

Design of Controllers for DC-DC Buck Converters

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ABSTRACT

The design of controllers for DC-DC buck converters using PID controller and fuzzy logic controller has been the subject of numerous research studies in recent years. The objective of these studies is to improve the performance of the buck converter in terms of output voltage regulation, transient response, and efficiency.

PID controller is a commonly used feedback control mechanism that uses proportional, integral and derivative terms to adjust the output of the system. The PID controller is widely used in DC-DC buck converters due to its simplicity and effectiveness. The proportional term of the PID controller adjusts the output based on the difference between the actual and desired output, the integral term is used to eliminate steady-state error, and the derivative term improves the transient response of the system.

On the other hand, the Fuzzy Logic Controller (FLC) is a more complex control mechanism that uses linguistic rules and fuzzy sets to adjust the output of the system. FLCs have been shown to be effective in DC-DC buck converters due to their ability to handle non-linearities and uncertainties in the system.

In this paper, we are simulating PID control and fuzzy logic control for both single stage and cascaded converter. The hardware implementation of the former is done as well, and the results are compared based on rise time, settling time, peak overshoot and offset at steady state.

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Introduction

DC-DC buck converters are widely used in power electronics for voltage regulation in various applications such as portable electronic devices, power supplies and motor drives. The primary function of a buck converter is to step down a high input voltage to a lower output voltage by controlling the duty cycle of the switch. In order to maintain stable and accurate output voltage, a feedback control system is required. This control system can be implemented using various techniques such as proportional-integral-derivative (PID) and fuzzy logic controllers.

PID controllers are widely used in control systems because of their simplicity and ease of implementation. The PID controller consists of three terms: proportional, integral and derivative. The proportional term is proportional to the error between the desired output voltage and the measured output voltage. The integral term accumulates the error over time and corrects for any steady-state error. The derivative term is proportional to the rate of change of the error and is used to dampen any oscillations in the system.

Fuzzy logic controllers are an alternative to PID controllers that use fuzzy set theory to describe the control action. Fuzzy logic controllers are particularly useful in systems with nonlinearities and uncertainties. The fuzzy logic controller consists of a fuzzy inference system that maps the input variables to the output variable using fuzzy rules.

The performance of both PID and fuzzy logic controllers can be evaluated using various metrics such as rise time, settling time, overshoot and steady-state error. The choice of controller depends on the specific application and the desired performance criteria.

Buck Converter

A buck converter is a step-down DC to DC converter. For a DC-DC converter, input and output voltages are both DC. It uses a power semiconductor device as a switch to turn on and off the DC supply to the load. The switching action can be implemented by a BJT, a MOSFET, or an IGBT. Figure 1 shows a simplified block diagram of a buck converter that accepts a DC input and uses pulse-width modulation (PWM) of switching frequency to control the switch. An external diode, together with external inductor and output capacitor, produces the regulated dc output. Buck, or step-down converters produce an average output voltage lower than the input source voltage.

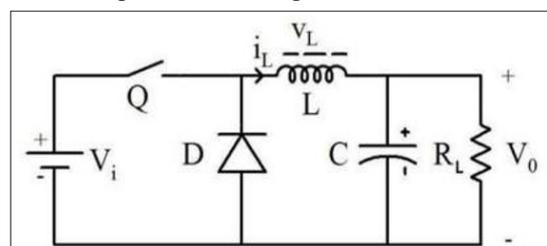


Figure 1: Buck Converter

Buck Converter Operation

The operation of a buck converter happens in two modes. The first mode is when switch Q closes, and the second one is when switch Q opens. When switch Q closes, current flows from the supply voltage V_i through the inductor and into the load, charging the inductor by increasing its magnetic field and increasing V_o . Diode D will be on reverse bias, thus blocking the path for current.

An inductor reduces ripple in current passing through it and the output voltage would contain less ripple content since the current through the load resistor is the same as that of the inductor.

At the same time, the current through the inductor increases and the energy stored in the inductor increases. When V_o reaches the desired value, switch Q is open and diode D is turned on. Figure 2 shows this mode.

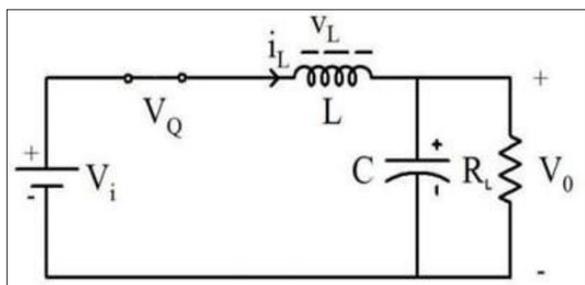


Figure 2: Switch Q Closed

When the switch Q opens, the inductor acts as a source and maintains the current through the load resistor. During this period, the energy stored in the inductor decreases and its current falls. Current continues to flow in the inductor through the diode D as the magnetic field collapses and the inductor discharges. Before the inductor completely discharges, diode D is open and Q is closed and the cycle repeats. It is important that there is continuous conduction through the load for this circuit. Figure 3 shows this mode.

