Improved Dynamic Response of Buck Converter using Fuzzy Controller

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Abstract

This paper presents comparative performance of Buck Converter in both open as well as closed loop. With the help state equations Mathematical Model of Buck Converter is designed in MATLAB/SIMULINK. The obtained output response of open loop Buck Converter is sluggish, not optimum and consists of peak overshoots. PI Controller is used in closed loop model of Buck Converter. Output Voltage is compared with a reference signal, which then is processed through a controller (PI/Fuzzy). The obtained signal is superimposed with a carrier signal and given to switching device used. To further optimize the performance of Buck Converter and eliminate the peak overshoot present in output response, Fuzzy controller is used. Here Suguno type Fuzzy is used.

Keywords: Buck Converter, PI Controller, Fuzzy Controller, Suguno, Pulse Width Modulation

1. Introduction

Modern electronic devices require efficient, high quality, light weight power supplies. We have linear power regulators, whose principle of operation depends on current or voltage division which is inefficient. The main area of application is at low power levels. When it comes to high power levels switching regulators are used where switch operates in on and off states. Latest power electronic switches can operate at high frequencies. Therefore, faster dynamic response to rapid changes is the load current is possible with high operating frequencies. These High frequency electronic power processors are used in dc-dc power conversion

The main functions of dc-dc converters are:

1. It converts DC input voltage into DC output voltage.
2. It provides isolation between source and load.
3. It can regulate the output voltage against load.
4. It can reduce the ac voltage ripple on the dc output voltage.

PWM dc to dc converters which are very popular for the last few decades and can be used at all power levels [1].

Pulse width modulation (PWM) is the most widely used method for controlling the output voltage. It maintains a constant switching frequency and varies the duty cycle. Duty cycle is defined as the ratio of switch on time to reciprocal of the switching frequency (fsw). Since the switching frequency is fixed, this modulation scheme has a relatively narrow noise spectrum allowing a simple low pass filter to sharply reduce peak-to-peak ripple at output voltage. This requirement is achieved by arranging an inductor and capacitor in the converter in such a manner as to form a low pass filter network. This requires the frequency of low pass filter to be much less than switching frequency (fsw).

Some applications have additional technical constraints. Consider the power supplies used in battery powered electronics, such as laptop computers or mobile phones have a requirement of maintaining high efficiency over a wide range of loads. In desktop computers and servers, the microprocessor supplies must include the capabilities of digitally programmed output voltage. The output must depend on the load as well the dynamic response must be faster even for large load transients. Voltage Regulator Modules have multi phase architectures

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consisting of several buck or similar converter modules which operate in parallel to share the load current in order to improve dynamic response [2].

DC/DC converter performance optimization is important to accommodate the growing need for efficiency in portable electronic device battery life and an ever increasing world climate of energy maximization. Existing efficiency work focuses largely on performance of the buck converter [3][4][5][6][7][8]; Various techniques exist which improve buck converter performance, including synchronous rectification [4][7], Mode Hopping (CCM/DCM) [8], Zero-Voltage Switching (ZVS) [9][10], variable switching frequency[2][8], and Hybrid (Mode Hopping and variable frequency) [9]. These techniques are summarized and compared by Zhou [3]. Djekic et. al. compared synchronous and asynchronous rectification buck converters for efficiency at various loads and switching frequencies [4].

There are various simulation packages available to design power electronic systems. Without these simulation packages, designing power electronic systems is difficult, laborious, expensive and time consuming. Among the available various simulation packages, MATLAB/SIMULINK is used. Buck Converter is simulated using MATLAB/SIMULINK. PWM technique is used to control to control output response. Its output response i.e open loop response, closed loop response with PI controller, closed loop response with Fuzzy controller is compared. It has been shown that dynamic response of closed loop buck converter has improved using fuzzy controller when compared to PI controller and open loop buck converter.

2. Buck Converter

A buck converter acts like a switch mode power supply (SMPS). SMPS can achieve high energy efficiency and high voltage accuracy even it is non linear and discontinues in nature. A linear regulator can also be used in the place of a buck converter, but the energy dissipation is high for linear regulators, so to overcome this drawback we opt for buck converter. The dc-dc buck converter topology is most widely used power management and microprocessor voltage-regulator applications. These applications require high frequency and transient response over a wide load current range. They can convert high voltage into low regulated voltage. Buck converter can be used in computers, where we need voltage to be stepped down. Buck converter provides long battery life for mobile phones which spend most of the time in stand-by state [11].

The name “Buck Converter” itself indicates that the input voltage is bucked or attenuated and low voltage appears at the output. A buck converter or step down voltage regulator provides non isolated, switch mode dc-dc conversion with the advantage of simplicity and low cost [11].

