CHAPTER 3

PROPORTIONAL-INTEGRAL CONTROLLER FOR CONVERTERS

3.1 INTRODUCTION

PI control is becoming more popular because of its ability to maintain exact set point. This chapter aims at establishing the design and implementation of the conventional PI controllers at various operating points of the buck and boost converter. Simulation is done by using MATLAB 7.1 and the controller is subjected to various disturbances of input voltage and load changes.

3.2 PI CONTROL MODE

Proportional-Integral controller mode results from the combination of the proportional and the integral mode. Certain advantages of both control actions can be obtained from this mode. This mode is also called as the proportional plus reset action controller. Equations for the proportional mode and integral mode are combined, to have an analytic expression for this mode, which is given below:

$$P = K_p\, e_p + K_p\, K_t \int e_p\, dt + p_{t(0)} \ldots\ldots \qquad (3.1)$$

where

$p_{t(0)}$ = Integral term value at t = 0 (initial value)

The proportional gain, by design, also changes the net integration mode gain, but the integration gain, can be independently adjusted. It is understood that the proportional offset occurred, when a load change required a new nominal controller output, and this could not be provided except by a fixed error from the set point. In the present mode, the integral function provides the required new controller output, thereby allowing the error to be zero after a load change. The integral feature effectively provides a ‘reset’ of the zero error output, after the load change occurs. At time t_1 a load change occurs, that produces the error. The accommodation of the new load condition requires a new controller output. The controller output is provided through a sum of proportional plus integral action that finally leaves the error at zero. The proportional part is obviously just an image of the error.

3.3 CHARACTERISTICS OF THE PI MODE

- When the error is zero, the controller output is fixed at the value that the integral term had, when the error reduced to zero. This output is given by $p_{t(0)}$ simply because we choose to define the time at which observation starts, as $t = 0$.
- If the error is not zero, the proportional term contributes a correction and the integral term begins to increase or decrease the accumulated value [initial $p_{t(0)}$], depending on the sign of the error and its direct or reverse direction. The integral term cannot become negative; thus it will saturate at zero, if the error and the action try to drive the area to a net negative value.
- The transfer function is given by

  $$K_p + (K_I/s) \qquad (3.2)$$

The integral action adjustment is the integral time T_1 ($=K_I$). For a step deviation ‘e’, the integral time or reset time is the time for proportional action. ‘Reset rate’ is defined as the number of times per minute that the proportional part of the response is duplicated. Reset Rate is therefore called ‘repeats per minute’, and is the inverse of integral type.

During the design of the PI controller for the buck and boost converter, a closed loop operation is performed. The open loop operation is insensitive to load and line disturbances. So this operation is ineffective. Therefore the closed loop operation is selected. The closed loop control uses a feedback signal from the process, a desired value or set point (output voltage) and a control system that compares the two and derives an error signal. The error signal is then processed and used to control the converter to try to reduce the error. The error signal processing can be very complex because of delays in the system. The error signal is usually processed using a Proportional - Integral (PI) controller whose parameters can be adjusted to optimize the performance and stability of the system. Once a system is set up and is stable, very efficient and accurate control can be achieved.

- Input is the voltage error (reference voltage subtracted from the actual voltage)
- Output is the incremental duty ratio.

The controller specifications of a converter are

- Minimum steady state error.
- Less settling time.

3.4 ZIEGLER-NICHOLS TUNING RULE

The proportional gain and the derivative gain are determined by the Ziegler Nichols method. It is the pioneer method to determine the closed loop on live tuning (Gopal 2003). It consists of two steps to get the tuning values.

Step 1 : The determination of the dynamic characteristics or personality of the control loop.

Step 2 : The estimation of the controller tuning parameters that produce a designed response to the dynamic characteristics, determined in the first step.

In this method, the parameters by which the dynamic characteristics of the process are represented, by the ultimate gain of a proportional controller and ultimate period of oscillation are estimated. The ultimate gain and period can be experimentally determined by the following procedure.

1. Switch off the integral and derivative actions of the feed back controller so as to have a proportional controller. In some models the integral action cannot be switched off, but can be determined only by setting the integral time to its maximum value or equivalently the integral rate to its minimum value.

2. With the controller in closed loop action, increase the proportional gain until the loop oscillates with constant amplitude. Record the value of the gain that produces sustained oscillations as K_{cu} (ultimate gain).

3. From a time recording of the controlled variable, the period of oscillation is measured and recorded as T_u (ultimate period).

The Ziegler-Nichols controller settings of P, PI and PID controllers are shown in Table 3.1

Table 3.1 Ziegler – Nichols Controller Settings

Type of Control	$G_c(s)$	K_c	T_I	T_D
Proportional	K_c	K_{cu}	-	-
Proportional – Integral	$\left(K_c + \frac{1}{T_I S}\right)$	0.45 K_{cu}	$\frac{T_u}{1-2}$	-
PID	$K_c\left(1+\frac{1}{T_I S} + T_D S\right)$	0.6 K_{cu}	$\frac{T_u}{2}$	$\frac{T_D}{8}$

3.5 BLOCK DIAGRAM

The block diagram shown in Figure 3.1 explains the implementation of the PI controller for buck and boost converters. The actual output voltage of the buck and boost converter and the constant reference voltage are compared, to form the error signal. The error signal is amplified and given to the PI controller. The PI controller generates the control signal based on the error signal for varying the turn on and turn off time of the regulator switch of the buck/boost converter, to maintain the constant output voltage (V_o) irrespective of the input voltage and load variations.

