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RESEARCH ARTICLE OPEN ACCESS

Proportional-Integral (PI) Controller for Quad Buck-Boost Converter with Single Switch

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ABSTRACT
In this paper, the design of Proportional Integral (PI) control based quad buck-boost converter with a single switch with continual input and output current is presented. In contrast to typical buck-boost converters proposed converter has a large scale conversion ratio of voltage with same duty cycle. The converter proposed is constructed and analyzed with a Proportional-Integral /PIC controller and it is compared with the quad buck-boost converter without a controller (open loop). Ultimately the research of the quad buck-boost converter is simulated in MATLAB/Simulink software, outcome is documented to authenticate the effectualness of output voltage control in Quad buck-boost converter in both step-down-up mode where the input voltage is varied to different values with and without PIC controller and a comparative analysis is carried out to check the maintenance of constant output voltage, to reduce overshoot, settling time.

Keywords – Output Voltage, Proportional Integral (PI) Controller, Quad buck-boost, Single switch.

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I. INTRODUCTION

Nowadays, with the evolution of the power electronic industry use of the inexhaustible/green energy sources are in the focus of attention as the upcoming sources due to the consequences of the exhaustible energy sources on environment. However the inexhaustible energy sources will have the variable output voltage because of the differing environmental conditions. To attain a cut above performance DC-DC converters are brought into play for inexhaustible energy sources to reach the load demand. They are implemented in diverse applications like electric motor vehicles, Photovoltaic/solar panel, solar/PV based street lights, batteries/supercapacitors.

The quadratic converters where its duty cycle has a quadratic relationship for voltage conversion ratio and works in an implementations such as i/p o/p conversion [1]-[2]. A large amount of investigations are done on quadratic buck converters where it's numerical pattern, different techniques of control are studied [3]-[5], the distinct study of quadratic boost converters is investigated in [6]-[7]. Barely any analysis is carried out on quadratic buck-boost converters. Some of the research works, where the quadratic buck-boost converter is formed by fusing two typical quadratic buck-boost converters where it has interrupted i/p and o/p current [8]-[9] where these type of converters can be used in a wide range of applications such as batteries/supercapacitors which acts as energy banks with electrical-electrochemical method is analyzed in [10]. These converters are affordable, low priced and designed in a better way than the quadratic boost converters.

Due to change in the environmental conditions the output voltage will not be constant hence an accurate control is essential, this is where the different control techniques, controllers come into play for precise control , to meet load demand, to reduce the overshoot and settling time. A few study that is done on the Proportional-Integral controller where its different approaches across various devices are seen.

Few of the studies on the PI controllers like current regulation of PWM (pulse width modulation) converters with LCL filters which are linked to the grid where diverse damping applications are studied in [11], asymptotically stabilizing PIC is designed for SPC- switched power converters [12], appropriate techniques to determine the adaptive PIC variables which is used for the voltage control of DC link in 1-Ø GCCs (Grid connected converters) [13], a tracking precision of load voltage i.e. $\pm 0.05V$ for a fourth order cuk converter [14], a stability analysis which is effective in studying the time-variant character of single phase four quadrant converter which are utilized in high speed trains uses PIC for correct tuning [15].

The main aim of this paper is to design a controller i.e. Proportional-Integral controller (PIC) to a quad buck boost converter and differentiate it with a converter without a controller by varying input voltage. These type of converters are extensively applied in batteries/supercapacitors which are used as energy banks, solar/PV streetlights, electric motor vehicles etc. because of the inexhaustible energy sources used in these applications the output will be variable to overcome this problems the control techniques like proportional integral has to be implemented to meet the load demands and to minimize overshoot and settling time.

II. CONVENTIONAL AND PROPOSED QUAD BUCK-BOOST CONVERTER

Typical quadratic buck-boost converter operates with interrupted i/p and o/p currents creating complications in the layout of i/p and o/p filters [1]-[2]. The typical quadratic buck-boost converter as in Fig 1 is modeled by the merger of two standard buck-boost converters. Here the input side inductor L_1 current is identical to the i/p current i_{in} when switch is on similarly the output side inductor L_2 current is identical to the o/p current when switch is off. Due to this the i/p and o/p current becomes interrupted.

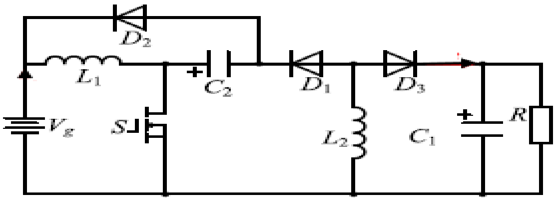

Fig 1: Conventional quadratic buck-boost converter

To get control of these disadvantages a new quad buck-boost converter is designed as most of the approaches in industries are carried out in uninterrupted mode of current. Fig 2 shows the novel, proposed quad buck-boost converter. It is fusion of typical buck, boost, and buck-boost converter. This converter can work in uninterrupted mode of inductor current with a simplified construction of i/p and o/p filters.

