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Closed Loop Control of Bidirectional Buck-Boost Converter for Battery Management in Automotive Systems

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Abstract

A new control logic is constructed for bidirectional buck-boost converter (BBC) through mathematical modeling and implemented in Simulink. The BBC bridges 12 V and 24 V in dual battery automotive systems to meet the power load requirements of advanced automotive electronics. From mathematical modeling, gains of proportional, integral, derivative with filter (PIDN) control law are obtained. Mode selection circuit is developed for Buck and Boost mode control. For each mode of operation, separate PIDN control law and pulse width modulation (PWM) system is developed in control topology under voltage feedback control method. Auto mode transition is realized based on DC bus voltage. Load and line regulations in both buck and boost mode of BBC are realized based on load voltage. The constructed control logic offers accurate bidirectional voltage regulation which ensures precise power transfer in both the directions. Battery charging and discharging characteristics are realized. PIDN control law is compared with proportional, integral, derivative (PID) control law.

Keywords— *Closed loop control, DC-DC converter, Battery management, automotive systems, PIDN control.*

1. INTRODUCTION

In automobile industries, a strict emission regulations are increasing. Also a power load requirements of advanced automotive electronics and the conversion from mechanical components to electronics functions are growing[1]. The traditional 12V automotive battery has reached its current carrying capacity[2]. In response to it, 24V electrical system finds itself an important role to deliver more power at lower currents than a traditional 12V battery can produce alone. The 24V Electrical system answers 12V limits. This configuration consists of two separate branches. The traditional 12 V bus utilizes a conventional lead-acid battery for customary loads such as lighting ,windows and infotainment ; While the 24V system can support heavier loads such as starter generator units, air-conditioning compressors, active chassis systems, electric superchargers, turbochargers and regenerative braking. Bidirectional buck-boost converter bridges the 12V and 24V systems as shown in fig.1 .

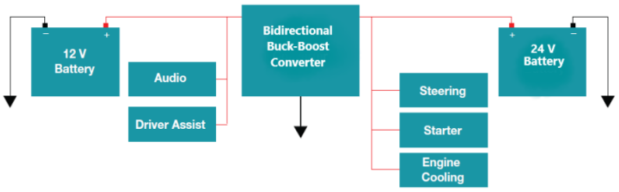


Fig.1. Bidirectional buck-boost converter for battery management in automotive systems.

This results in lighter-weight vehicle which is more fuel efficient and emits less carbon dioxide. The 24V system saves weight in the wiring harness. A higher voltage allows for smaller wire gauge which reduces cable size and weight by reducing current level without reducing performance. Along with bidirectional buck-boost converter, traditional 12 V battery and DC bus of 24V (where battery can be connected) round out the dual-battery system to deliver up to 5KW of available power. Bidirectional power transfer is required to charge either battery if its discharged and provide extra power for the opposite voltage bus in an overload condition[3]. For power transfer from the 24V DC bus to the 12V battery, buck converter is used[4][5]. While power transfer from 12V battery to 24V bus, boost converter is used. These are well-known in power electronics, but designing two separate converters takes valuable board space and increase system complexity and cost[6][7]. Typically 12V and 24V dual-DC power system can be implemented using digital control scheme which includes discrete components like voltage sensors, gate drivers and protection circuits. As an alternative, there is mixed architecture where microcontroller handles higher-level intelligent management and an integrated analog controller.24V bus can provide up to 5kW of power for driving various systems[8].

2. MODELING AND CONTROL METHOD

In this section, Bidirectional buck/boost converter (BBC) is modeled using state space average large signal modeling approach to obtain transfer function. Since BDC works in two modes, buck mode in one direction and boost mode in another direction, state-space modeling is applied separately for each mode to obtain transfer function separately for each mode. Working of BBC is depicted in the table I.