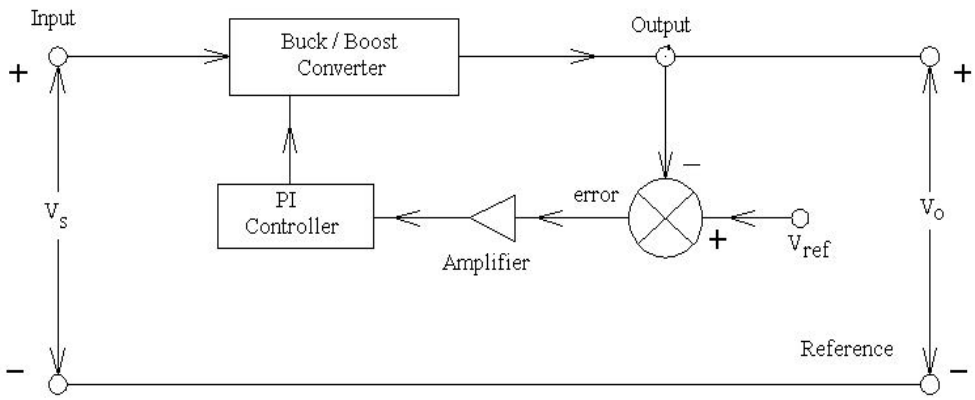


Figure 3.1 Block Diagram of the Buck/ Boost Converter with the PI Controller

3.6 SIMULATION STUDIES

The PI control algorithm is verified by simulation using MATLAB7.1 software. The simulation is performed in time domain for load and input voltage variations, for the buck and boost converter.

3.6.1 Buck Converter

The 54 volts, 200 watts bench mark buck converter is used for simulation; which is shown in Figure 3.2 with Inductor = 1mH, Capacitor = 100μF, Resistance = 11 Ω to 100 Ω and the input voltage from 120V to 150V. The proportional gain $K_p = 0.01$ and the integral gain $K_i = 0.8$. The actual output voltage of the converter and the constant reference voltage are compared, to form the error signal. The error signal is given to the PI controller. The PI controller generates the change in the duty cycle based on the input signal and the change in the duty cycle is added to the theoretical duty cycle to generate the actual duty cycle for closed loop operation. The actual duty cycle is given to the transfer function model of the buck converter to maintain the required output voltage.

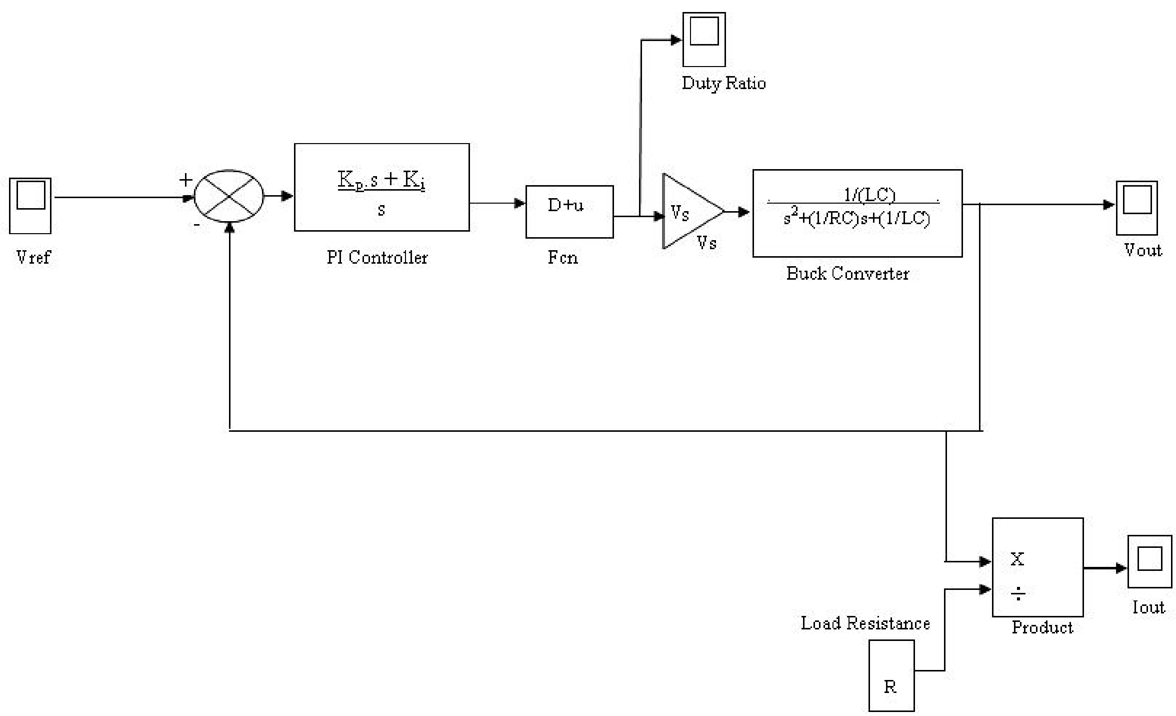


Figure 3.2 Simulation Model of the Buck Converter with the PI Controller

3.6.2 Boost Converter

The 25 volts, 50 watts bench mark boost converter is used for simulation; which is shown in Figure 3.3 with Inductor = 275µH, Capacitor = 540 µF, Resistance = 12.5 Ω to 100 Ω and the input voltage from 10V to 20V. The proportional gain K_p = 0.02 and the integral gain K_i = 17.25. The converter is represented by the small signal state space averaged model. The actual output voltage of the converter and the constant reference voltage are compared, to form the error signal. The error signal is given to the PI controller. The PI controller generates the control signal (change in the duty cycle) and the change in the duty cycle is added to the theoretical duty cycle to generate the actual duty cycle for closed loop operation. The actual duty cycle is given to the transfer function model of the boost converter to maintain the required output voltage.