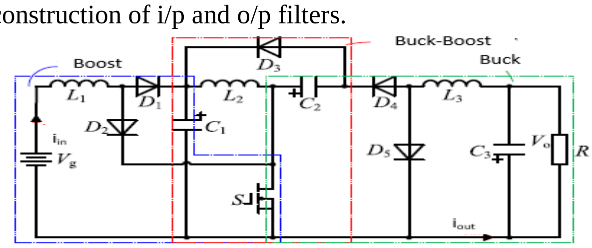

Fig 2: Proposed quad buck-boost converter

Modes of operation in CCM mode:

Mode 1: In time interval dt during the turn on of switch the equations are given by

$$\frac{di_{L1}}{dt} = \frac{vg}{L1}, \frac{di_{L2}}{dt} = \frac{V_{C1}}{L2}, \frac{di_{L3}}{dt} = \frac{V_{C2}-V_0}{L3} \quad (1)$$

$$\frac{dV_{C1}}{dt} = \frac{i_{L2}}{C_1}, \frac{dV_{C2}}{dt} = \frac{i_{L3}}{C_2}, \frac{dV_0}{dt} = \frac{1}{C3}\left(i_{l3} - \frac{V_0}{R}\right) \quad (2)$$

Mode 2: In time interval (1-d)t when switch is turned off, the equation are given by

$$\frac{di_{L1}}{dt} = \frac{Vg - V_{C1}}{L1}, \frac{di_{L2}}{dt} = \frac{-V_{C2}}{L2}, \frac{di_{L3}}{dt} = \frac{-V_0}{L3} \quad (3)$$

$$\frac{dV_{C1}}{dt} = \frac{-i_{L1}}{C_1}, \frac{dV_{C2}}{dt} = \frac{-i_{L2}}{C_2}, \frac{dV_0}{dt} = \frac{1}{C3}\left(i_{l3} - \frac{V_0}{R}\right) \quad (4)$$

III. PROPOSED QUAD BUCK-BOOST CONVERTER WITH PI CONTROL

Control techniques are employed to the converters which are used in the inexhaustible energy sources as the output of these converters is not constant depending on different environmental conditions. Hence to achieve the required range of output voltage to meet the load demand, closed loop control is implemented. By the application of these control techniques settling time, overshoot can be reduced.

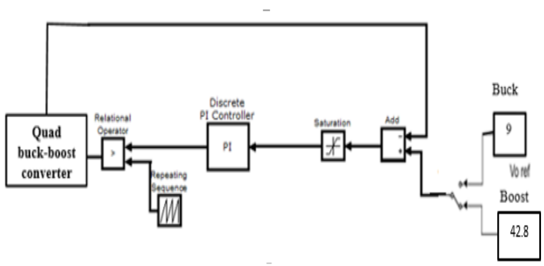

Fig 3: Quad buck-boost with PI Controller

Many of the industrial applications use the control loop techniques like Proportional-Integral (PI) controllers which does not require any physical input. Fig 3 indicates the proposed converter which is PI controlled.

Approach of PI controlled quad buck-boost converter is as follows:

The converter (quad buck-boost) output voltage is differentiated with the recommended (reference) value, the error signal of this differentiation is supplied to the saturation block. The output of the saturation block is fed to the PI controller where the correction is done based on the Kp and Ki i.e. proportional and integral terms, the relational operator receives the rectified output

where it is compared with the triangular pulses resulting in the generation of the gate pulses which is supplied to the gate terminal of the switch.
The control equation of PI controller is as follows

$$U(s) = K_p\ E(s) + \frac{1}{s} K_i \int E(s) \quad (5)$$

$$\frac{U(s)}{E(s)} = G_c = K_p + K_i \frac{1}{s} \quad (6)$$

$$G_c = K_p \left(1 + \frac{1}{T_i\ S}\right) \quad (7)$$

The equation (7) represents the general transfer function of a PI controller. Where G_c – transfer function of controller, K_p - proportional gain, K_i - integral gain, T_i - integral time $= \frac{Kp}{Ki}$.

The values of Kp and Ki is found using the ZN (Ziegler-Nicholos) method is used, where the rules are proposed for controller tuning. Basing the values of Kp the values if Tu and Ki are set. A series of tuning values are taken until the justifiable outcome is attained. Ziegler and Nichols tuning rules table is indicated in Table I from which tuning values van be calculated.