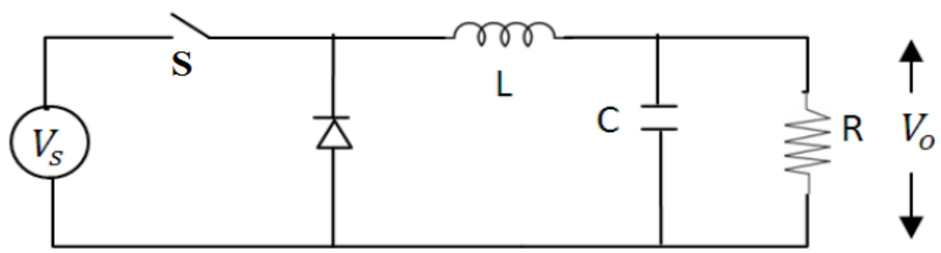

Figure 1. Circuit Diagram of Buck Converter

Figure 2, shows a simplified dc-dc buck converter that accepts a dc input and uses pulse width modulation of switching frequency to control the output voltage. Switch mode power supply is generally used to provide the output voltage which is less than the input voltage to the load from an intermediate DC input voltage bus or a battery source. A simplified buck converter point of load which has power supply from a switch mode buck converter is shown in Figure.3. The buck converter consists of main power switch, a diode, a low-pass filter (L and C) and a load [2]. The basic buck converter operates in ON and OFF states. In ON state i.e. when the switch is closed the current to load is supplied from source voltage through inductor, where inductor gets charged to its peak level. Where as in OFF state i.e. when switch is open the inductor acts as source to the load.

2.1. Two States of operation of Buck Converter

2.1.1. On State

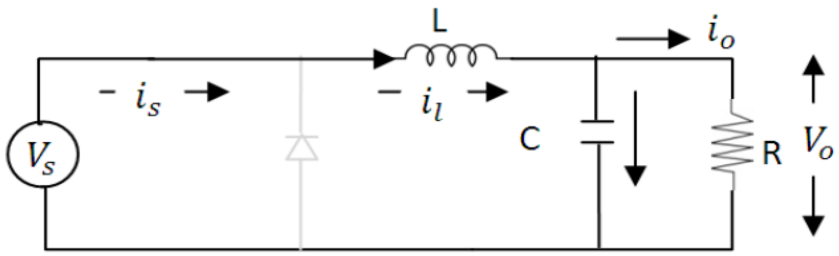

Figure 2. Equivalent Circuit during ON State

2.1.2 Off State

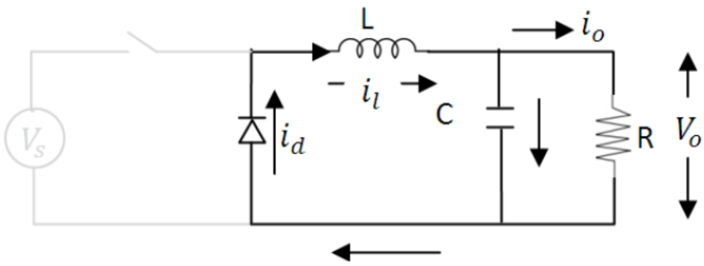

Figure 3. Equivalent Circuit during OFF State

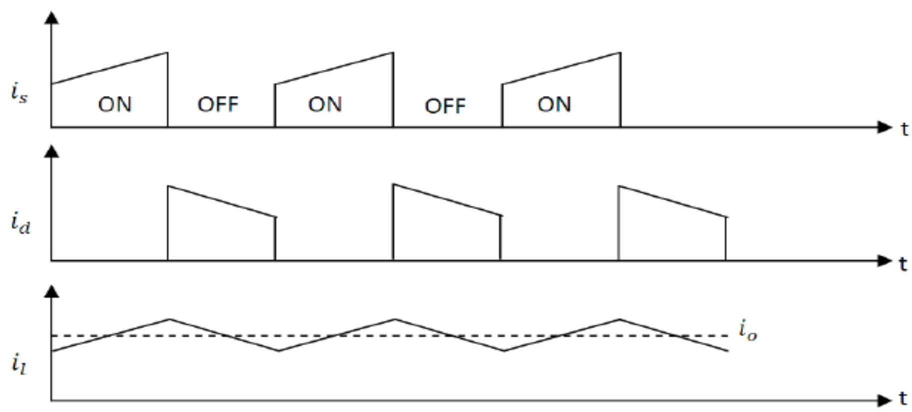

Figure 4. Waveforms of Buck Converter

The relationship between input voltage, output voltage and the switch duty cycle 'D' can be derived from VL waveform. According to Faraday's law, the inductor volt second product over a period of steady state operation is zero [1].