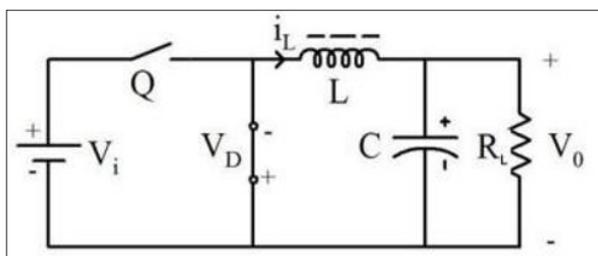


Figure 3: Switch Q Open

CCM and DCM

The buck converter can operate in two different modes; continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The difference between the two is that in CCM the current in the inductor does not fall to zero. A buck converter operates in continuous mode if the current through the inductor never falls to zero during the commutation cycle. In DCM, the current through the inductor falls to zero during part of the period. Practically, the converter can operate in either operation mode. Figure 4 shows CCM and DCM mode.

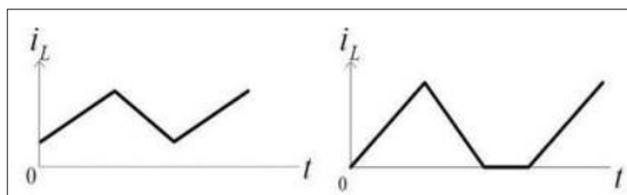


Figure 4: (a) CCM (b)DCM

Buck Converter Duty Cycle

The ratio of output voltage, V_{out} to input voltage, V_{in} can be adjusted by varying the duty cycle of switch Q. The longer Q is turned on, the greater V_{out} will be. The duty cycle of Q is usually called the converter's duty cycle. If the switches and the inductor are lossless, V_{in} is converted to V_{out} with no loss of power and the conversion is 100% efficient. Figure 5 shows variation of duty cycle. Duty cycle is always being presented in percentage value. A 60% duty cycle means the power is on 60% of the time and off 40% of the time.

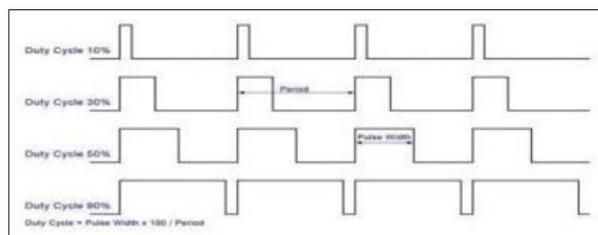


Figure 5: Duty Cycle

Mathematical Model Analysis

Two states of operation are considered. First, switch Q is on and D is turned off. After steady state condition has been reached, switch Q will turn off and D turn on. Figure 6 shows these two operations.

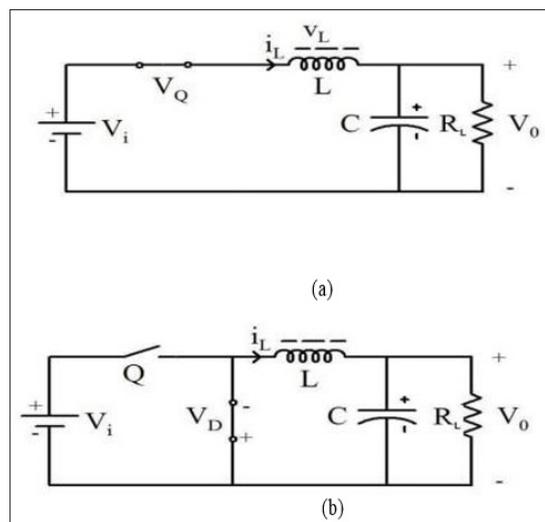


Figure 6: Buck Converter Operation (A) Q Turn On (B) Q Turn Off

By using Kirchoff's Voltage Law (KVL), the voltage across the inductor when switch Q is closed is –
 $V_L = V_i - V_Q - V_O$ (1.0)

At the same time, the voltage V_L across the inductor is related to the change in current flowing through it is –
 $V_L = L(di_L / dt)$ (1.1)

Put the VL value in equation (1.0) will result in
 $L (diL / dt) = V_i - V_Q - V_O$

So, the amount of inductor current is:
 $diL / dt = (V_i - V_Q - V_O) / L$ (1.2)

The duty cycle of the buck converter is defined as:
 $D = T_{ON} / (T_{ON} + T_{OFF}) = T_{ON} / T$ (1.3)

When switch Q open, the voltage across inductor is:
 $V_L = V_O + V_D$ (1.4)

Now $V_L = L (diL / dt)$, we get

$$L (di_L / dt) = V_o + V_D$$

$$diL / dt = (V_o + V_D) / L$$
 (1.5)

These two equations can be equated and solved for VO to obtain the continuous conduction mode buck voltage conversion relationship.

