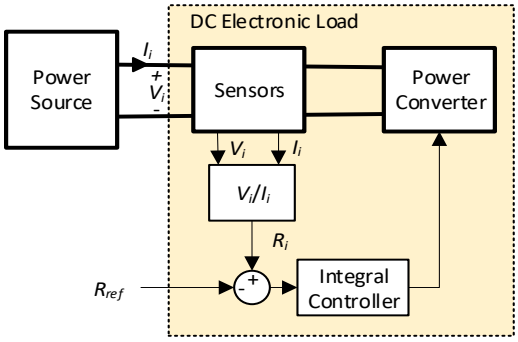

Figure 1. The block diagram of the DC electronic load

2.1. Linear regulator

The first power converter for the DC electronic load is the linear regulator. The MOSFET is chosen for the DC electronic load since it is easier to control compared to the transistor. The MOSFET has 3 terminals, which are the drain, source, and gate. The MOSFET is controlled by adjusting the gate-source voltage, V_{gs}. The higher the V_{gs}, the higher the drain current, I_d, that can pass through the MOSFET.

To design the DC electronic load using MOSFET, many characteristics of the MOSFET needs to be considered. The first characteristic is the safe operating zone, as shown in Figure 2. Since the electronic load is DC, the safe operating zone is small. The operation of the DC electronic load needs to maintain within the zone to avoid damaging the MOSFET. The temperature needs to be considered when it comes to the safe operating zone. When the temperature increases, this zone becomes smaller. Therefore, it is recommended to obtain a safe operating zone for the MOSFET at high temperature from the manufacturer. It is also important to install a large heat sink at the MOSFET to reduce the temperature increase at the MOSFET [22].

The I-V characteristic of the MOSFET is controlled by the V_{gs}. Nonetheless, the I_d and drain-source voltage, V_{ds}, also affects the I-V characteristic of the MOSFET, as shown in Figure 3. If the power source connected to the input of the DC electronic load is the voltage source, the V_{ds} becomes the V_i when the MOSFET is used in the DC electronic load using the linear regulator. The adjustment of V_{gs} results in the adjustment of the I_d. While if the power source connected to the input of the DC electronic load is the current source, the I_d becomes the I_i when the MOSFET is used in the DC electronic load using the linear regulator. The adjustment of V_{gs} results in the adjustment of the V_{ds}. The I_d-V_{ds} characteristic also changes when the temperature changes. Therefore, the open-loop operation is not possible since the control input V_{gs} changes over time.

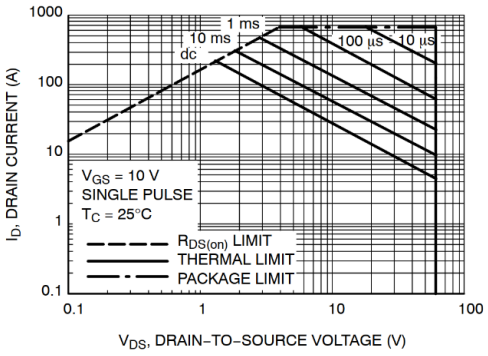

Figure 2. Example of the safe operating zone for the MOSFET at 25 °C [23]

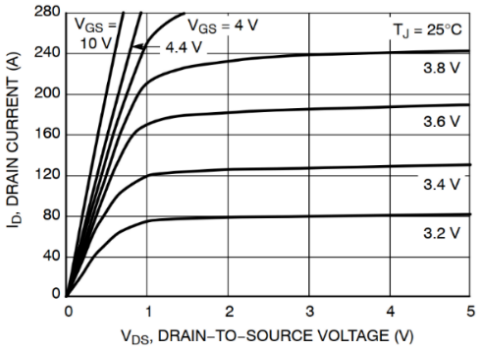

Figure 3. The I_d-V_{ds} characteristic curve for different V_{gs} at 25 °C [23]

The design of the DC electronic load is implemented in MATLAB/Simulink, as shown in Figure 4. It is based on the block diagram in Figure 1. There are two components inside the power converter, which are the MOSFET and the controlled voltage source block. Since the simulation does not have a safe operating zone and a proper temperature variation input, these effects cannot be simulated. The integral gain, K_i, is adjusted manually using the try and error method. Since the MOSFET response quickly, the K_i can be set at a high value without resulting in an unstable operation. The K_i chosen is 1000.