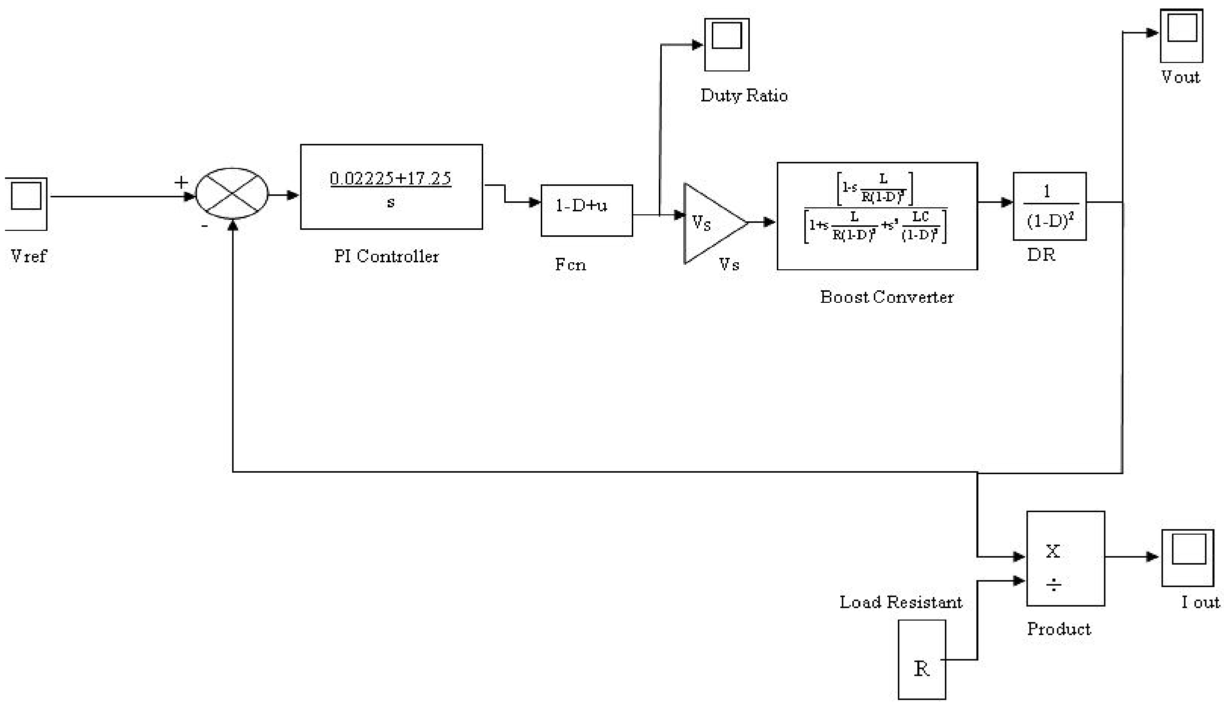


Figure 3.3 Simulation Model of the Boost Converter with the PI Controller

3.7 RESULTS AND DISCUSSION

Simulations which were carried out using MATLAB 7.1 for the various input voltage and load condition for the buck and boost converters with the PI controller, are given below.

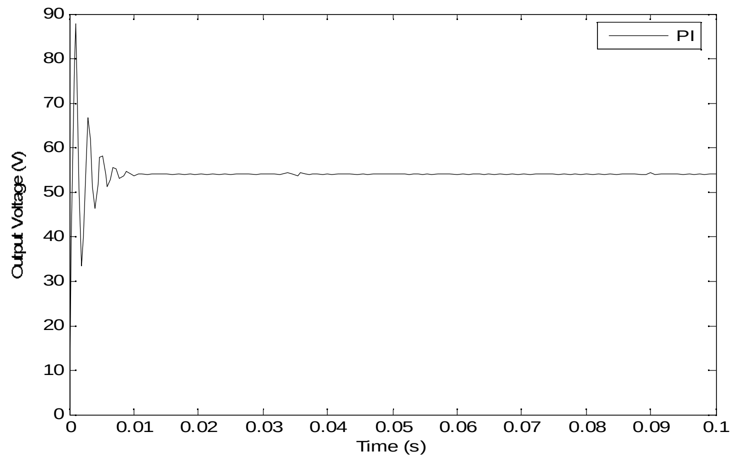
3.7.1 Buck Converter

To verify the efficiency of the buck converter, five operating points spanning the entire operating region of the converter have been chosen.

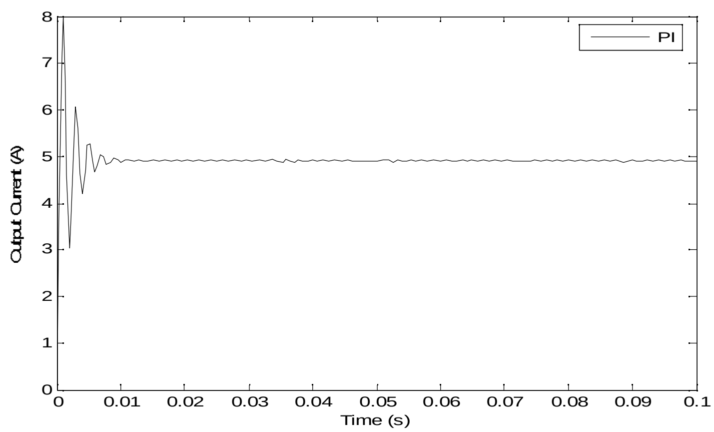
1. Minimum input voltage and maximum load condition: $V_s = 130V$, $R = 11\Omega$, $V_o = 54V$.
2. Minimum input voltage and light load condition: $V_s = 130V$, $R = 100\Omega$, $V_o = 54V$.
3. Midrange input voltage and load condition $V_s = 135V$, $R = 40\ \Omega$, $V_o = 54V$.
4. Maximum input voltage and maximum load condition $V_s = 140V$, $R = 11\Omega$, $V_o = 54V$.
5. Maximum input voltage and light load condition $V_s = 140V$, $R = 100\ \Omega$, $V_o = 54V$.

