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Pulse Width Modulation Control Model for Stabilizing Boost Converter Output Voltage Using LQR

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Abstract: DC-DC Boost Converter works to produce an output voltage greater than the input voltage. can be used to supply voltage in various systems. To supply voltage to a system, the boost converter works by applying a switch driven by a PWM generator. This paper presents the design of a control system to adjust the amount of duty cycle on a PWM generator. The use of the LQR control system and integral state feedback to control the duty cycle of the DC-DC Boost Converter is proven to be able to stabilize the output voltage. By providing a frequency of 500 Hz with an input voltage of 1.5 Volts and a reference voltage of 7 Volts, the best performance can be achieved, namely settling time at 5.28 seconds and rise time at 2.6 seconds. The expected performance can be achieved by adjusting the system's power supply requirements, such as determining the reference voltage and frequency of PWM generator.
Keywords: Boost Converter, DC-DC Converter, LQR, Integral State Feedback, Pulse Width Modulation

I. INTRODUCTION

Regulated dc power supply frequently employ dc-dc converters, a kind of electrical power circuits. Boost converter or step-up dc-dc topologies increase the voltage of the output by momentarily storing the energy from the input and releasing it at a higher voltage level [1][2][3], furthermore is to keep the output voltage as close as possible to the reference value that is required. [4]. Boost converters are often utilized in current industrial control applications such battery power systems [5][6], hybrid electric vehicle systems, new energy power systems [7], and DC motor control systems. The working principle of the boost converter is a power control circuit switching will give a signal to the transistor or Metal Oxide Semiconductor Field Effect Transistor (MOSFET). The classic switching technique commonly used is Pulse Width Modulation (PWM). One of the difficulties of using this technique is determining the right switching duty cycle to get the expected output voltage. The boost converter requires a controller in order to maintain the reference voltage and lower the harmonic level [8][9]. Boost converters had been built using a variety of control methods in earlier studies. Similar to [10][11], the boost converter's control was constructed with a PI controller, and the duty cycle approach was used. There are a number of techniques that are often employed in addition to PID controllers, including fuzzy [12][13], adaptive neuro fuzzy inference system (ANFIS) [14], sliding mode [15] and Linear Quadratic Regulator (LQR) controller [16]. LQR is a robust, high-performing[17], and optimum control approach [18]. LQR is a cutting-edge control technique for resolving optimal control issues. LQR may provide an optimum answer based on design requirements, it is more fascinating than other methods [19]. Stability and robustness are guaranteed by LQR[20]. Based on some of the advantages of using the LQR method, the goal of this research is to present an integrated converter that can regulate line voltage by controlling the duty cycle of the PWM using LQR.

II. DC-DC BOOST CONVERTER MODEL

The working principle of this circuit is a power control circuit switching will give a signal to the transistor or MOSFET. If the transistor or MOSFET is OFF then the current will flow to the inductor, the energy stored in the inductor will increase. When the transistor or MOSFET switch is ON, the energy in the inductor will drop and current will flow towards the load. In this way, the average value of the output voltage will correspond to the ratio between the opening time and the closing time of the switch. This is what makes this topology capable of producing an average output/load voltage value that can be higher or lower than the source voltage. Figure 1 demonstrate how the boost converter work, where V_{in} is input voltage, L is inductor, D is diode, C is capacitance and R is resistance.

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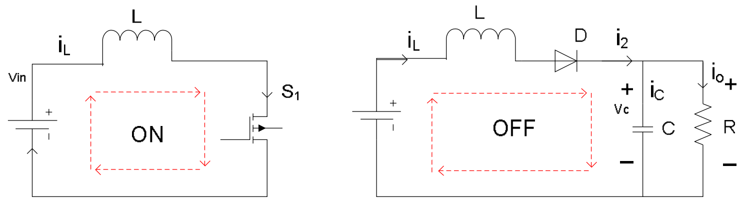

Fig 1. Boost Converter (a) Switch S_1 ON (b) Switch S_1 OFF

The boost converter equation is derived based on changes in voltage and current when the switch is ON and OFF. When the switch is ON as depicted in Fig 1(a). The change in current and voltage in the inductor and capacitor is stated in equations 1 and 2.