For the buck converter:

$$(V_s - V_o)DT = -V_o(1 - D)T$$

Where
Vs: Source Voltage
Vo: Load Voltage
T: Time Period
D: Duty Cycle

Hence the dc voltage transfer function can be defined as the ratio of the output voltage to the input voltage,

$$D = \frac{V_o}{V_s}$$

3. PID Controller

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism widely used in industrial control systems. A PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly.The PID controller calculation (algorithm) involves three separate parameters; the Proportional, the Integral and Derivative values. The Proportional value determines the reaction to the current error, the Integral determines the reaction based on the sum of recent errors and the Derivative determines the reaction to the rate at which the error has been changing. The weighted sum of these three actions is used to adjust the process via a control element such as the position of a control valve or the power supply of a heating element.By "tuning" the three constants in the PID controller algorithm the PID can provide control action designed for specific process requirements. The response of the controller can be described in terms of the responsiveness of the controller to an error, the degree to which the controller overshoots the setpoint and the degree of system oscillation. Note that the use of the PID algorithm for control does not guarantee optimal control of the system.

3.1. Proportional term

The proportional term makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant Kp, called the proportional gain.
The proportional term is given by:

$$P_{OUT} = K_p e(t)$$

where
Pout: Proportional output
Kp: Proportional Gain, a tuning parameter
e: Error = SP − PV
t: Time or instantaneous time (the present)

A high proportional gain results in a large change in the output for a given change in the error. If the proportional gain is too high, the system can become unstable. In contrast, a small gain results in a small output response to a large input error, and a less responsive (or sensitive) controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances. In the absence of disturbances pure proportional control will not settle at its target value, but will retain a steady state error that is a function of the proportional gain and the process gain. Despite the steady-state offset, both tuning theory and industrial practice indicate that it is the proportional term that should contribute the bulk of the output change.

3.2. Integral Term

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time (integrating the error) gives the accumulated offset that should have been corrected previously. The accumulated error is then multiplied by the integral gain and added to the controller output. The magnitude of the contribution of the integral term to the overall control action is determined by the integral gain, Ki. The integral term is given by:

$$I_{OUT} = K_i \int_0^t e(\tau)\, d\tau$$

where
Iout: Integral output
Ki: Integral Gain, a tuning parameter
e: Error = SP − PV
t: Time in the past contributing to the integral response

The integral term (when added to the proportional term) accelerates the movement of the process towards set point and eliminates the residual steady-state error that occurs with a proportional only controller. However, since the integral term is responding to accumulated errors from the past, it can cause the present value to overshoot the setpoint value (cross over the set point and then create a deviation in the other direction).

3.3. Derivative Term

The rate of change of the process error is calculated by determining the slope of the error over time (i.e. its first derivative with respect to time) and multiplying this rate of change by the derivative gain Kd. The magnitude of the contribution of the derivative term to the overall control action is determined the derivative gain, Kd.
The derivative term is given by:

$$D_{OUT} = K_d \frac{de}{dt}$$

where
Dout: Derivative output
Kd: Derivative Gain, a tuning parameter
e: Error = SP − PV
t: Time or instantaneous time (the present)

The derivative term slows the rate of change of the controller output and this effect is most noticeable close to the controller setpoint. Hence, derivative control is used to reduce the magnitude of the overshoot produced by the integral component and improve the combined controller-process stability. However, differentiation of a signal amplifies noise in the signal and thus this term in the controller is highly sensitive to noise in the error term, and can cause a process to become unstable if the noise and the derivative gain are sufficiently large.
The output from the three terms, the proportional, the integral and the derivative terms are summed to calculate the output of the PID controller.

Kp: Proportional Gain - Larger Kp typically means faster response since the larger the error, the larger the feedback to compensate. An excessively large proportional gain will lead to process instability. Ki: Integral Gain - Larger Ki implies steady state errors are eliminated quicker. The trade-off is larger overshoot: any negative error integrated during transient response must be integrated away by positive error before we reach steady state. Kd: Derivative Gain - Larger Kd decreases overshoot, but slows down transient response and may lead to instability.