3.7.1.1 Minimum input voltage and maximum load condition

The buck converter is fed with the minimum input voltage and maximum load condition during which an input voltage of magnitude 130V is given to the converter and the load applied is 11Ω. The set value of the output voltage is 54V. The response for the DC-DC converter in the given case is shown in Figure 3.4 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 98 volts, and the settling time of voltage and current is 0.035 seconds.



(a)

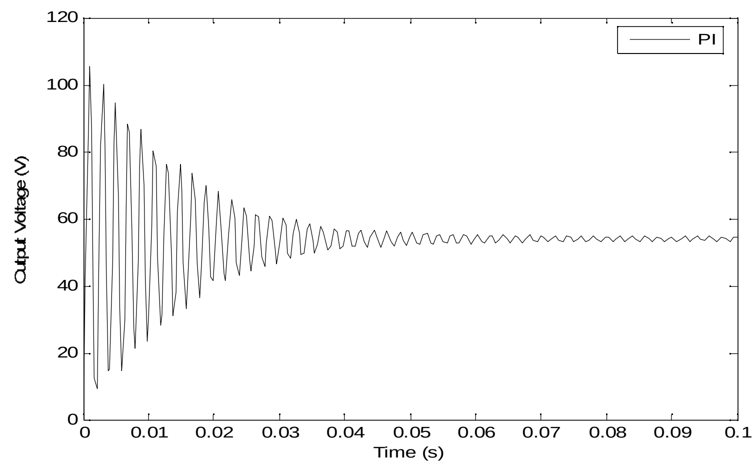


(b)

Figure 3.4 Simulation Results of the Buck Converter with the PI Controller for Minimum Input Voltage and Maximum Load Condition a) Output Voltage b) Output Current with Time

3.7.1.2 Minimum input voltage and light load condition

The buck converter is fed with minimum input voltage and light load condition during which an input voltage of magnitude 130V is given to the converter and the load applied is 100 Ω. The set value of the output voltage is 54V. The response for the DC-DC converter in the given case is shown in Figure 3.5 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 107 volts, and the settling time of current and voltage is 0.08 seconds.



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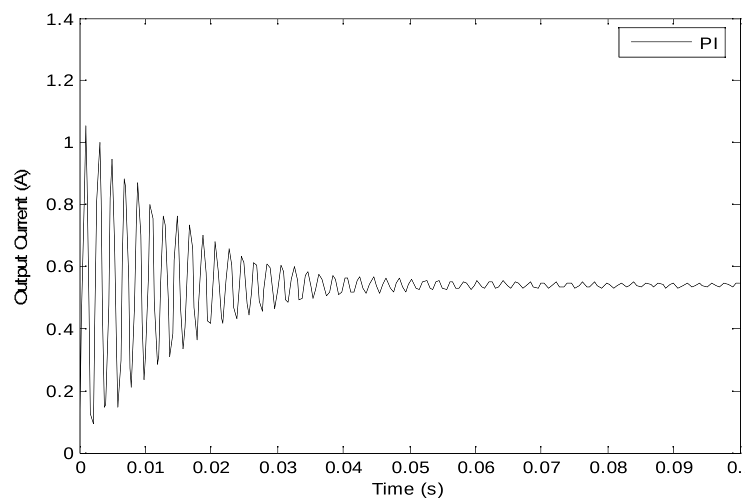
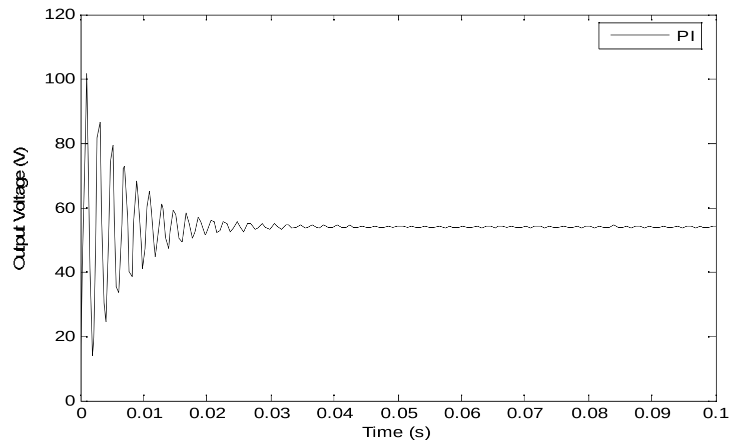


(b)

Figure 3.5 Simulation Results of the Buck Converter with the PI Controller for Minimum Input Voltage and Light Load Condition a) Output Voltage b) Output Current with Time

3.7.1.3 Midrange input voltage and load condition

The buck converter is fed with midrange input voltage and load condition during which an input voltage of magnitude 130V is given to the converter with the load of 40 Ω. The set value of the output voltage is 54V. The response for the DC-DC converter in the given case is shown in Figure 3.6 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 106 volts, and the settling time of voltage and current is 0.055 seconds.



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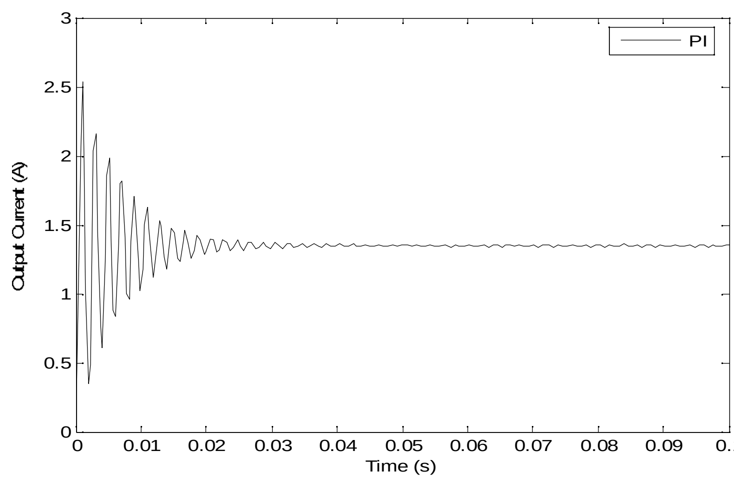