$$[(V_i - V_Q - V_O) / L] T_{ON} = [(V_O + V_D) / L] T_{OFF}$$

$$V_i T_{ON} - V_Q T_{ON} - V_O T_{ON} = V_O T_{OFF} + V_D T_{OFF}$$

$$V_i T_{ON} + V_O T_{OFF} = V_i T_{ON} - V_Q T_{ON} - V_D T_{OFF}$$

$$V_o (T_{ON} + T_{OFF}) = V_i T_{ON} - V_Q T_{ON} - V_D T_{OFF}$$

$$V_o T = T_{ON} (V_i - V_Q) - V_D T_{OFF}$$

$$V_o = [T_{ON} (V_i - V_Q) - V_D T_{OFF}] / T$$

$$V_o = (V_i - V_Q) D - V_D T_{OFF} / T$$
 (1.6)

Add using

$$(1-D) = T_{OFF} / T$$
 (1.7)
$$V_o = (V_i - V_Q) D - V_D (1-D)$$
 (1.8)

The steady-state equation for V_o is:

$$V_o = (V_i - V_Q) D - V_D (1-D)$$

This equation demonstrates the fact that output voltage VO is defined with the duty cycle, D for the converter. For this explanation, the buck converter output voltage is lower than input voltage because D is a number between 0 and 1. To generalize, V_o and V_D are neglected because they are small enough to ignore. Simplified output voltage can be calculated by:

$$V_o = V_i D$$
 (1.9)

In a steady state, inductor current is given by:

$$I_L = I_c + I_o$$
 (1.10)

Since $I_c = 0$ in steady state condition, we have:

$$I_L = I_o$$
 (1.11)

Ohm's law required that

$$I_o = V_o / R_L$$
 (1.12)

So the average value of IL is:

$$I_L = I_o = V_o / R_L$$

From Figure 5 we can write:

$$I_L (max) = I_L + |\Delta I_L| / 2$$
 (1.13)

Now we can write in equation 1.12:

$$I_L (max) = V_o / R_L + V_o / 2L (1-D) T$$
 (1.14)

Similarly, from Figure 5 we can write

$$I_L (min) = I_L - |\Delta I_L| / 2$$
 (1.15) Or
$$I_L (min) = V_o / R_L - V_o / 2L (1-D) T$$
 (1.16)

To guarantee an uninterrupted flow of IL through the inductor, we need $I_L (min) > 0$. So, we need

$$I_L (min) = V_o / R_L - V_o / 2L (1-D) T > 0$$

$$V_o / R_L > V_o / 2L (1-D) T$$

$$L > (1-D) / 2 T R_L$$

$$L > (1-D) / 2 f R_L$$

Where $F = 1/T$

Control of Buck Converter by Pid Controller PID Controller

A proper proportional-integral-derivative controller (PID controller or three-term controller) is a control loop mechanism employing feedback that is widely used in industrial control system and a variety of other applications requiring continuously modulated control. A PID controller continuously calculates an error value as the difference between a desired setpoint (SP) and a measured process variable (PV) and applies a correction based on proportional, integral and derivative terms (denoted by P, I and D respectively).

Proportional Term

The proportional term produces an output value that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p , called the proportional gain constant. The proportional term is given by: $P_{out} = K_p e(t)$. A high proportional gain results in a large change in the output for a given change in error. If the proportional gain is too high, the system can be unstable. In contrast, a small gain results in a small output response to a large input error, and a less responsive or less sensitive controller. If the proportional gain is too low, the control action may be too small when responding to system disturbances. Tuning theory and industrial practise indicate that the proportional term contributes the bulk of the output change.

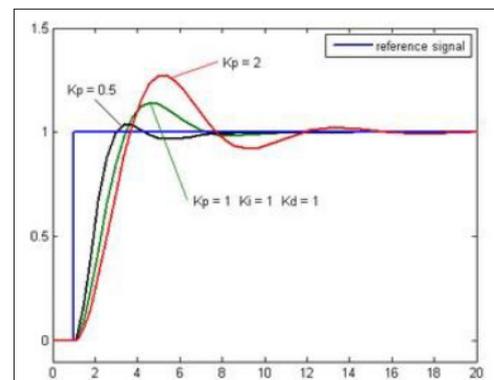


Figure 7: The Effect of add Kp (Kd And Ki) Held Constant

Integral Term

The contribution from the integral term is proportional to both the magnitude of the duration of the error. The integral in a PID controller is the sum of the instantaneous error over time and gives the accumulated offset that should have been corrected previously.

The accumulated error is then multiplied by the integral gain K_i and added to the controller output.

The integral term accelerates the movement of the process towards the set point and eliminates the residual steady-state error that occurs with a pure proportional controller. However, since the integral term responds to accumulated errors from the past, it can cause the present value to overshoot the set-point value.

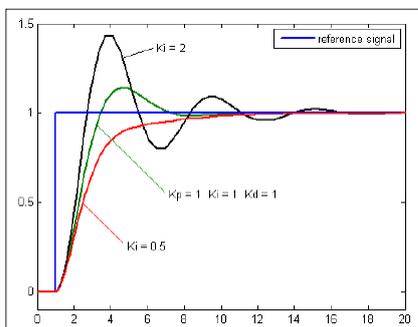


Figure 8a: The Effect of add K_i (K_p And K_d) Held Constant

Derivative Term

The derivative of the process error is calculated by determining the slope of the error over time and multiplying this rate of change by the derivative gain K_d . The magnitude of the contribution of the derivative term to the overall control action is termed the derivative gain, K_d .