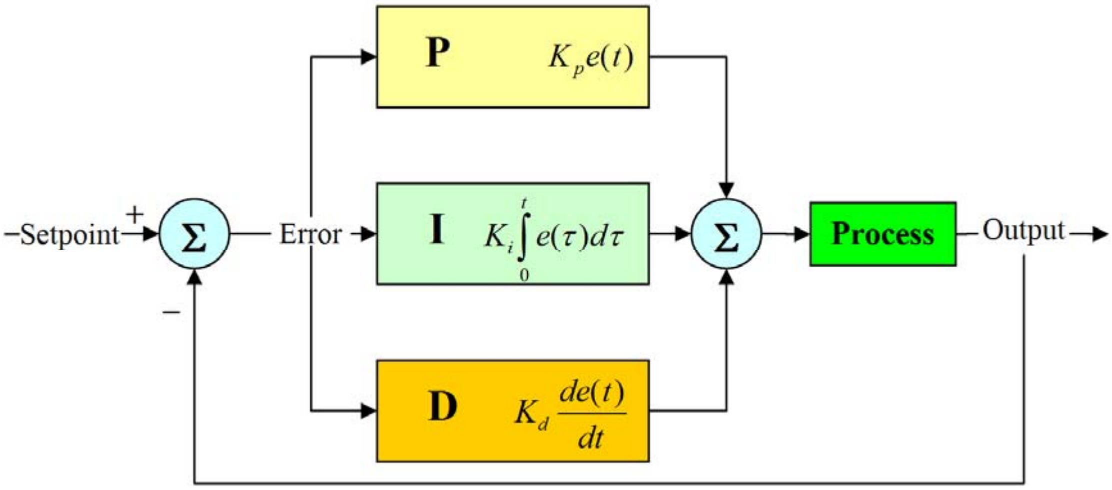

Figure 5. Block Diagram of a PID Controller

4. Fuzzy Controller

A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed by expert experience or knowledge database. First, set the error e(t) and the error variation de(t) of the angular velocity to be the input variables of the fuzzy logic controller. The control voltage u(t) is the output variable of the fuzzy logic controller. The linguistic variables are defined as {mf1, mf2, mf3, mf4, mf5, mf6, mf7}

The fuzzy rules are summarized in Table 3. The type of fuzzy inference engine is Suguno.

ce(pu) \ e(pu)	mf1	mf2	mf3	mf4	mf5	mf6	mf7
mf1	mf1	mf1	mf2	mf2	mf3	mf3	mf4
mf2	mf1	mf2	mf2	mf3	mf3	mf4	mf5
mf3	mf2	mf2	mf3	mf3	mf4	mf5	mf5
mf4	mf2	mf3	mf3	mf4	mf5	mf5	mf6
mf5	mf3	mf3	mf4	mf5	mf5	mf6	mf6
mf6	mf3	mf4	mf5	mf5	mf6	mf6	mf7
mf7	mf4	mf5	mf5	mf6	mf6	mf7	mf7

Figure 6. Fuzzy Rules

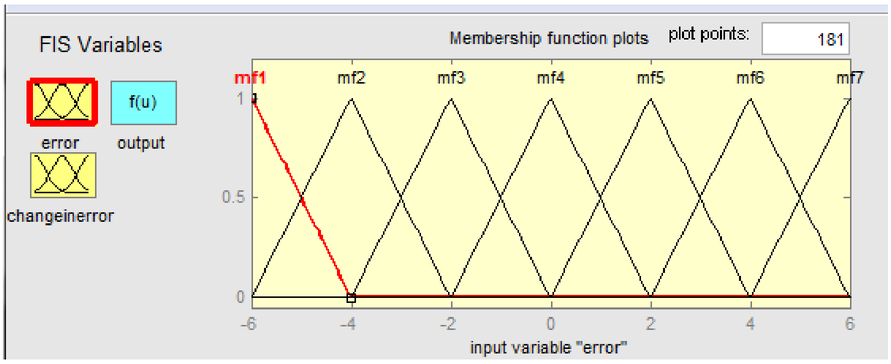

Figure 7. Membership functions for error normalized input

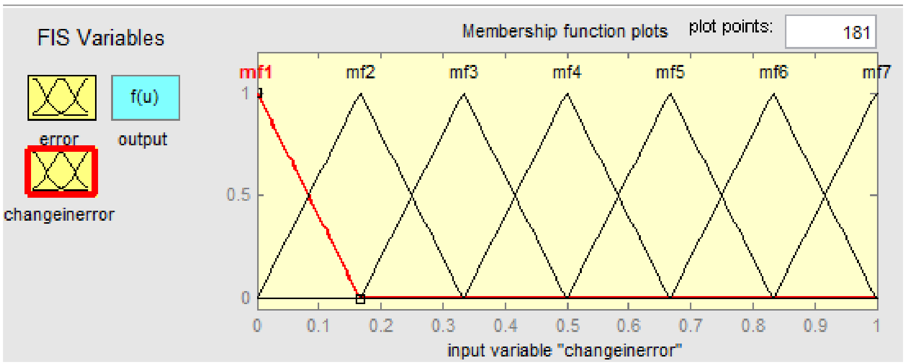

Figure 7. Membership functions for changeinerror normalized input

5. Simulation Results

5.1. Open Loop Simulink Model of Buck Converter

Buck Converter has been modeled using the following equations:

$$\frac{di_L}{dt} = \frac{1}{L}(V_g * d - i_L * R_L - V_o)$$

$$\frac{dV_C}{dt} = \frac{1}{C}(i_L - i_o)$$

$$V_o = V_C + ESR(i_L - i_o)$$

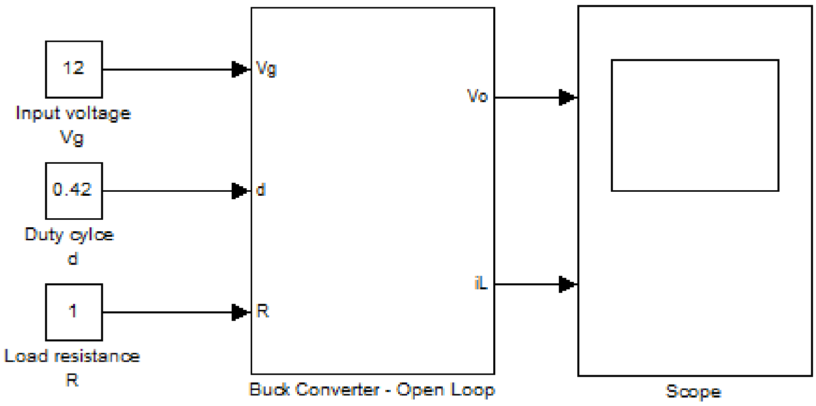

Figure 8. Simulink Model of Open Loop Buck Converter

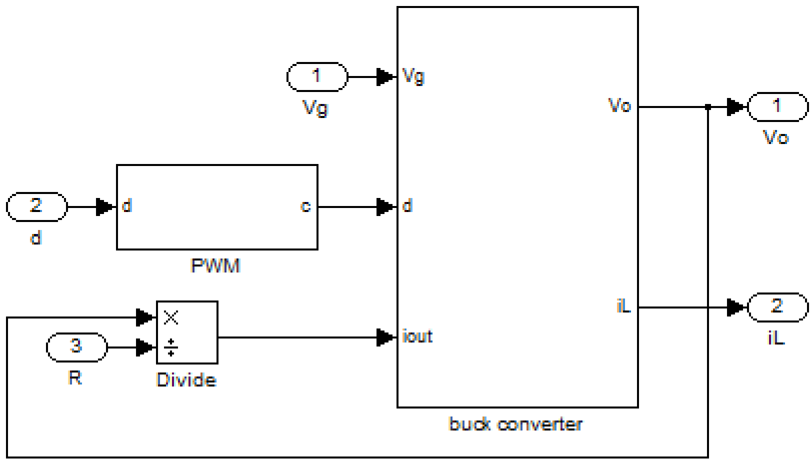

Figure 9. Subsystem of Open Loop Buck Converter

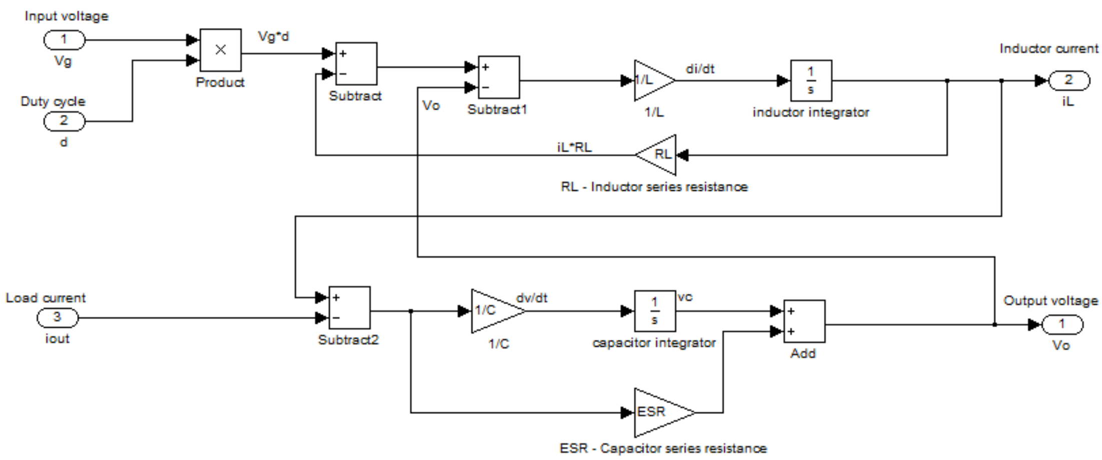

Figure 10. Subsystem of Buck Converter

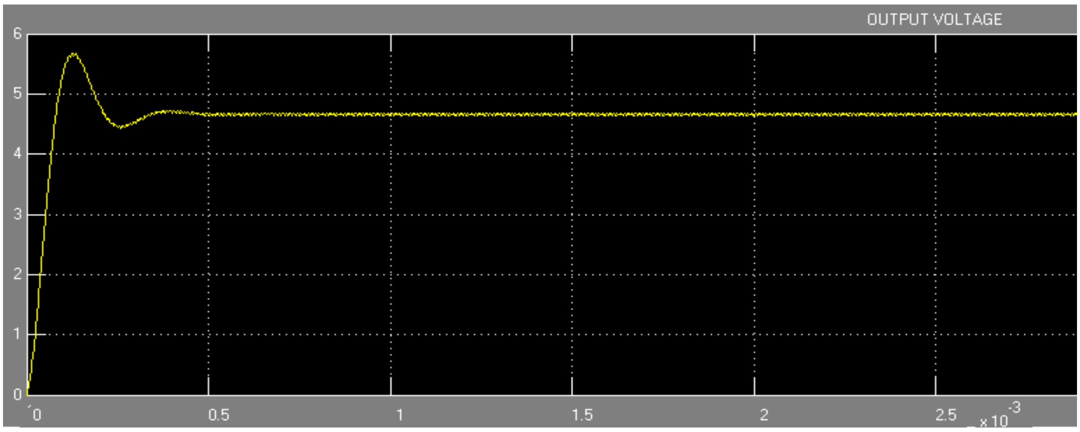

Figure 11.Output Voltage waveform of buck converter using Open loop model

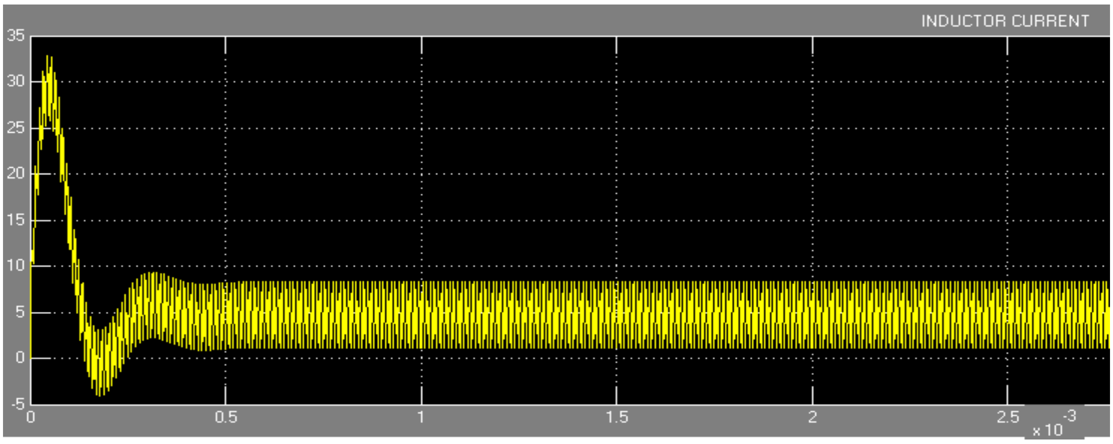