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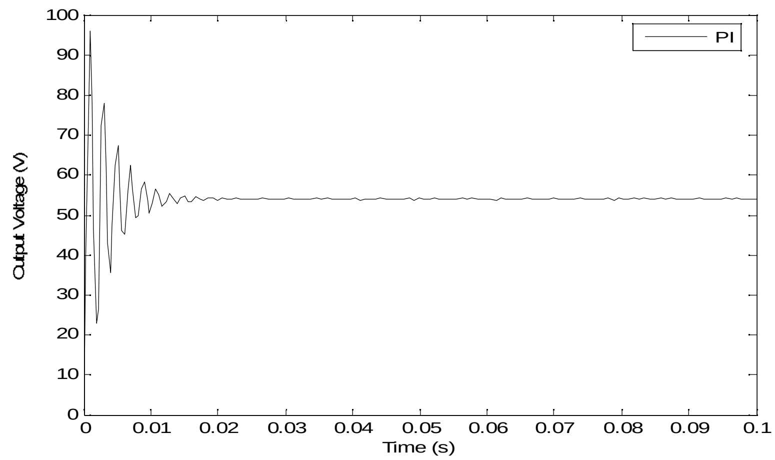
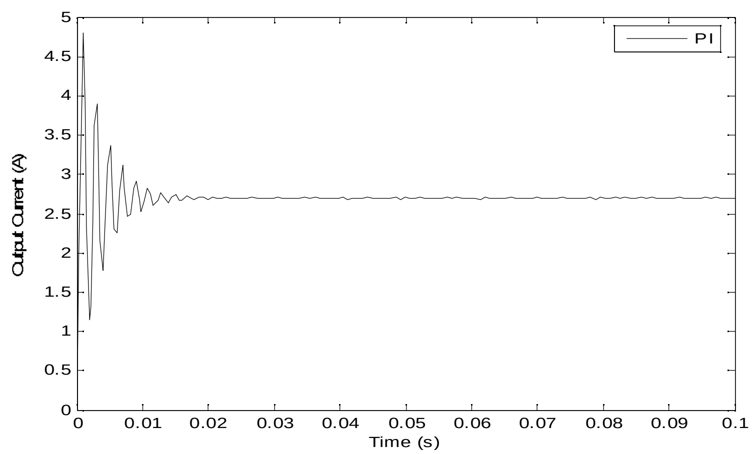
Figure 3.6 Simulation Results of the Buck Converter with the PI Controller for Midrange Input Voltage and Load Condition a) Output Voltage b) Output Current with Time

3.7.1.4 Maximum input voltage and maximum load condition

The buck converter is fed with extreme input voltage and maximum load condition, during which an input voltage of magnitude 140V is given to the converter and the load applied is 11 Ω. The set value of the output voltage is 54V. The response for the DC-DC converter in the given case is shown in Figure 3.7 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 100 volts, and the settling time of voltage current is 0.04 seconds.



(a)

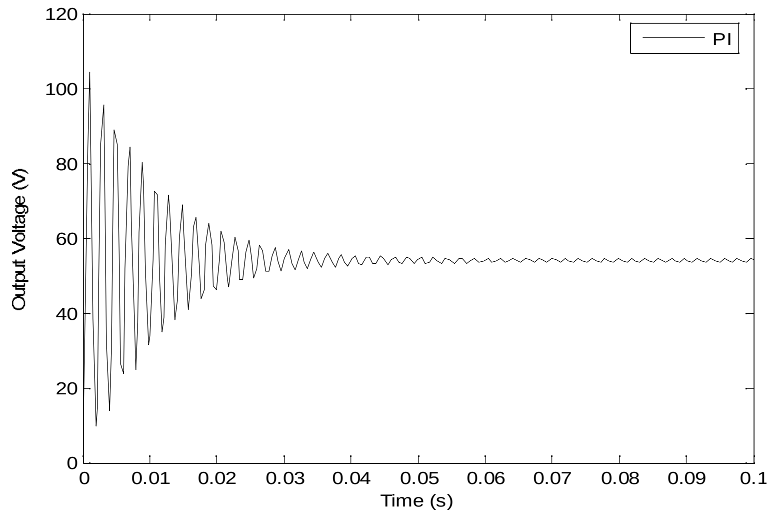


(b)

Figure 3.7 Simulation Results of the Buck Converter with the PI Controller for Maximum Input Voltage and Maximum Load Condition a) Output Voltage b) Output Current with Time

3.7.1.5 Maximum input voltage and light load condition

The buck converter is fed with extreme input voltage and light load condition, during which an input voltage of magnitude 140V is given to the converter and the load applied is 100 Ω. The set value of the output voltage is 54V. The response for the DC-DC converter in the given case is shown in Figure 3.8 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that, during the instant of parameter variation the voltage overshoot is 108 volts, and the settling time of voltage and current is 0.08 seconds.