Derivative action predicts system behaviour and thus improves settling time and stability of the system. An ideal derivative is not casual, so that implementation of PID controllers include an additional low pass filtering for the derivative term, to limit the high frequency gain and noise. Derivative action is seldom used in practise though- by one estimate in only 20% of deployed controllers- because of its variable impact on system stability in real-world applications.

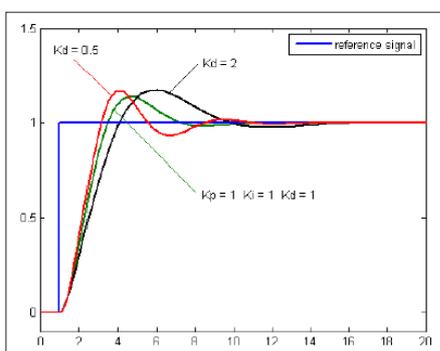


Figure 9b: The Effect of add K_d (K_p and K_i) Held Constant

Equipment Used

Buck converter



Figure 10: Buck Converter Hardware Model

The board used has a wide input voltage range from 24V to 60V, and an output voltage range of 80V. It operates at a frequency range of 10kHz to 20kHz. FR4 material is used in the construction of the board.

The kit consists of:

- DC-DC Converter
- 12V Adapter

It has the following features

- Input / Output are 2 PIN XY Connectors
- Feedback – input voltage, output voltage, input current
- Gate pulse Amplitude 3.3v
- Over voltage Protection Parameters

Table 1: Parameters of Equipment used

CONVERTER INPUT	20V
CAPACITOR	470uF
INDUCTOR	144uH
MOSFET	IRFB4115
CONVERTER OUTPUT	5V
RATED POWER	500W
GATE PULSE	3.3V

dSPACE 1103

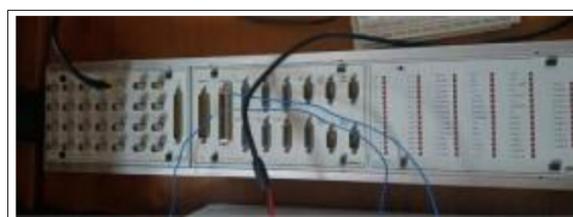


Figure 11: a dSPACE 1103

dSpace is an open-source repository software package typically used for creating open access repositories for scholarly and/or published digital content. Here, it is the connecting link between the hardware components (i.e. buck converter, dc source, resistors etc.) and software components (control system for the converter built in Simulink). It converts analog signals to digital signals and vice versa.

The entire system is shown below.



Figure 12b: Experimental setup

The buck converter is supplied with an input voltage of 10-20V. Its output is connected to a dSPACE channel, which converts it from an analog signal to a digital signal and supplies it to the control system built in Simulink. This system gives the duty

cycle as the output which can be used to control the output of the buck converter using the pulse width modulator. This is how the hardware implementation of the various control methods of the buck converter takes place.

Single Stage Converter

A simulation of the single stage buck converter controlled using a PID controller is built using MATLAB software. The reference voltage is set to 5V. An input of 20V is supplied at first, which is increased to 24V at 0.04 seconds and decreased to 16V at 0.07 seconds. The difference between the output is the reference, i.e., the error is fed into the PID controller, whose output is given to the pulse width modulator (PWM). The duty cycle is controlled by the PWM through the switching action of the MOSFET.

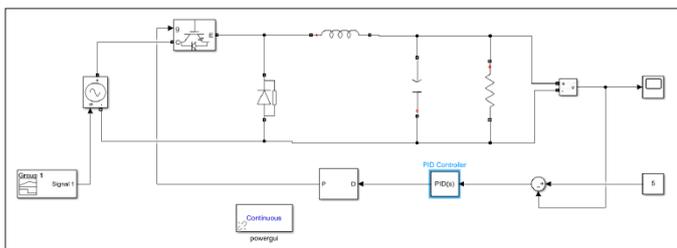


Figure 13: a Simulink Model of PID Control of Single Stage Buck Converter

The autotuning tool in Simulink is used to find the K_p , K_i , K_d and N (filter coefficient) values. To obtain the plant model, the process of system identification is used, where data is used instead of physics to model a system. The characteristics of the test signal and the output obtained are shown in the figure below.