Figure 12. Inductor Current waveform of buck converter using Open Loop model

It can be observed that the obtained response is sluggish and takes a longer time to obtain steady state value. Our objective is to step down the voltage from 12V to 5V. Here we can observe that the output voltage has not stepped down to 5V but to a value near to 5V. This error has been corrected by implementing closed loop configuration using PI controller and Fuzzy Controller.

5.2. Closed Loop Simulink Model of Buck Converter using PI Controller

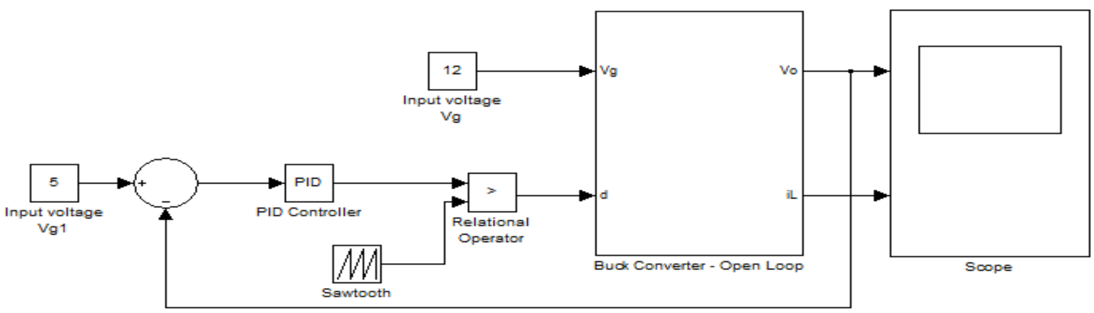

Figure 13. Closed loop model of Buck Converter using PI Conntroller.