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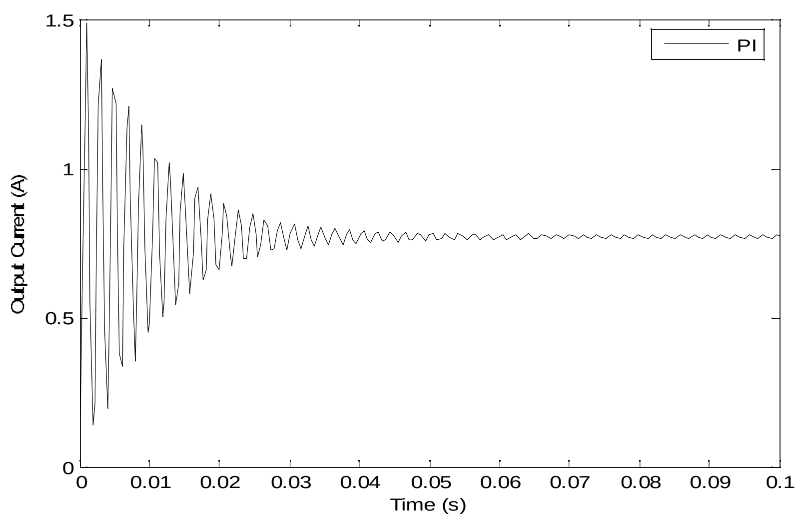


(b)

Figure 3.8 Simulation Results of the Buck Converter with the PI Controller for Maximum Input Voltage and Light Load Condition a) Output Voltage b) Output Current with Time

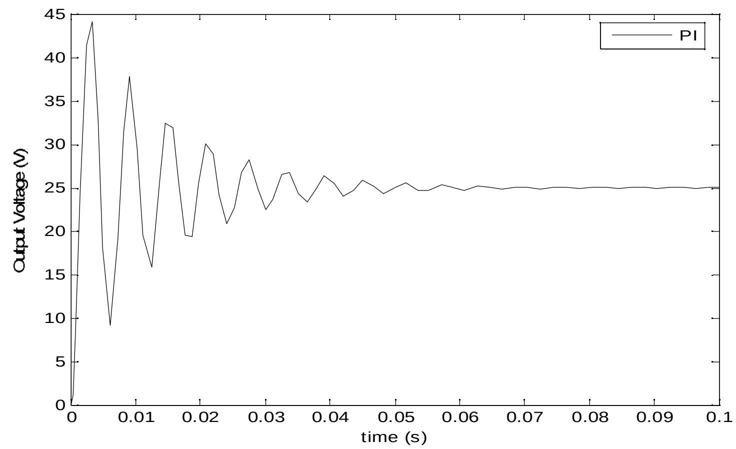
3.7.2 Boost Converter

To verify the efficiency of the boost converter, five operating points spanning the entire operating region of the converter have been chosen.

1. Minimum input voltage and maximum load condition: V_s = 10V, I_o = 2A, V_o = 25V.
2. Minimum input voltage and light load condition: V_s = 10V, I_o = 0.5A, V_o = 25V.
3. Midrange input voltage and load condition V_s = 15V, I_o = 1A, V_o = 25V.
4. Maximum input voltage and maximum load condition V_s = 20V, I_o = 2A, V_o = 25V.
5. Maximum input voltage and light load condition V_s = 20V, I_o = 0.5A, V_o = 25V.

3.7.2.1 Minimum input voltage and maximum load condition

The boost converter is fed with minimum input voltage and maximum load condition during which an input voltage of magnitude 10V is given to the converter with the load current of 2 A. The set value of the output voltage is 25V. The response for the DC-DC converter in the given case is shown in Figure 3.9 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 45 volts, and the settling time of voltage and current is 0.12 seconds



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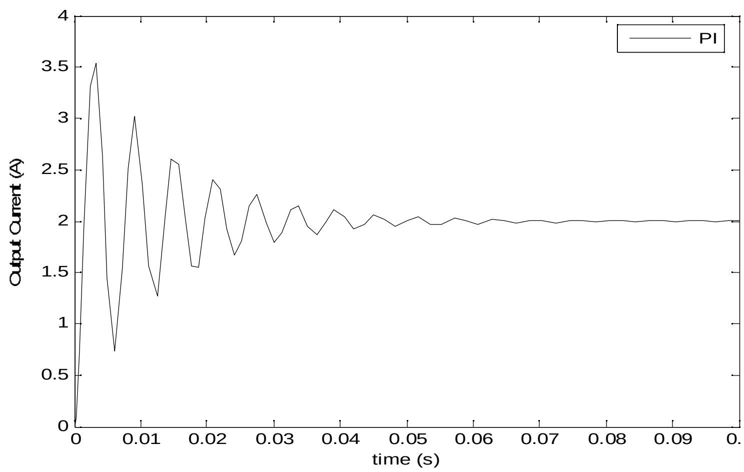
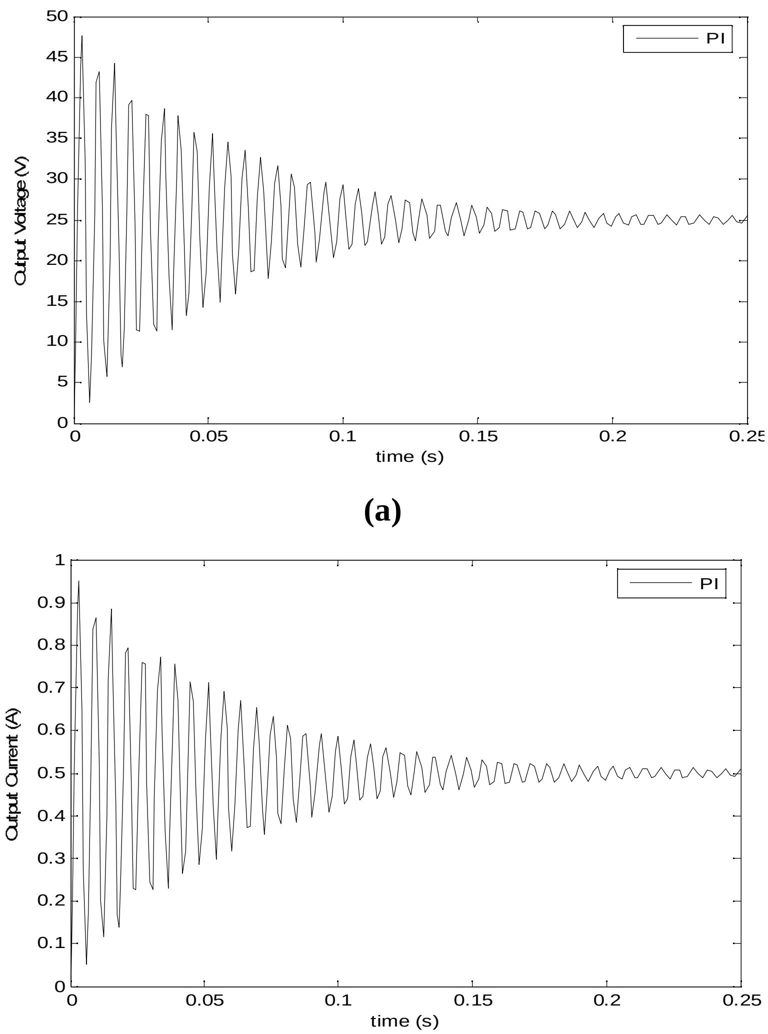