$$\frac{di_L}{dt} = \frac{v_{in}}{L} \tag{1}$$

$$\frac{dv_c}{dt} = \frac{-v_c}{RC} - \frac{i_{load}}{C} \tag{2}$$

Whereas when the switch is off as shown in Fig 1(b), changes in the voltage and current of the inductor and capacitor are expressed by equations 3 and 4.

$$\frac{di_L}{dt} = \frac{-v_C}{L} + \frac{v_{in}}{L} \tag{3}$$

$$\frac{dv_c}{dt} = \frac{i_L}{C} - \frac{v_c}{RC} - \frac{i_{load}}{C} \tag{4}$$

Furthermore, in order to be analysed, equations 1-4 are converted into state space equations. This is done during the switching phase, or the ON and OFF period. When switching ON, the time period T equals dT, and when switching OFF, it equals (1-d)T, where d is the duty cycle. In order to create a single equation known as state space averaging, the two switching conditions ON and OFF periods are merged.

If $\boldsymbol{x} = \begin{bmatrix} i_L \\ v_C \end{bmatrix}$ and $\boldsymbol{u} = \begin{bmatrix} v_{in} \\ v_{load} \end{bmatrix}$, then the state space averaging can be generated by entering the duty cycle value. Then the results can be seen in Equation 5.

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_C \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L}(1-d) \\ \frac{1}{C}(1-d) & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -\frac{1}{C} \end{bmatrix} \begin{bmatrix} v_{in} \\ i_{load} \end{bmatrix} \tag{5}$$

Equation 5 is then linearized so that the control system may be developed. Equation 6 could be used to express the outcome of this procedure in state space.

$$[\dot{x}] = \begin{bmatrix} 0 & -\frac{1}{L}(1-d) \\ \frac{1}{C}(1-d) & -\frac{1}{RC} \end{bmatrix} \boldsymbol{x} + \begin{bmatrix} \frac{v_{in}}{L(1-d)} \\ \frac{-v_{in}}{RC(1-d)^2} \end{bmatrix} d + \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & -\frac{1}{C} \end{bmatrix} \boldsymbol{w} \tag{6}$$

where $\boldsymbol{x} = \begin{bmatrix} i_L \\ v_C \end{bmatrix}$, $\boldsymbol{w} = \begin{bmatrix} v_{in} \\ i_{load} \end{bmatrix}$ and d is the duty ratio. Meanwhile, the system output when the switch is ON or OFF is $y = v_C = v_{out}$, which can be stated in state-space as in equation 7.

$$\mathbf{y} = [0 \quad 1]\,\mathbf{x} \tag{7}$$

III. CONTROL MODEL

In accordance with the objectives of this research, the control system is used to adjust the PWM duty cycle on the Boost Converter. The research utilizes two control strategies: LQR and integral state feedback. A state-space model $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$ will depict the regulated system. The proposed model of the control system is presented in Fig 2. The fundamental idea behind this control system is to add an integrator to the feedforward path between the PWM generator and the error comparator resulting from comparing the output voltage of the boost converter to the reference voltage.

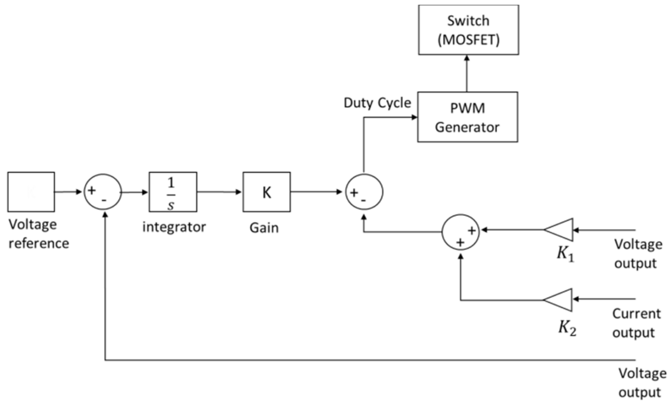

Fig 2. Proposed Control System

Based on Fig 2, integrator in integral state feedback is used to eliminate steady-state error, while the value of the gain K is obtained by using the optimum control, in this case is LQR is represented as $\mathbf{K} = [K_1 \quad K_2]$.