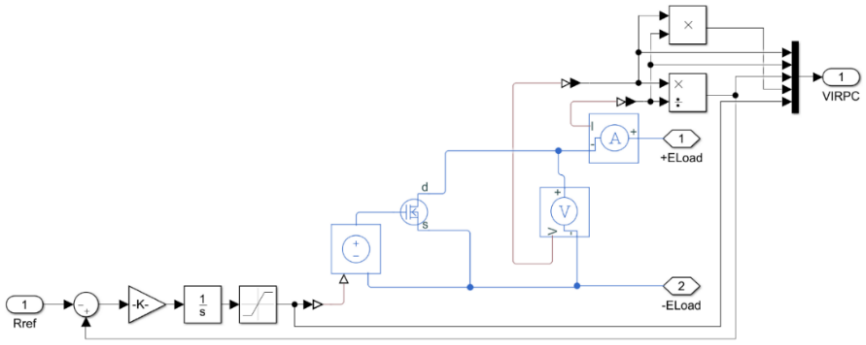

Figure 4. The implementation of the DC electronic load using the MOSFET

2.2. Boost converter

The important design step for the linear converter is on the safe operating zone and I_d-V_{ds} characteristic curve. However, the design of the boost converter shown in Figure 5 focuses on different aspects, which is the duty cycle, *d* and ripple [24]. The design consideration on the boost converter is the *d*. Since the *d* is limited from 0 to 1, a proper design of the R_o is crucial to avoid the operation outside the *d* limit. The boost converter is chosen from the SMPS category due to its low number of components and low I_i ripple. This is an important characteristic because the ideal DC electronic load should not have ripples. Nonetheless, the power converter under the SMPS category contains current or voltage ripples. Therefore, it is essential to choose the power converter with the low ripple, especially at the V_i and I_i. The control input from the integral controller is the *d* and it is converted into switching pulse, p_s, by the pulse width modulation, PWM.

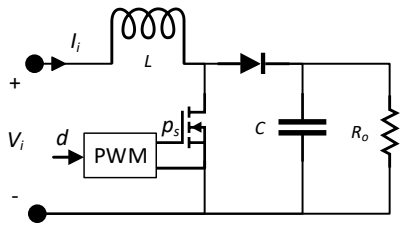

Figure 5. The circuit diagram of the boost converter

The *d*-R_o relationship is crucial when using the boost converter for the DC electronic load. This relationship is shown in (1) [24]. In an ideal condition, the d is "0 to 1". However, the boost converter unable to follow this range doe to the nonideality factor [25]. It is recommended that the operation of the boost converter is "0.10 to 0.75" to avoid voltage regulation problem. This is because when the d is above 0.75, the output voltage, V_o, begins to drop and affect the performance of the electronic load. Therefore, the minimum and maximum *d* (d_{min} and d_{max}) are 0.10 and 0.75, respectively. Then, the minimum and maximum R_i (R_{i_min} and R_{i_max}) need to be chosen. The R_{i_min} and R_{i_max} become the range of emulated resistance for the DC electronic load. The R_{i_min} and R_{i_max} need to obey the range in (2) [24]. In this design, the R_{i_min} and R_{i_max} are set to 10 and 100, respectively and the range obey (2). Then, the R_o is chosen within the range of (2).

$$R_o = \frac{R_i}{(1-d)^2} \tag{1}$$

$$\frac{R_{i\_max}}{(1-d_{min})^2} \leq R_o \leq \frac{R_{i\_min}}{(1-d_{max})^2} \tag{2}$$

$$V_i = \sqrt{P_{Ro} R_i} \tag{3}$$

The list of parameters is tabulated in Table 1. Since most of the power is transmitted to R_o, it is essential to ensure the R_o capable to handle the power. The power transmitted to R_o, P_{Ro}, is calculated using (3) [24]. The rating of the R_o is highly depended on the V_i, which is the voltage rating of the DC electronic load, and the R_i. Note that the rating of V_i is based on R_i and P_{Ro}. Therefore, the chosen R_o is 130 Ω (within the range of 123.5 Ω and 160.0 Ω).