Table I: Ziegler and Nichols tuning

controller	Kp	Ki	Kd
p	0.5*Ku	-	-
PI	0.45*Ku	1.2*Kp/Tu	-
PID	0.6*Ku	2*Kp/Tu	Kp*Tu/8

Considering value of Ku and Tu as 0.0222 and 0.012, referring to Table I for PI controller the Kp and Ki values are found to be 0.01 and 1. Substituting these values in in equation (7) the transfer function of the controller is given by

$$G_c = 0.01 + \frac{1}{S} \quad (8)$$

IV. MATLAB / SIMULINK EXECUTION, RESULTS AND DISCUSSION

4.1 Proposed converter without controller (open loop)

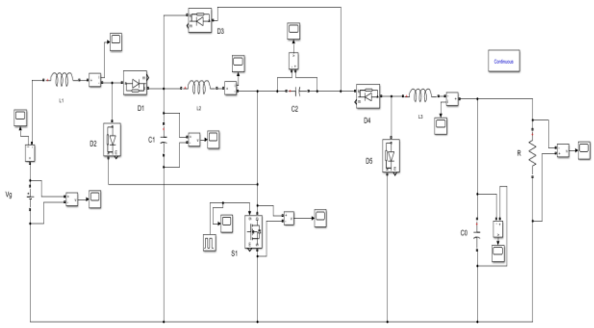

Fig 4: Simulation circuit of quad buck-boost Converter without controller (open loop)

The Fig 4 shows the simulation circuit of the quad buck boost converter without a controller i.e. open loop control. The factors required for simulation is chosen from Table II.

4.2 Proposed converter with controller- PI controller (closed loop)

Fig 5 shows the Simulink/MATLAB model of proposed quad buck-boost converter with PI controller with an output of 43.7V in step-up and 9v in step down mode with variable input. The Kp and Ki values are obtained from Z-N method which is 0.01 and 1.

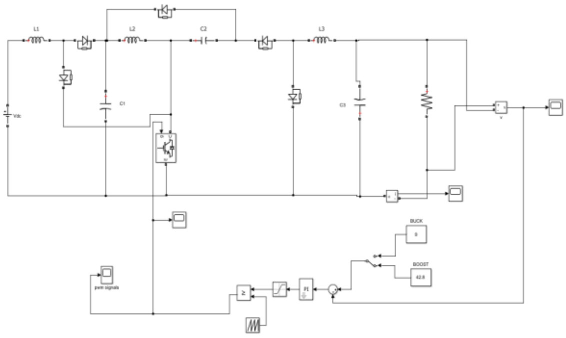

Fig 5: Simulation circuit of PI controlled Quad Buck-Boost Converter (closed loop)

Table II: Simulation variables of the converter proposed.

Input voltage (Vg)	20v
Output voltage (V0) [for step-up] [for step-down]	42.8.7V 9V
Inductor L1, L2, L3	100 µH,400 µH,3mH
Capacitors (C1, C2) (C0)	47 e-6 F 220 e-6 F
Switching frequency	40kHz
Duty cycle [for Step-up] [for Step-down]	>50% <50%
Resistance [for step-up] [for step-down]	60Ω 6Ω

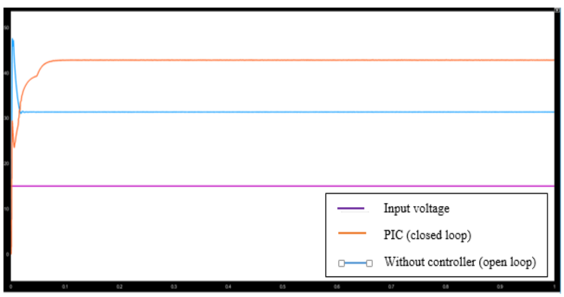

Fig 6.1: comparison of quad buck-boost converter with PIC and without PIC for an input of 15V in boost mode.

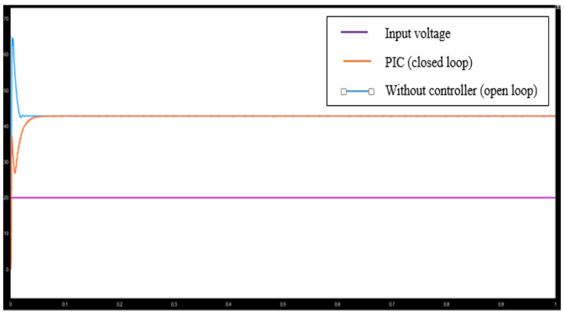

Fig 6.2: comparison of quad buck-boost converter with PIC and without PIC for an input of 20V in boost mode.

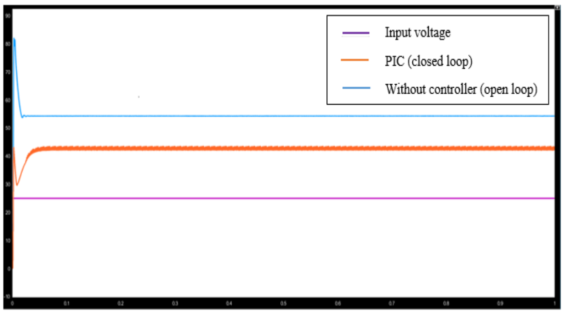

Fig 6.3: comparison of quad buck-boost converter with PIC and without PIC for an input of 25v in boost mode.