IV. RESULT AND DISCUSSION

A current and voltage control mechanism in the boost converter is suggested to achieve these goals. Fig 2 depicts the suggested control system, which Simulink is then used to simulate. The following are boost converter parameters, input voltage $v_{in} = 2{,}2\ Volt$ [21], resistance $R = 28\ \Omega$, inductance $L = 330\ \mu H$, frequency switch 5000 Hz.

While the setpoint and state feedback error gain $(\widehat{\mathbf{K}})$ are control system parameters. The LQR formula, $\widehat{K} = LQR(\widehat{\mathbf{A}}, \widehat{\mathbf{B}}, \mathbf{Q}, \mathbf{R})$, is used to calculate the state feedback error gain. By calculating out the value of the A and B matrices, A and B are determined. The above parameter, which may be represented as follows,

$$A = \begin{bmatrix} 0 & -1424.24 \\ 989 & -75.21 \end{bmatrix} B = \begin{bmatrix} 103159.25 \\ -5414.91 \end{bmatrix} C = [0 \quad 1] \tag{8}$$

To calculate value of $\widehat{\mathbf{K}}$, it is necessary to determine the matrix of weight values of Q and R. The first simulation was done using three variations of Q and R values. The value of $Q_1 = [1\,0\,0 ; 0\,1\,0 ; 0\,0\,1]$ and $R = \{1\}$.

In this research, the simulation is carried out in two ways, Boost converter with PWM without and with control system. By implementing the Boost Converter circuit in Fig 1 using Simulink, it can be seen the effect of the duty cycle to generate the output voltage. In this study the simulation was carried out by providing a fixed input voltage 1.5 Volt and 3 Volt, duty cycle (0.2, 0.5, 0.8) and frequencies (10 Hz, 100Hz), as seen in Table 1.

TABLE 1. Output Voltage Without PWM Control System

Vin (Volt)	Duty Cycle (D)	Frequency (Hz)	Vout (Volt)
1.5	0.2	10	2,32
	0.5		3,068
	0.8		4,044
	0.2	100	4,456
	0.5		7,584
	0.8		9,018
3	0.2	10	4,956
	0.5		6,549
	0.8		6,641
	0.2	100	9,345
	0.5		15,6
	0.8		18,47

Based on table 1, the magnitude of the boost converter voltage output is very dependent on the duty cycle and frequency given. By providing the same input voltage and duty cycle, the output voltage will be greater if the frequency given is greater.