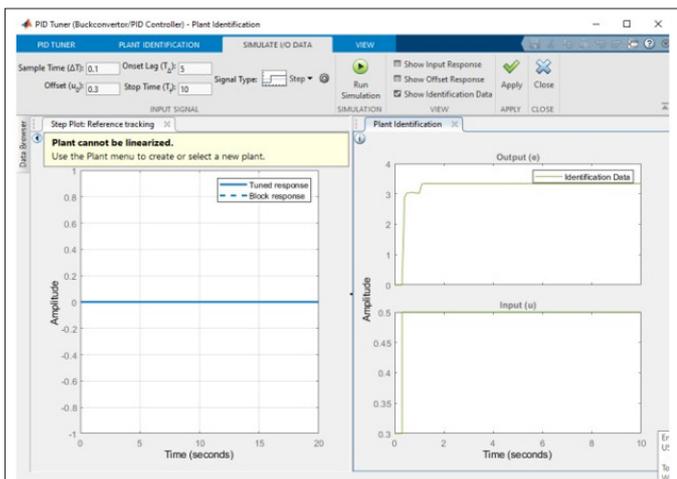


Figure 14b: Characteristics of Test Signal and Corresponding Output

The measured output data is preprocessed to give an identified plant model response. The appropriate model structure is selected, which in this case is an underdamped pair.

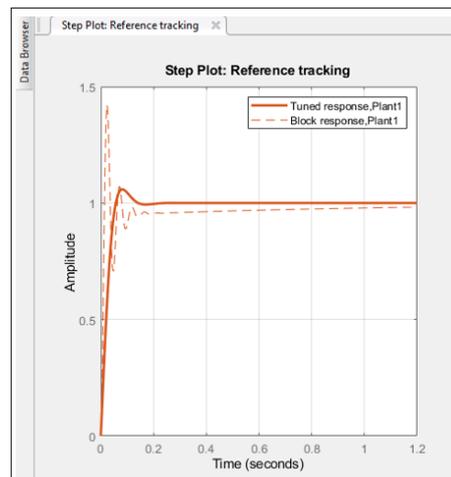


Figure 15c: Tuned Response of Plant

Thus, the plant model is identified. The block response indicated in the above figure is the response before tuning. It is observed that the large number of oscillations and high offset value in the block response is corrected in the response after tuning. The response time and transient behavior are adjusted and the block parameters are updated.

After tuning, we get the following values for the PID controller

Parameter	Value
K_p	0.113921135755727
K_i	26.4132759908127
K_d	0.000121900528898269
N	64069.166416936

It is observed that the output settles down to the set point of 5V even when the input is varied. However, the settling time as well as the fluctuations in steady state are significant. The output also takes quite some time to settle back to 5V when the input is increased or decreased. The overshoot values are significant as well.

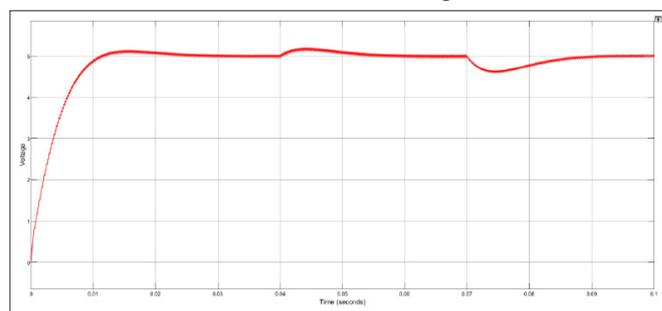


Figure 16b: Single Stage PID Control Output

Cascaded Converter

Two buck converters are connected in cascade, and the output of the first converter is the input of the second. A DC voltage that varies between 16V and 24V as explained above is supplied, which results in an output of 10V. This output is fed as input to the second converter so that it is stepped down to 5V.

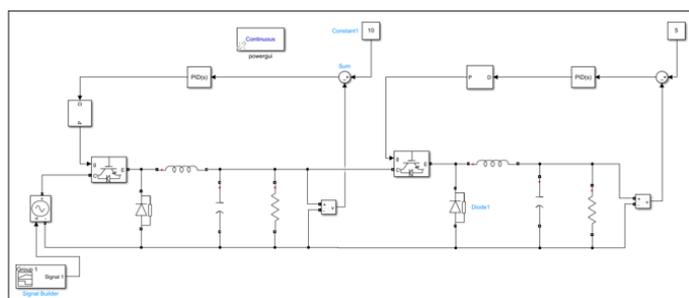


Figure 17a: Simulink Model of PID Control of Cascaded Buck Converter After Tuning, the following Parameters are Obtained

PID parameters:

Parameter	Stage 1	Stage 2
Kp	0.103228336519631	0.222647984234644
Ki	164.268788294433	66.5102907084306
Kd	1.60939278962201e-05	0.000180388848272772
N	439731.153517967	59227.2194271718

The control feedback loop works the same as above, with two PID controllers for the two buck converters.