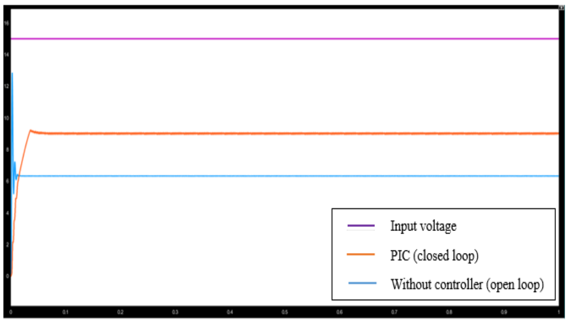

Fig 7.1: comparison of quad buck-boost converter with PIC and without PIC for an input of 15v in buck mode.

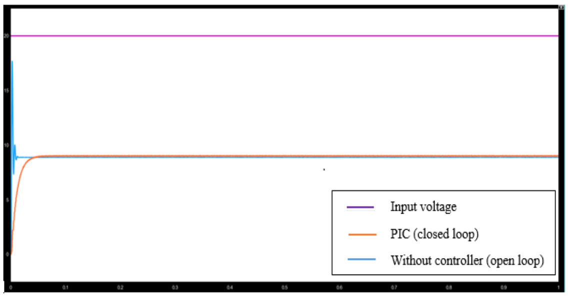

Fig 7.2: comparison of quad buck-boost converter with PIC and without PIC for an input of 20V in buck mode.

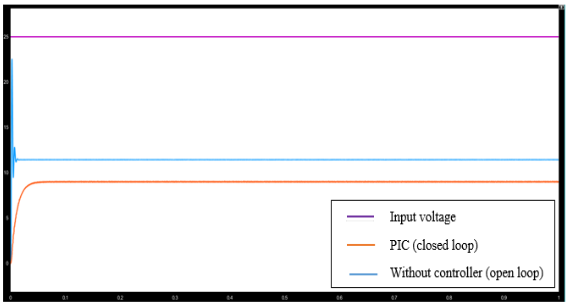

Fig 7.3: comparison of quad buck-boost converter with PIC and without PIC for an input of 25V in buck mode.

4.3 Comparison table of proposed converter with PI controller and without controller

Table III: Comparison of response of proposed converter with controller and without controller in boost mode.

Input voltage	parameters	With PIC (closed loop)	Without PIC (open loop)
15V	Output Voltage	42.8V	31.5V
	Overshoot	0.29%	0.48%
	Settling time	0.006s	0.02s
20V	Output voltage	42.8V	42.8V
	Overshoot	0.371%	0.65%
	Settling time	0.008s	0.02s
25V	Output voltage	42.8V	54.3V
	Overshoot	0.44%	0.85%
	Settling time	0.008s	0.02s

Table IV: Comparison of response of proposed converter with controller and without controller in buck mode.

Input voltage	parameters	With PIC (closed loop)	Without PIC (open loop)
15V	Output Voltage	9V	6.35V
	Overshoot	0%	0.128%
	Settling time	0s	0.015s
20V	Output voltage	9V	9V
	Overshoot	0%	0.177%
	Settling time	0s	0.015s
25V	Output voltage	9V	11.45V
	Overshoot	0%	0.229%
	Settling time	0s	0.015s

In above Table III and Table IV shows the comparison of the proposed converter with PI controller (closed loop) and without a controller (open loop) which is inferred from figure Fig 6.1, 6.2, 6.3 and Fig 7.1, 7,2, 7.3. From the above tables it is inferred that the proposed converter which is controlled by PIC gives a constant output voltage even with a variable input whereas the quad buck-boost converter without a PI controller will have variable output with the change in the input voltage. And over shoot, settling time is very much reduced when a converter is implemented with PI controller.

V. CONCLUSION

In this paper the Proportional-Integral controller technique is used to administer the output voltage of proposed quad buck-boost converter. The simulation of the circuit is executed using MATLAB/Simulink software to evidence the circuit function. The simulated results indicate that the given structure of quad buck-boost converter which gives rise to the step-up voltage of 42.8V and step-down voltage of 9V with an input of 20V both with and without PIC but when the input is varied due to various environmental conditions the quad buck-boost converter with PIC gives a constant output voltage of 42.8V and 9V in boost and buck mode but for a converter without a PI controller the output voltage is variable. The results show that the proposed converter with PI controller gives constant output voltage for variable input with reduced overshoot, settling time compared to the quad buck-boost converter without PIC. Hence control techniques like PI controllers plays a vital role to meet the load demands.

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