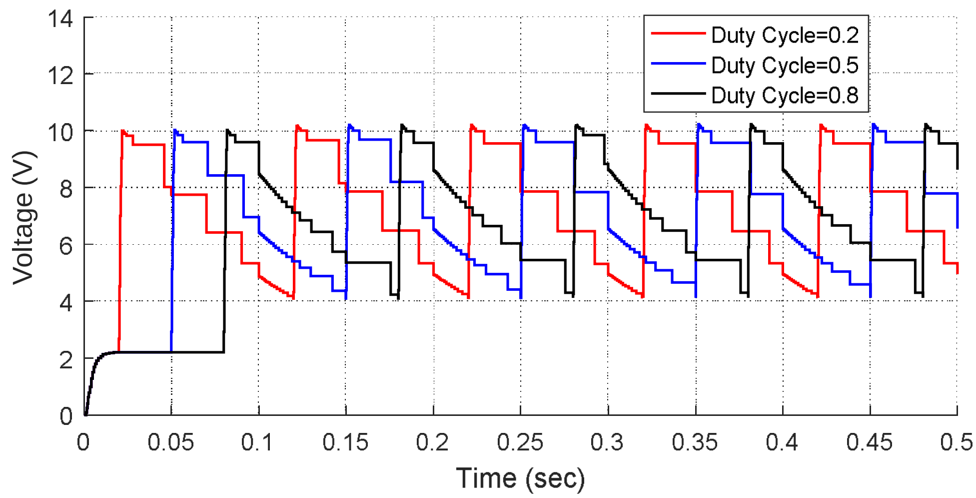

Fig 3. Output voltage without PWM controller

Graphically, this output voltage can be seen in Figure 3. The shape of the voltage fluctuates following the ON-OFF duty cycle period and fluctuates according to the given frequency. Likewise, the generated current will fluctuate following the ON-OFF period given in the duty cycle. Based on these results, setting the duty cycle is necessary so that the output voltage and current match the required load.

The use of LQR and integral state feedback as duty cycle controllers on the PWM generator is able to stabilize the output voltage. In addition, by adding a reference voltage, the output voltage can also be adjusted to the expected voltage, as shown in Fig 4.

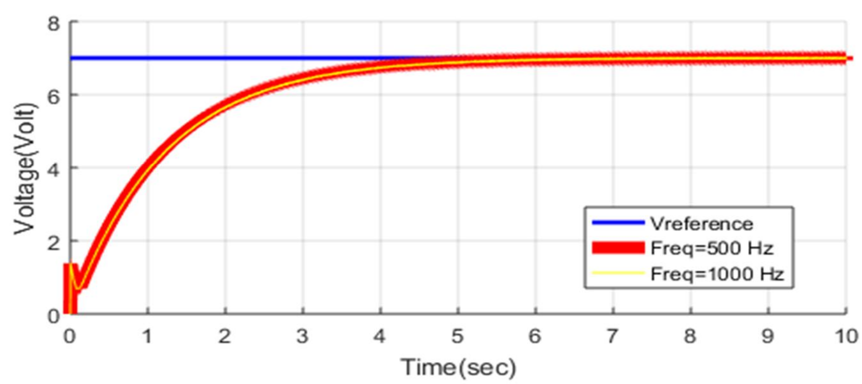

Fig 4. Output Voltage with LQR controller

Figure 4 above is a graph of the output voltage when the Boost Converter is given an input voltage of 1.5 Volts and a reference voltage of 7 Volts. The duty cycle is determined based on the control signal generated by LQR and integral state feedback, while the PWM generator frequency used is 500 Hz and 1000 Hz. The two graphs show that the control system that is used can work well, can stabilize the output voltage and is in accordance with the reference voltage.

The performance of the control system can be seen in Table 2, which is determined based on the rise time, settling time and the magnitude of the steady state error (SSE). When the PWM generator is given a frequency of 1000 Hz, the control system reaches stability at 5.08 seconds. This is slightly faster than when the PWM generator is given a frequency of 500Hz, which is stable at 5.28 seconds. In addition, the greater the frequency of the PWM generator, the smaller the error will be. In Table 2 it can be seen that the error at a frequency of 1000 Hz is also slightly smaller than 500Hz.

TABLE 2. Performance LQR Control System

Vin (Volt)	Vreference(Volt)	Freq(Hz)	RiseTime	SettlingTime	SSE (%)
1.5	7	10	NaN	NaN	6.3
		100	NaN	NaN	6.3
		500	2.6393	5.2832	0.0207
		1000	2.7559	5.0818	0.0185
		5000	2.6104	5.3988	0.0458
		10000	2.6011	5.4526	0.0580

However, the use of this control system also has limitations, namely it cannot be stable at certain frequencies, either very low or high. In this case, the control system is no longer able to achieve stability at frequencies smaller than 100 Hz. The table also shows that when the frequency increases, it will also reach stability longer. This is indicated by the settling time value of 5.45 seconds for the 10KHz frequency and 5.39 for the 5KHz frequency.

V. CONCLUSIONS

DC-DC Boost Converter can work well by controlling the PWM generator duty cycle. The LQR method and integral state feedback are able to stabilize the output voltage of the boost converter and produce a relatively small error. Using the controller, the duty cycle can be set precisely. After the duty cycle controller is used, the next determinant is the frequency used in the PWM generator. By providing a frequency of 500 Hz with an input voltage of 1.5 Volts and a reference voltage of 7 Volts, the best performance can be achieved, namely settling time at 5.28 seconds and rise time at 2.6 seconds.