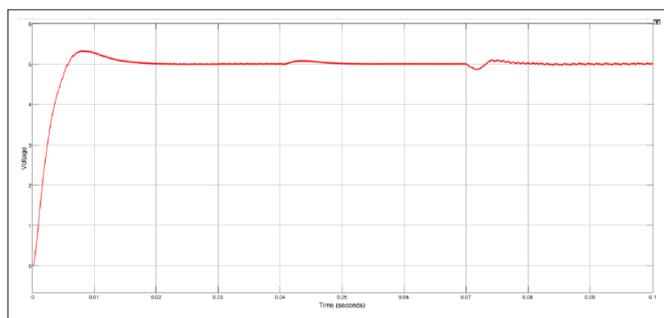


Figure 18b: Cascaded PID Control Output

The settling time is reduced in this case. The error at steady state as well as the time taken to come back to the reference point when input is varied has reduced as well, though it is still not negligible. It has a higher peak overshoot value when compared to the single stage converter,

Hardware Implementation of PID Controller

The above Simulink model for a single stage converter is implemented in the hardware system. The input is varied between 8V and 12V as done during the simulation and the output is observed.

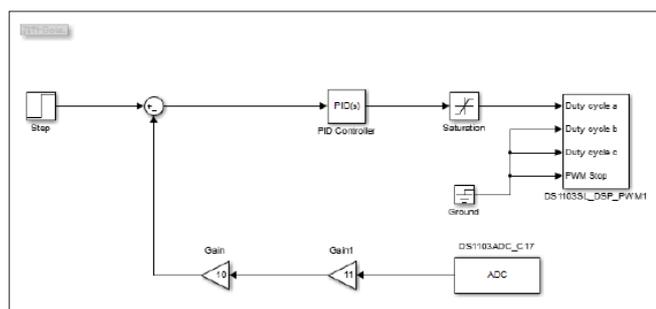


Figure 19a: Block Diagram for PID Hardware Implementation

The output is converted from an analog signal to a digital signal using dSPACE and entered into the software. The value to duty cycle obtained from the software is converted into an analog signal and fed into the pulse width modulator of the buck converter.

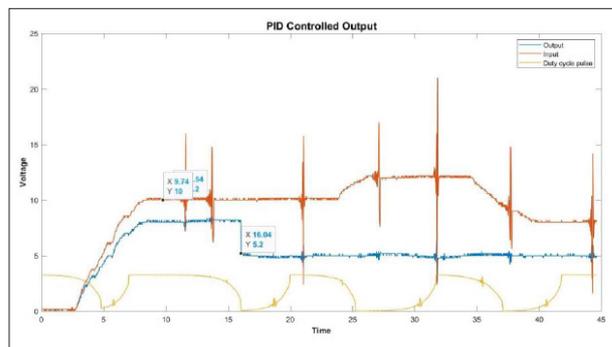


Figure 20: PID Controller Output (Hardware)

The output takes time to come to the reference point as the control signal supplied by the PID controller must come down to a value below 1. The peak overshoot is high as well.

Chapter 5 Fuzzy Logic Control

Fuzzy Logic Control

Fuzzy logic control is based on the Fuzzy set theory. Each element has a degree of membership with which it belongs to any particular set. Fuzzy sets are like classical sets without much sharper boundaries. Fuzzy Logic Controller (FLC) is more used when the precision required is moderate and the plant is to be devoid of complex mathematical analysis. The three main components of a Fuzzy Logic controller are

- Fuzzification
- Fuzzy Rule base and Interfacing engine
- Defuzzification

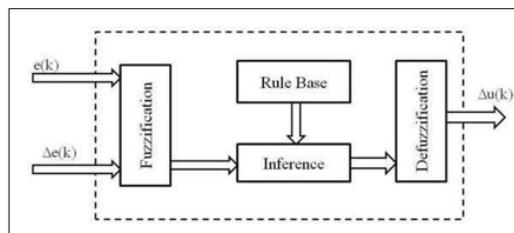


Figure 21: Block Diagram of Fuzzy Logic Controller

Fuzzification

The most important step in formulating a design for the fuzzy controller is to identify the state variables which efficiently control the plant. After determining the state variables, they are to be passed through the fuzzification block. As the fuzzy rule base employs rules on only linguistic variables, the numerical inputs have to be converted to fuzzy linguistic variables first, the process of which is called fuzzification.

The variables generally used here are the error and the change in error. The membership function is the graphical representation of the degree of belonging of an element to the fuzzy set.

So generally, fuzzification is the process by which the crisp inputs are converted into fuzzy sets using Membership Functions (MFs). Both inputs and outputs range from -1 to 1. Five fuzzy sets have been defined which are Negative Big, Negative Small, Zero Error, Positive Small, Positive Big.

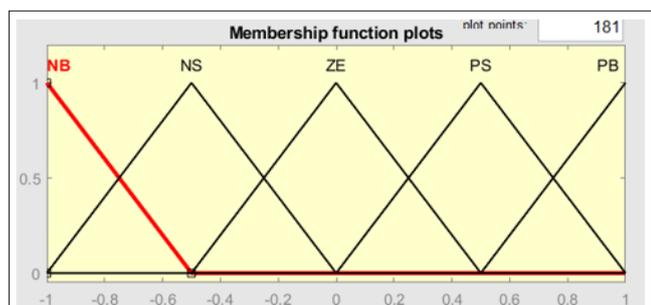


Figure 22: Membership Function Plots

Fuzzy Inference System

The fuzzy inference system converts the fuzzy inputs to fuzzy outputs with the help of the rule base stored in it. The rule base is given below.