(b)

Figure 3.9 Simulation Results of the Boost Converter with the PI Controller for Minimum Input Voltage and Maximum Load Condition a) Output Voltage b) Output Current with Time

3.7.2.2 Minimum input voltage and light load condition

The boost converter is fed with minimum input voltage and light load condition during which an input voltage of magnitude 10V is given to the converter with the load current of 0.5A. The set value of the output voltage is 25V. The response for the DC-DC converter in the given case is shown in Figure 3.10 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 48 volts, and the settling time of current and voltage is 0.24 seconds.



(a)

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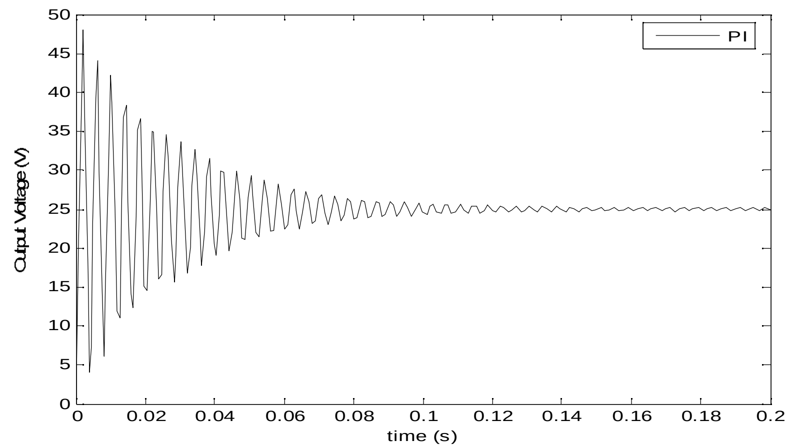
Figure 3.10 Simulation Results of the Boost Converter with the PI Controller for Minimum Input Voltage and Light Load Condition a) Output Voltage b) Output Current with Time

3.7.2.3 Midrange input voltage and load condition

The boost converter is fed with midrange input voltage and load condition during which an input voltage of magnitude 15V is given to the converter with the load current of 1A. The set value of the output voltage is

25V. The response for the DC-DC converter in the given case is shown in Figure 3.11 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 48 volts, and the settling time of voltage and current is 0.2 seconds.



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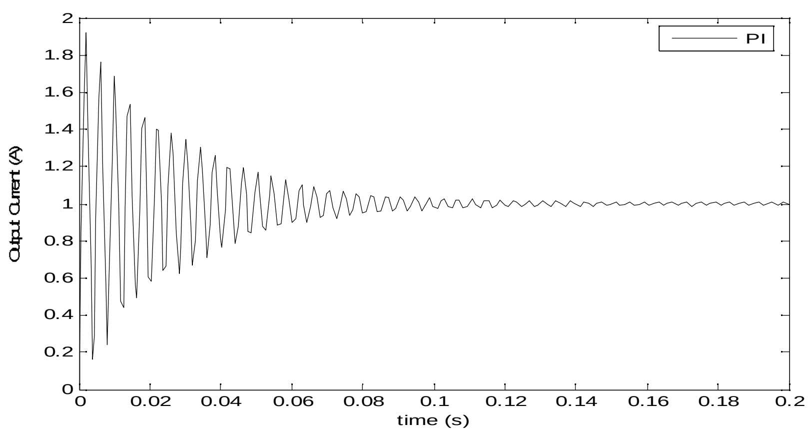
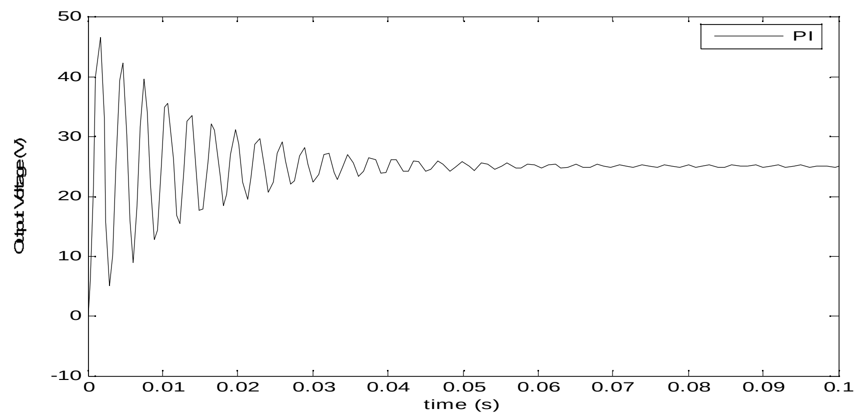


(b)

Figure 3.11 Simulation Results of the Boost Converter with the PI Controller for Midrange Input Voltage and Load Condition a) Output Voltage b) Output Current with Time

3.7.2.4 Maximum input voltage and maximum load condition

The boost converter is fed with maximum input voltage and maximum load condition during which an input voltage of magnitude 20V is given to the converter with the load current of 2 A. The set value of the output voltage is 25V. The response for the DC-DC converter in the given case is shown in Figure 3.12 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 48 volts, and the settling time of voltage and current is 0.09 seconds.