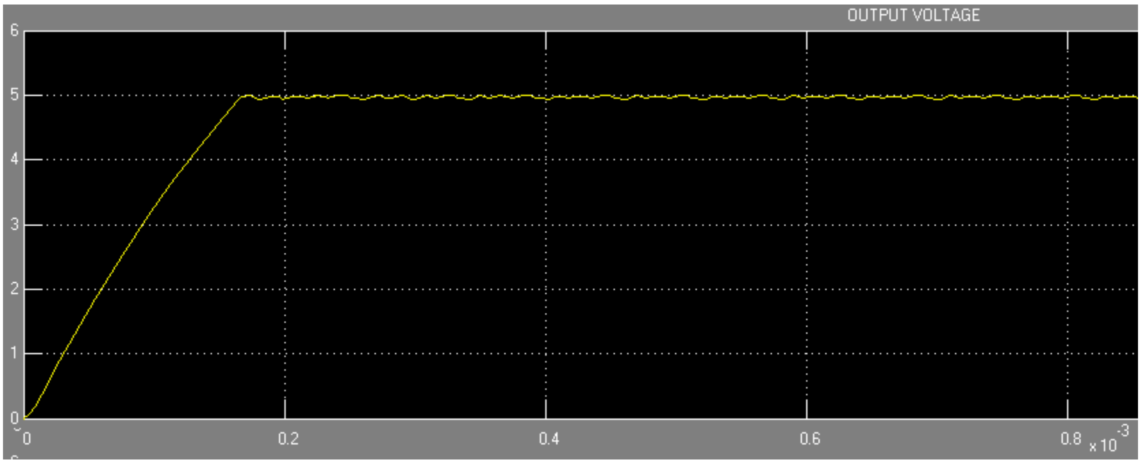

Figure 14. Output Voltage waveform of buck converter using PI Controller

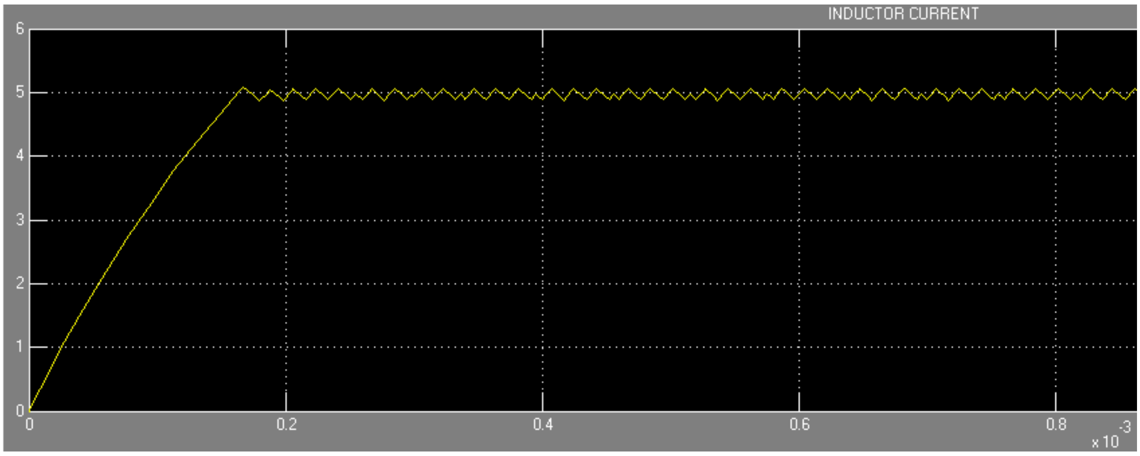

Figure 15. Inductor Current waveform of buck converter using PI Controller

It can be observed that dynamic response of output voltage and inductor current has been improved using PI controller. Desired output voltage of 5V has been obtained. The ripple content in inductor current has been reduced when compared to open circuit configuration.