Table 1. The desired specification and calculated parameters for the DC electronic load using the boost

Parameter	Value
Minimum Input Resistance, R_{i_min}	10 Ω
Maximum Input Resistance, R_{i_max}	100 Ω
Minimum Duty Cycle, D_{min}	0.10
Maximum Duty Cycle, D_{max}	0.75
Maximum Input Voltage, V_{i_max}	50 V
Switching Frequency, f_s (kHz)	100 kHz
Output Voltage Ripple Factor, γ_{Vo}	1%
Input Current Ripple Factor, γ_{Ii}	1%
Output Resistance, R_o	130 Ω
Inductance, *L* (mH)	19.26 mH
Capacitance, *C* (µF)	5.56 µF

A resistive load does not produce any voltage and current ripple. Nonetheless, the boost converter contains ripples and cannot be eliminated. To remove the current ripple at I_i, the inductance, L, chosen needs to be infinity. The infinity L is an impractical solution and results in a slow transient. Therefore, a 1% I_i ripple factor, γ_{Ii}, is chosen since it is accurate enough to produce a steady current. The L is calculated using (4) [24], which equals to19.26 mH. Although the V_o ripple factor, γ_{Vo}, can be ignored since this parameter is not considered in the DC electronic load, it still essential to avoid unstable operation. The γ_{Vo} is calculated using (5) [24], which equals to 5.56 µF.

$$L = \frac{4R_o}{27\gamma_{Ii}f_s} \tag{4}$$

$$C = \frac{1}{\gamma_{Vo}f_s}\left(\frac{1}{R_o} - \sqrt{\frac{R_{i\_min}}{{R_o}^3}}\right) \tag{5}$$

Since the boost converter consists of an inductor and capacitor, the transient response is much slower compared to the linear regulator. Therefore, the K_i is adjusted properly to ensure the stability of the electronic load. Using the try and error method, the chosen K_i is 3. The design of boost converter is then implemented into MATLAB/Simulink, as shown in Figure 6.

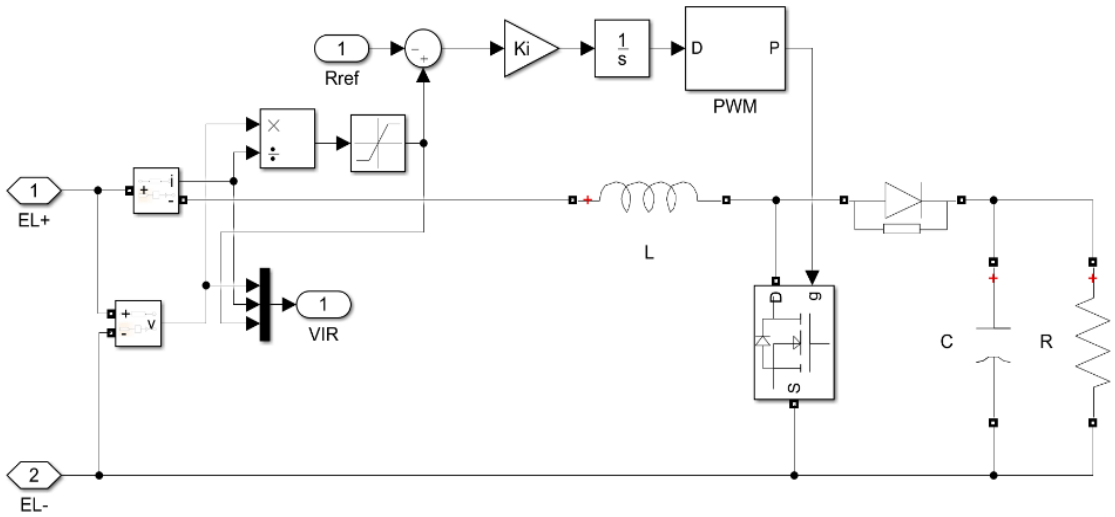

Figure 6. The implementation of the DC electronic load using the boost converter.

3. RESULTS AND DISCUSSION

A high accuracy emulation of the load is important for the DC electronic load. The lower the percentage error, $e_{\%}$, the higher the accuracy. The $e_{\%}$ is calculated using (6). The DC electronic loads using the linear regulator and boost converter are simulated separately with R_{ref} from 10 Ω to 100 Ω. Both electronic loads are connected to the 100 V voltage source. The V_i and I_i are measured to determine R_i. The $e_{\%}$ obtained at various R_{ref} are visualized in Figure 7. The results show that the electronic load using the linear regulator has a lower $e_{\%}$ compared to the electronic load using the boost converter. This means that the electronic load using the linear regulator has higher accuracy compared to the electronic load using the boost converter. This effect is caused by the I_i ripple present in the boost converter. According to [24], the highest ripple occur when the R_i is 4/9 out of R_o. Since R_o is 130 Ω, the highest I_i occur when R_i equals to 57.78 Ω. Based on Figure 7, it is clearly shown that $e_{\%}$ is the highest doing that condition. Therefore, the I_i ripple affects the accuracy of the electronic load using the boost converter.

$$e_{\%} = \frac{|R_i - R_{ref}|}{R_{ref}} \times 100\% \tag{6}$$

For the electronic load using the linear regulator, the result shows that the $e_{\%}$ becomes higher when the R_{ref} increases. Nonetheless, it is significantly lower compared to the electronic load using the boost

converter. It is worth mention that the simulation does not consider the effect of temperature variation and electrical noise. As mention before, the V_{gs} requires to emulate load changes with time. Therefore, it is harder to control the electronic load and may result in a higher error. The slight change of V_{gs} also affects the emulation of the load. Therefore, the electrical noise in the V_{gs} may significantly affect the accuracy of the electronic load using the linear regulator. The hardware implementation is required to analyst this effect, which is out of the scope of the study.

