On comparing the performance of the Two-Stage DC – DC converter with PI and Fuzzy Logic Controllers

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Abstract — Cascaded Buck and Boost converters are suitable for getting the required regulated voltage with input voltages varying with wide voltage ranges. Structurally the two stage converter consists of a buck and a boost converter stages cascaded one after the other. The cascaded two stage DC – DC converter since it is meant for input voltages varying from time to time, the structure requires a voltage regulator arrangement to meet the disturbances rising at the input voltages. Disturbances faced by the load voltage due to changes in load should also be addressed. The objective of this work is to design a PI and a fuzzy logic controller and compare the performance of them both. A cascaded buck and boost converter with input voltage ranging between 12v and 36v to deliver DC power to a 24W / 24V load is considered. Simulation in the MATLAB / SIMULINK was carried out. An experimental verification has also been carried out. It was concluded that the fuzzy logic controller offers less Integral Square Error with insignificant overshoot.

Keywords — Two Switched Buck and Boost Converter, PI controller, Fuzzy Logic Controller, Stability Analysis.

I. INTRODUCTION (SIZE 10 & BOLD)

The cascaded buck and boost combination is also known as the Two Switch Buck Boost converter (TSBB). The block schematic and the topology of the TSBB are given in figures 1 and 2 [1]. While the TSBB is capable of buck and boost operations it has the added advantage of non-polarity inversion as compared to the traditional buck boost converter. The Cuk, Zeta and the Sepic converters also offer the feature of non-polarity reversal [2, 3, 4, and 5]. Since these converters use only one switch the exhibit higher voltage stress on the switching device as compared the TSBB which has two switches and these switches are subjected to lower voltage stresses.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Switch 1</th>
<th>Switch 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>Active PWM</td>
<td>Off State</td>
</tr>
<tr>
<td>Boost</td>
<td>On State</td>
<td>Active PWM</td>
</tr>
</tbody>
</table>

As compared to the aforesaid versions of DC to DC buck boost converters the TSBB is more suitable for situations where the source voltage may be subjected to wide changes and this includes operating loads with batteries and fuel cells [4, 5, and 6]. Solar powered systems are also subjected to wide input voltage variations as dictated by the solar insolation and under such circumstances the TSBB can be the choice.

The TSBB offers more efficiency as compared to the traditional converters. Therefore for power applications in low power ranges the TSBB will be proffered. Besides the TSBB has two switches and that means it has two degrees of freedom to regulate the output voltage. The two switches S1 and S2 in the TSBB can be operated in three possible modes viz. operated simultaneously or one at a time. Thus there are three possibilities of operations of the TSBB and they are the Buck mode operation, the Boost mode operation and in both these two modes only one switch is in active switching operation while the other switch is either in the On state or in the Off state as laid down in table 1.
In either mode of operation the switching pulses are to be derived from a common controller. The control scheme involves two activities. The first activity is to choose the mode of operation and the second activity is the PWM operation on the selected mode so that the required voltage at the output terminals can be maintained.

If the available source voltage is much above the required output voltage then the converter will be driven in the buck mode. On the other hand if the source voltage is much less than the required output voltage then the converter will be operated in the boost mode. However if the source voltage frequently swings above and below the required output voltage then the two switches S1 and S2 are operated with different duty cycles depending upon the requirement.

In this work, only the two distinct modes of operation are dealt with. In either case of operation the PI controller and the fuzzy logic controller are used and the performance of the TSBB converter is studied. As for the buck mode of operation the relationship between the input voltage and the output voltage is governed by the relation \( V_o = k * V_{in} \)[6,7,8]. Where k is the duty cycle. This relationship is a linear relationship.

In the boost mode of operation the relationship between the input voltage and the output voltage is governed by the relation \( V_o = \frac{V_{in}}{1 - k} \) where k is the duty cycle. This relationship is a nonlinear relationship. Therefore it is usually a challenging task to design a common controller that will regulate the output voltage with required performance parameters and also stable.

PI controllers [9,10,11,12] are good with linear time invariant systems and as such PI controllers can perform sufficiently well in the buck mode and not so in the boost mode. A fuzzy logic controller (FLC) on the other hand does not require any mathematical model of the system under control and that it can handle nonlinear systems as well with the required control performance.