5.3. Closed Loop Simulink Model of Buck Converter using Fuzzy Controller

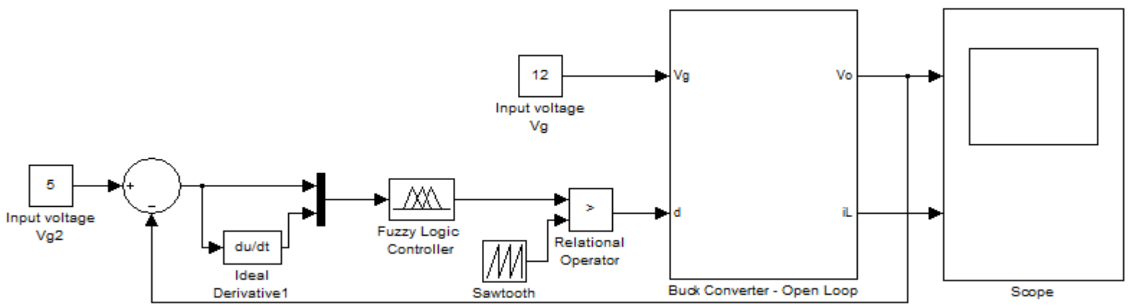

Figure 16. Simulink Model of Buck Converter using Fuzzy Controller

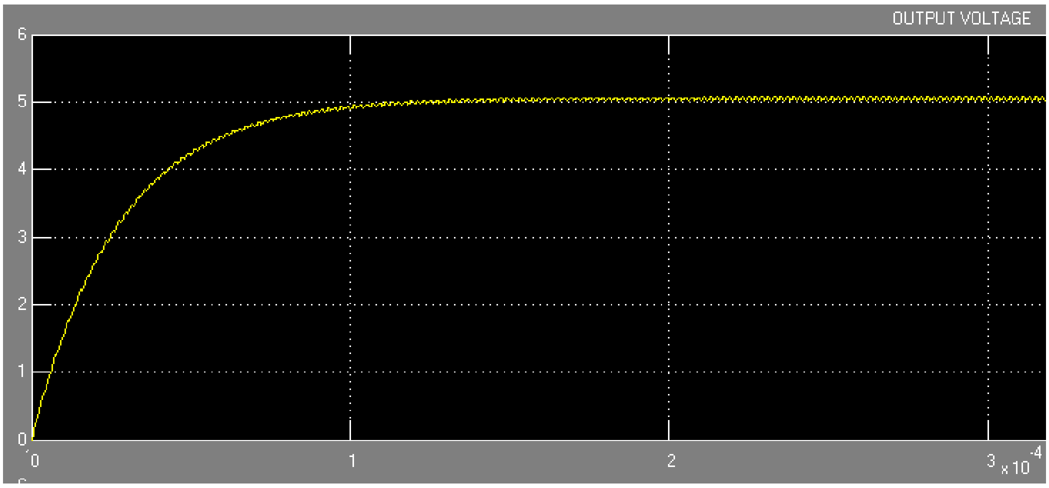

Figure 17. Waveform of Output Voltage of Buck Converter using Fuzzy Controller

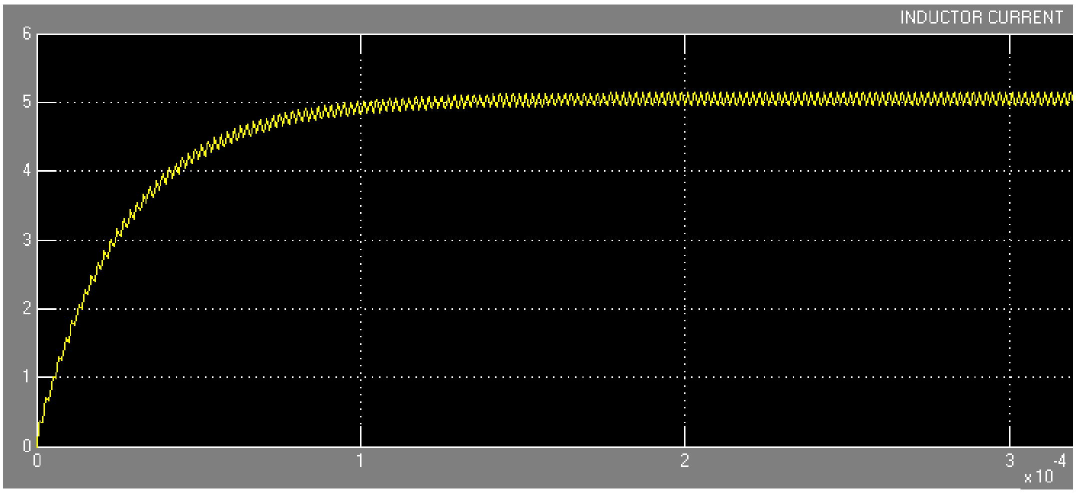

Figure 18. Waveform of Inductor Current of Buck Converter using Fuzzy Controller

It can be observed that the dynamic response of both output voltage as well as inductor current has been further improved when compared to reponse obtained by PI controller.

6. Conclusion

Open Loop Buck Converter and Closed Loop Buck Converter have been simulated using MATLAB/SIMULINK. It can be observed from the obtained results that the dynamic response of Closed Loop buck converter has improved using Fuzzy Controller when compared to dynamic response of Closed Loop buck converter using PI Controller and Open Loop Buck Converter. The results obtained from different methods are shown below.

Buck Configuration	%Mp	Settling Time
Open Loop	60	0.5 msec
Closed Loop(PI)	0	0.19 msec
Closed Loop(Fuzzy)	0	0.09 m sec

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