The electronic load using the linear regulator and boost converter are simulated separately with the R_{ref} is stepped-up from 20 Ω to 80 Ω at 0.03 s and stepped-down from 80 Ω to 20 Ω at 0.06 s. The simulation is conducted to ensure the electronic load transient response does not affect the experimental result during load emulation. The desired response for the electronic load is the I_i changes instantaneously. By referring to Figure 8, the electronic load using the linear regulator able to change instantaneously. However, the electronic load using the boost converter has a slow transient response. Assume that the steady-state time, t_s, is defined as the time taken for the parameter to achieve within 2% of its final value, the t_s during stepped-up load is 9.2 ms. While the t_s during stepped-down load is 12.9 ms.

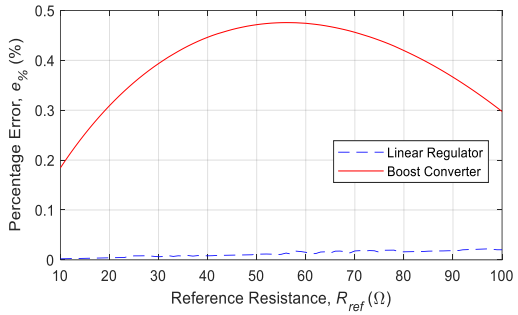

Figure 7. The $e_{\%}$ against R_{ref} for the linear regulator and boost converter in the DC electronic load application

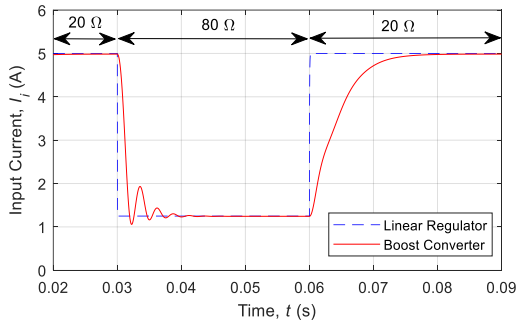

Figure 8. The transient response of I_i when the load is stepped-up from 20 Ω to 80 Ω and stepped-down from 80 Ω to 20 Ω

The delay during the load change is insignificant if the power converter connected to the electronic load has a slow response. However, the load emulation becomes inaccurate if the power converter connected to the electronic load has a faster response compared to the electronic load. The slow response is due to the requirement of the boost converter to has a large L, which reduced the I_i ripple. To avoid this problem, a higher fs is needed. Nonetheless, it may result in a higher switching loss. Which increase the heat generation at the power switch in the boost converter. If the transient response result is not collected for the experiment, the proposed electronic load can be applied to the experiment.

The power dissipation for the boost converter is mostly at the resistance. While the power dissipation for the linear regulator is mostly at the MOSFET. This is an undesired situation especially for high power load emulation since the MOSFET has limited safe operating area, especially during DC operation. The temperature is also a problem faced by the linear regulator based electronic load. Since the power dissipates mostly at the MOSFET, the temperature of the MOSFET increases significantly. This may lead to the failure of the MOSFET and the operation of the electronic load stops. The temperature increase also changes the V_{gs} significantly, thus a closed-loop system is needed to maintain the emulation of the load.

4. CONCLUSION

In general, the boost converter able to be used as the DC electronic load. Since the temperature is not significantly affecting the operating point, the open-loop system is an option. The power dissipation is located to the output resistance and not at the power switch. However, the electronic load using the boost converter is inferior compared to the electronic load using the linear regulator. When the temperature and electrical noise effects are discounted, the accuracy of the electronic load using the boost converter is lower compared to the electronic load using the linear regulator. This is due to the current ripple problem faced by the boost converter. The transient response of the electronic load using the boost converter is lower compared to the electronic load using the linear regulator. This is due to the large inductor needed to maintain a low current ripple. To summarize, the boost converter is suitable to be implemented for the DC electronic load. Nonetheless, it has lower accuracy and slower response when compared with the linear regulator.

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