In this paper the topology of the TSBB the design details of the PI controller and the details of an FLC are presented. The paper is organized as follows. After this introduction section the topology of the TSBB along with the power handling details are discussed in the next chapter. A chapter is devoted for the PI controller where a review of the PI controller is considered. The next chapter is on FLC. The MATLAB SIMULINK model is presented in the following the chapter on FLC. Details of experimental verification is then provided and finally the results are discussed in the last chapter followed by the conclusion and references.

II. THE TWO SWITCH BUCK BOOST CONVERTER

With reference to the topology of the TSBB as shown in figure 2 the source is DC with variable voltage ranging between 20v and 30v. The two switches are named S1 and S2. The inductor used in the converter is L. A capacitive filter C is provided across the load resistor R.

With reference to the circuit arrangement with switch S1 active and with switch S2 off the converter works in the buck mode. In this case the diode D1 acts as the freewheeling diode. The circuit obeys the steady state input output voltage relationship as given by \( V_{out} = V_{in} * k \). Where k is the duty cycle.

There are two energy storage elements in the circuit Lf and Cf. The transfer function of the system is given by

\[
TF = \frac{V_o}{V_{in}} \frac{\frac{2\pi}{f}}{\frac{2\pi}{f} + 1}
\]

The transfer function of the buck converter can be simplified after substituting the values for Lf and Cf. Lf = 500e-6H and Cf = 2200 MFD and Rl = 25 Ohms. (24 Ohms approximated to 25 Ohms.)

\[
TF = \frac{V_o}{V_{in}} \frac{\frac{2\pi}{f}}{\frac{2\pi}{f} + 1}
\]

The transient response of the system as found by MATLAB is as shown below.

In the buck converter mode the switch S1 is active and the switch S2 is in the Off state. The maximum and minimum input voltages expected are 20 v and 30 v. As long as the input voltage is more than 24 volts the TSBB will work as a buck converter. With an input voltage of 30 volts the duty cycle to deliver an output voltage will be \( k = 24/30 = 0.8 \). With an input voltage of 24 volts the value of k will be 1. Therefore the value of k will lie anywhere between 0.8 and 1 depending upon the source voltage.

III. THE PI CONTROLLER

The purpose of a controller is to maintain the output or any other parameter of a system at the desired level. In the context of a DC – DC converter, to be used as a voltage source, the purpose of a controller is to maintain the terminal voltage across the load at the desired level against disturbances occurring in the source side voltage, the load or any other change or changes that may occur to the parameters of the internal structure of the system.

In a DC – DC Converter the manipulated parameter is the duty cycle and therefore the PI controller should supply the appropriate duty cycle based on the error and the decay or growth of error calculated from time to time in the observed parameter under control.
The structure of a PI controller is as shown in figure 4. The error which is the difference between the actual output voltage and the set point voltage is applied to the PI controller. The input and output of a PI controller in the time domain is given by the following expression.

\[ U(t) = K_p e(t) + K_i \int_0^t e(\tau) \]

Following this equation the transfer function of the PI controller is given by the equation

\[ U(s) = \frac{K_p e(s) + K_i \cdot e(s)}{s} = \frac{e(s)(K_p + \frac{K_i}{s})}{s} \]

Thus the PI controller has a pole at the origin and a zero at -1. The overall transfer function of the closed loop control system with the PI controller is given as

\[ \frac{56.4s + 4.297 \times 10^5}{s^2 + 1108s + 4.405 \times 10^5} \]

### Controller Type

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>Kp</th>
<th>Ki</th>
<th>Kd</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>1/a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI</td>
<td>0.9/a</td>
<td>3L</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>1.2/a</td>
<td>2L</td>
<td>L/2</td>
</tr>
</tbody>
</table>

In the second method the plant is supplied with sinusoidal signals of varying frequency and the gain is increased until the resonant frequency is determined. Since some plants cannot be subjected to high frequency oscillation even for tuning purpose this method can be used for some special plant only.

In this work the first method of ZN is used and the values of Kp and Ki estimated are .1 and 0.2 respectively.

### C. Performance analysis of the Proposed converter with the PI controller

After implementing the TSBB along with the PI controller in MATLAB SIMULINK a step change in the set value was assigned and the transfer function between the command and the output were observed. The data in respect of time was collected at the workspace and the transfer function of the system was arrived at using the ‘tfest’ (Transfer function estimate) TFEST function available in MATLAB.