Table 2: Rules of Fuzzy Logic

CE/E	NB	NS	ZE	PS	PB
NB	PB	PB	PB	PS	PS
NS	PB	PS	PS	PS	ZE
ZE	PS	PS	ZE	NS	NS
PS	ZE	NS	NS	NS	NB
PB	NS	NB	NB	NB	NB

Defuzzification

Defuzzification can be done by either Mamdani or Sugeno method. The former is used in this case as the rule base is of IF-THEN form. This inference method expects output variables to be fuzzy sets. It is possible and also efficient to use a single spike in the output as a membership function rather than a distributed fuzzy set. This is known as the singleton output membership function. It enhances the Defuzzification process because it greatly simplifies the computation required by the more general Mamdani method which finds the centroid of the two-dimensional functions.

The MF of the output is given a value that is the minimum of the MFs of the two inputs. The crisp output can be determined by calculating the centroid of the area under the MFs of each fuzzy set in the output. This is demonstrated in the following diagram.

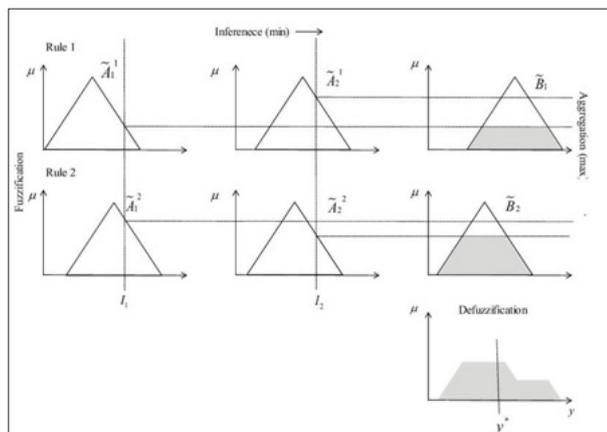


Figure 23: Mamdani Method of Defuzzification

Single Stage Fuzzy Converter

The fuzzy logic controller is set up as a closed feedback loop to the buck converter as shown in figure. The output of the controller is the change in duty cycle. A memory block and saturator with

upper limit of 0.8 is used to generate the duty cycle that controls the switching action of the MOSFET.

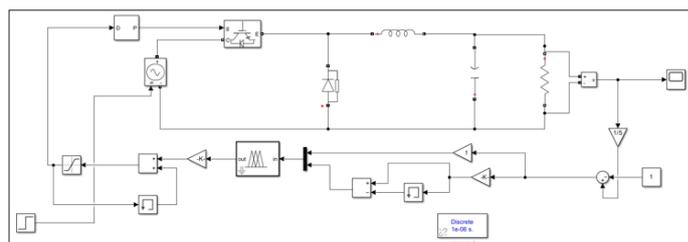


Figure 24a: Simulink Model of Fuzzy Logic Control of Single Stage Converter

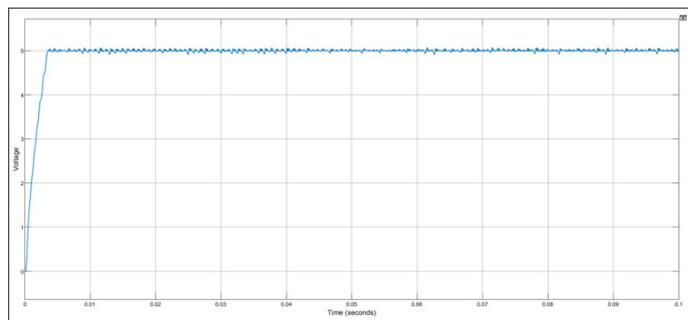


Figure 25b: Single Stage Fuzzy Logic Control Output

The settling time is much lower than that of the PID controller. The output hardly changes even when the input is varied and overshoot is negligible.

Cascaded Fuzzy Controller

The PID controllers are replaced by fuzzy logic controllers in the block diagram of the cascaded PID controlled converter.

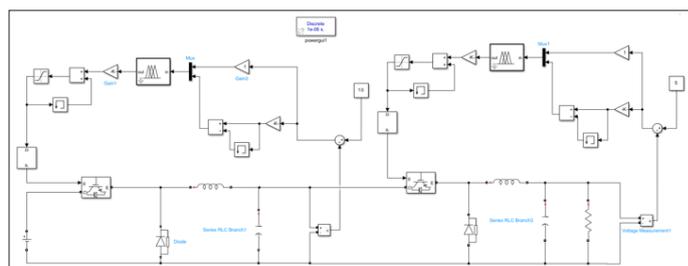


Figure 26a: Simulink Model of Fuzzy Logic Control of Cascaded Buck Converter

The inputs, output, membership function plots and fuzzy rules are the same as described above.