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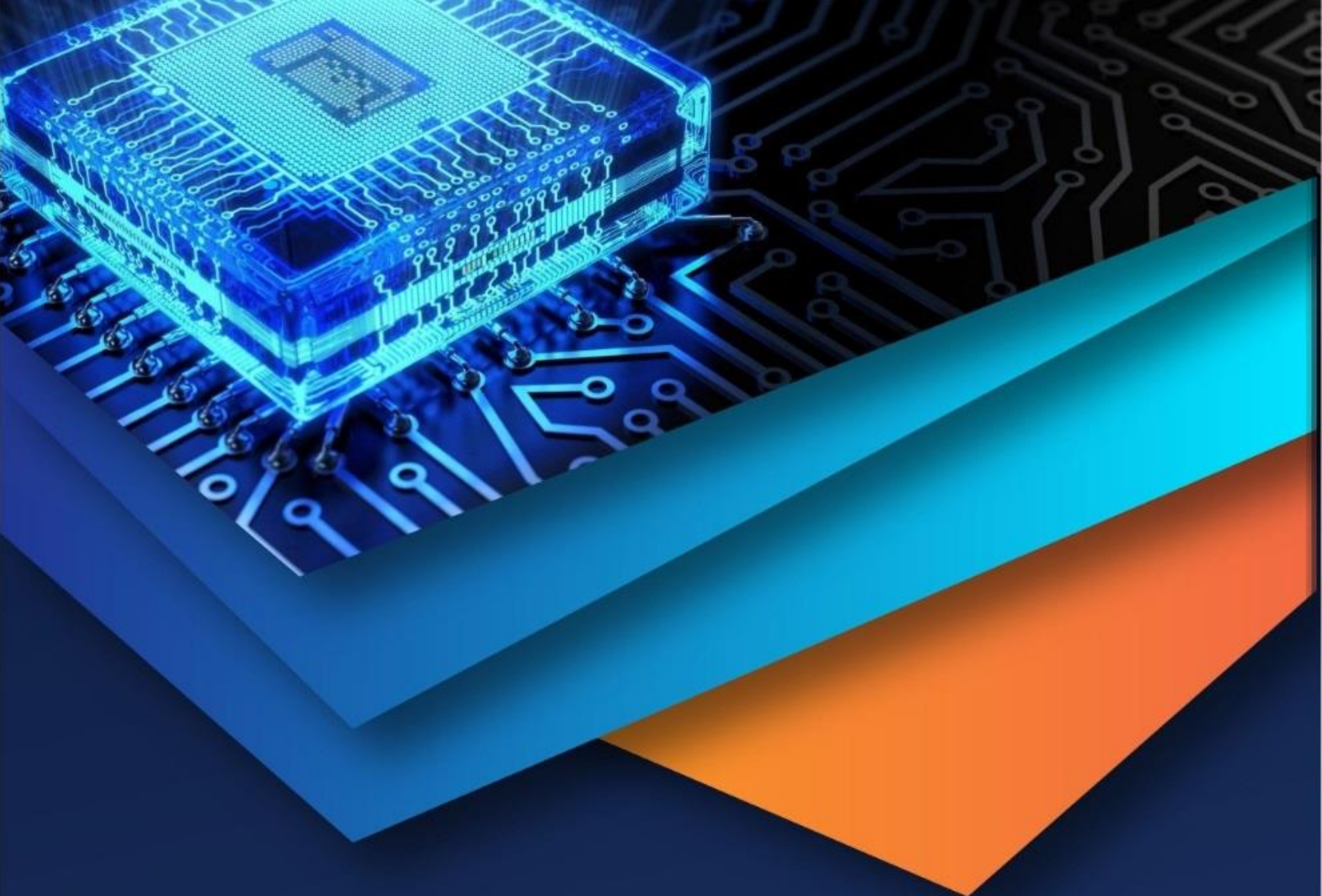

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