The transfer function thus obtained is as follows.

\[ \frac{56.4s + 4.297 \times 10^5}{s^2 + 1108s + 4.405 \times 10^5} \]

Various control system analysis like impulse response, step response, Root Locus and the Nyquist analysis were carried out and the results are shown in Figure4.
Fig. 4 Control system performance characteristics

With reference to the figure 4 associated with control system analysis it is clear that the system operates in a stable state

III. THE FUZZY LOGIC CONTROLLER

A fuzzy logic controller offers a control system the design of which does not require a mathematical model of the plant. However the design of a fuzzy logic controller does need the working experience of the human operator. The human experience is encoded in the form of a collection of certain number of, if then types of rules, and this collection of rules is known as the rule base.

Each rule of the rule base used by the fuzzy logic controller actually relates the input parameters and the output parameters after they are translated into the multi valued fuzzy logic form. The system that accepts the inputs in the fuzzified form and gives out the result to be used for actuating the plant is called the fuzzy engine.

The fuzzy engine usually or typically accepts the fuzzified form of error and error rate as inputs. Based on the rule that applies to the current values of error and the rate of change of error the fuzzy engine gives out a solution that will be used by the actuating section after properly scaling the signal. The operation of a fuzzy logic controller can be viewed to be in two phases. In the first phase the fuzzy engine finds out the rule that exactly matches for the current situation and finds out the range in which the required control action may be found. During the second phase the precise value of the required control quantity is located from within the range that has already been finalized.
A. Universe of Discourse Segmenta
tion and Membership function
Whatever parameter that is to be applied to a fuzzy logic controller has a range and the entire range of such parameters is called the universe of discourse of the parameter. For example error, error rate are the typical inputs and their universe of discourse could be -100 to 100. This universe of discourse could be divided into a number of segments. Each segment is assigned with a variable called the linguistic variable. Typical linguistic variables are NB, NS, ZE, PS and PB literally denoting Negative Big, Negative Small, Zero, Positive Small and Positive Big respectively.

An input after being normalized in the scale of -100 to 100 is matched against the UOD with segments and the segment in which the input lies is found. The ranges of each segment may be so selected that they overlap on each other. Under such a circumstance the input may parameter may lie in two consecutive segments but with different membership values. The membership of any incoming parameter in a particular segment can be of any value as dictated by the membership function. Membership functions are curves drawn over each segment describing the degree of membership of each the parameter in the segment. In this work triangular membership functions are used for each of overlapped segments as shown in figure 6. The rule matrix in action when a certain set of rules are fired in figure 7 and the surface formed by the rules shown in figure 8.

IV. Results and Discussion
The Two Switched Buck and Boost model schematic in MATLAB is shown in figure. The switching pulses and the relevant output voltage waveforms are also shown.
It has been observed that with reference to the simulations carried out the voltage regulating property of the fuzzy logic controller is far better as compared to that of the PI controller. There is a finite overshoot in the case of PI controller especially at the moment the input voltage is changed from a lower value to a higher value. However with reference to figure 8 where the output voltage is presented against changing input voltage conditions, it is obvious that the performance of the Fuzzy logic controller is better than the PI controller. Since the fuzzy logic controller does not exhibit it can be concluded that the control effort required to stabilize the output voltage at the required level is less in the case of the FLC as against the PI controller as compared in Table 3.

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>Input voltage</th>
<th>Steady Output voltage</th>
<th>Overshoot at 0.1 Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>30 v</td>
<td>24</td>
<td>27.5 (3.5v)</td>
</tr>
<tr>
<td>Fuzzy Logic Controller</td>
<td>20 v</td>
<td>24</td>
<td>24.01 (0.01v)</td>
</tr>
</tbody>
</table>
Fig. 8. Comparison of the performance of PI and Fuzzy Logic controllers in output voltage regulation against source disturbance.

V. Conclusion

A Two Switched Buck Boost converter has been proposed. The performance of the PI controller and the FLC on the TSBB has been analysed using the appropriate tools available with MATLAB. It has been observed that the FLC outperforms the PI controller in terms of reduced overshoot, and reduced Integral Square Error (ISE). The proposed technique has been experimentally verified by constructing a hardware. The results of hardware verification also confirm that the FLC is a better option for the TSBB.

REFERENCES