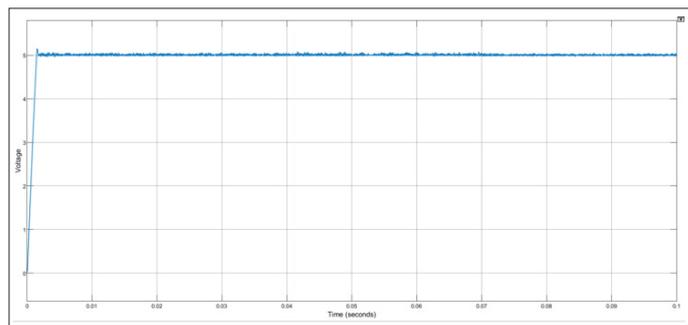


Figure 27b: Cascaded Fuzzy Logic Control Output

The response is similar to that of a single stage fuzzy controlled converter, but the settling time is faster and fluctuations at steady state are less randomized.

Hardware Implementation of Fuzzy Logic Controller

The above Simulink model is implemented in the hardware system for the single stage converter. The input is varied between 8V and 12V as done previously for hardware implementation of the PID controller [1-9].

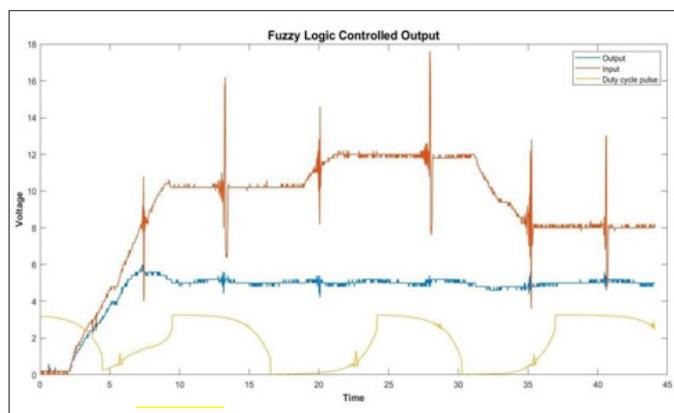


Figure 28: Fuzzy Logic Controller Output (hardware)

The settling time is faster and peak overshoot is lower when compared to the hardware implementation of the PID controller.

Results and Conclusions Comparison of Parameters Comparison of Software

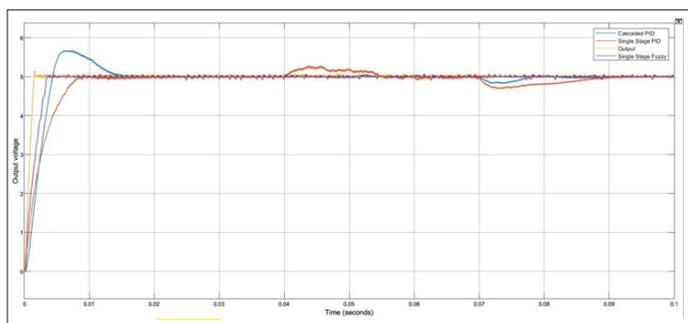


Figure 29: Comparison of Outputs

The following table is a comparison of the different parameters such as rise time, peak time, settling time and overshoot in all four cases.

Parameter	Single stage PID	Cascaded PID	Single stage Fuzzy	Cascaded Fuzzy
Rise time (sec)	0.011	0.005769	0.003621	0.001475
Peak time (sec)	0.015	0.007943	0.003674	0.001573
Settling time (sec)	0.024	0.018	0.0037	0.001741
Overshoot (V)	0.142	0.343	0.028	0.15
Settling time when input increased (sec)	0.016	0.008	0	0
Settling time when input increased (sec)	0.019	0.01	0	0

Table 3: Comparison of Time Domain Specifications of Single Stage PID, Cascaded PID, Single Stage Fuzzy and Cascaded Fuzzy (software)

Comparison of Hardware Implementation

Table 4: Comparison of Time Domain Specification of Single Stage PID and Single Stage Fuzzy (Hardware)

Parameter	Single stage PID	Single stage Fuzzy
Rise time (sec)	5	6
Peak time (sec)	9.74	7.5
Settling time (sec)	16.04	9
Overshoot (V)	3	0.9

Conclusions

The two control methods are simulated for both single stage and cascaded converters. The hardware implementation of PID and fuzzy control of single stage converters are done as well. For PID control, it is observed that the output of the single stage converter has comparatively less overshoot. However, the cascaded PID controller shows faster settling time, lesser deviations in steady state and faster response to input variations. Whereas the fuzzy controller shows less rise time, settling time as well as overshoot in both cases, more particularly in case of the cascaded controller. The overshoot is smaller to the point of being negligible for both. It has lesser deviations as well in steady state. Therefore, it can be concluded that the fuzzy controlled converter gives the best response.

When hardware implementation is done, it is noted that fuzzy logic control shows better results when compared to PID control. The overshoot is high and the output takes time to settle down until it lies between 0 and 1. Whereas, the fuzzy controller has a much lesser settling time and lower overshoot values. However, the variations in output when the input is changed is negligible in both cases.

Therefore, the hardware results prove that fuzzy logic control is a better alternative to PID control, as observed in the simulation.

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