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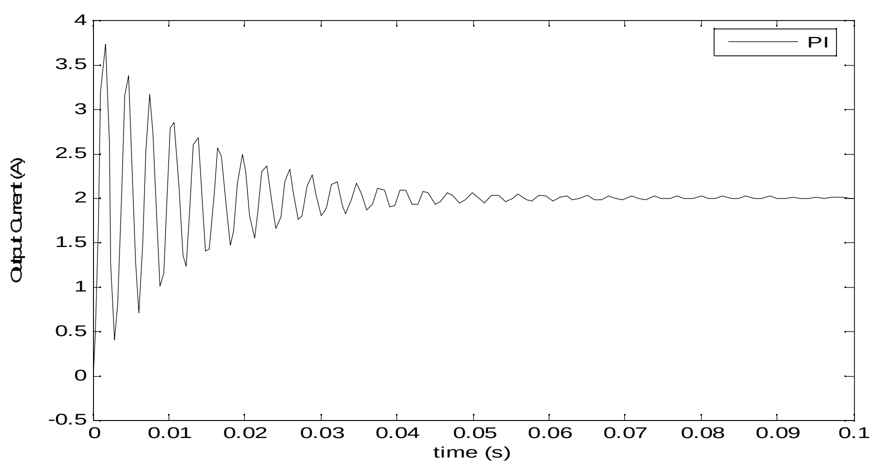

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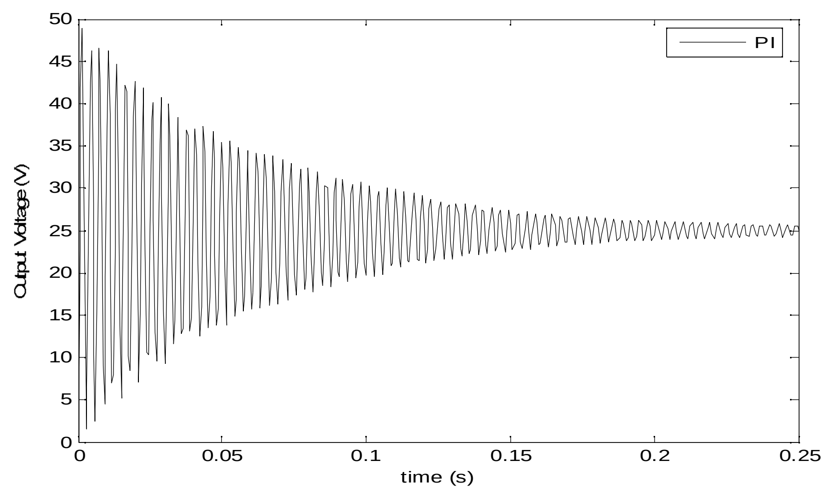
Figure 3.12 Simulation Results of the Boost Converter with the PI Controller for Maximum Input Voltage and Maximum Load Condition a) Output Voltage b) Output Current with Time

3.7.2.5 Maximum input voltage and light load condition

The boost converter is fed with maximum input voltage and light load condition during which an input voltage of magnitude 20V is given to the converter with the load current of 0.5A. The set value of the output voltage is 25V. The response for the DC-DC converter in the given case is shown in Figure 3.13 (a and b). Both the output voltage and current values have been plotted against the time. From the results it is found that the voltage overshoot is 49 volts, and the settling time of voltage and current is 0.25 seconds.



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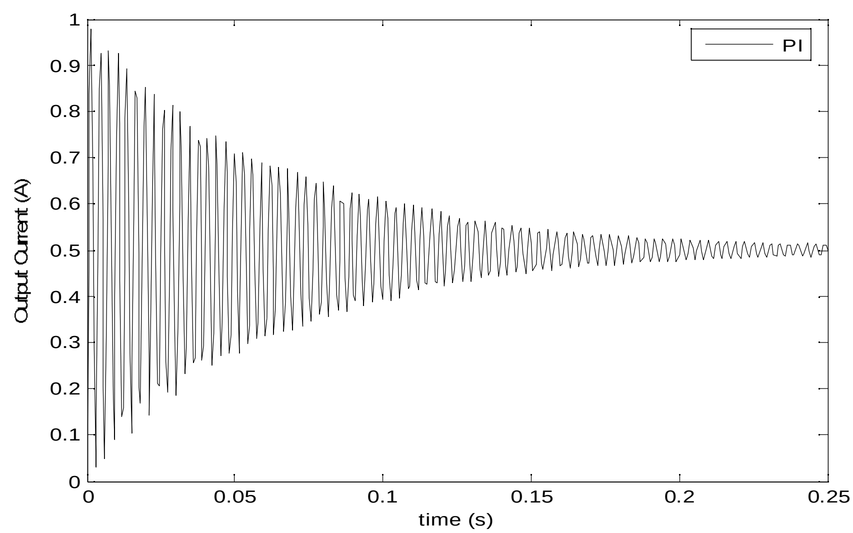

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Figure 3.13 Simulation Results of the Boost Converter with the PI Controller for Maximum Input Voltage and Light Load Condition a) Output Voltage b) Output Current with Time

3.8 CONCLUSION

In this chapter, work is carried out for the implementation of the PI controller for the buck and boost converters and the results are simulated using MATLAB 7.1. The PI controller behaves very effectively and has maintained constant output voltage subject to the input voltage and load variations. It is observed that its overshoot and settling time at the time of parameter variations are also less. The PI controller successfully controlled the process near a given setpoint. Far away from the setpoint, the linear PI controller efficiency will be less. To design an efficient control system, we have to combine the two kinds of available informations, the dynamic model of the linear controller and the experience of the human controller. When the first piece of information is a mathematical equation, the second one is usually expressed as linguistic rules, that state in what situation which action should be taken. An efficient controller that uses both informations simultaneously and cooperatively is explained in the next chapter.