Table I. Working of BBC

Mode of operation	**Devices ON**	**Devices OFF**	**Power flow**	**Battery state**
Boost mode	S2 followed by D1	S1 followed by D2	From battery to DC bus	Battery discharging
Buck mode	S1 followed by D2	S2 followed by D1	From DC bus to Battery	Battery charging

Simulink and MATLAB are chosen as modeling, implementation and test platforms. To begin with, the state space modeling is fundamentally represented in (i) and (ii), where A, B, C, D are the system matrix, x is the state variable, x' is the state variable derivative, u is the input, and y is the output. The fundamental BBC circuit is shown in fig.2. And its design specifications are given in table II.

$$x' = Ax + Bu \qquad (i)$$

$$y = Cx + Du \qquad (ii)$$

Table II. Specifications of BBC

Parameter	*Value*
DC Bus voltage (Vbus)	*24V*
DC Bus current (I_{bus})	*3 A*

Battery voltage (V_{Batt})	*12 V*
Switching frequency (F_s)	*20 KHz*
Load voltage (V_0)	*24 V*
Load Current (I_0)	*2.4 A*
Duty Cycle (d)	*0.5*
Inductor (L)	*1000 µH*
DC bus capacitor (C_{bus})	*250 µF*
Load resistor (R)	*10 Ω*
Capacitor across battery (C_0)	*125 µF*
*Battery resistance (R_{batt})= $\frac{Ns}{Np}$*R_{inter} = $\frac{6}{1}$*30 m Ω*	*0.18 Ω*

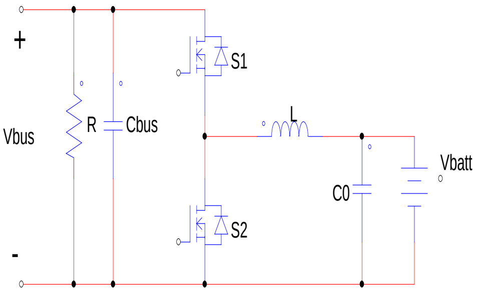


Fig. 2. Bidirectional buck/boost converter (BBC) fundamental circuit

a. Boost Mode

During ON state, the inductor is charged through Vbatt defined in (1).there is no current flow to the capacitor and resistor in this state, where i_L is zero as defined in (2).

$$Vbatt = L\frac{di_L}{dt}.........(1)$$

$$0 = C_{bus}\frac{dV_C}{dt} + \frac{V_C}{R}........(2)$$

The state derivative of i_L and Vc are obtained by rearranging (1) and (2).the state space matrix A and B in (5) for boost mode in ON state can be formulated using (3) and (4)

$$x'_1 = \frac{1}{L}V_{batt}.........(3)$$

$$x'_2 = -\frac{1}{RC_{bus}}x_2.........(4)$$

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC_{bus}} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} Vbatt.....(5)$$

When converter enters ’OFF’ state condition in boost mode.

$$V_C = Vbatt - L\frac{di_L}{dt}............(6)$$

$$i_L = C_{bus}\frac{dV_C}{dt} + \frac{V_C}{R}.....(7)$$

Its derivatives are obtained as shown in (8) and (9) by rearranging (6) and (7).

$$x_1' = -\frac{1}{L}x_2 + \frac{1}{L}V_{batt}....(8)$$

$$x_2' = \frac{1}{C_{bus}}x_1 - \frac{1}{RC_{bus}}x_2.....(9)$$

The state space matrix A and B are formulated using (8) and (9) in (10).

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C_{bus}} & -\frac{1}{RC_{bus}} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} Vbatt......(10)$$

The average of boost mode state space A and B matrix for its ‘ON’ and ‘OFF’ state can be formulated with the account of switching duty cycle ‘d’. The completed boost converter state space model is shown in (11) and (12).

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \begin{bmatrix} 0 & -\frac{(1-d)}{L} \\ \frac{(1-d)}{C_{bus}} & -\frac{1}{RC_{bus}} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{batt}....(11)$$

To obtain the output state of Vc and i_L, the output state space for C and D matrix is shown in (12)

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{batt}.....(12)$$

Continuous-time *transfer function* of BBC in boost mode obtained from eqn (11) and (12) by considering the design specifications and parameters of BBC given in table II, is shown in eqn (13) .

$$TF = \frac{2*10^6}{S^2 + 400S + 1*10^6}......(13)$$

Equation 14 represents transfer function of PID control with gains of kp = 4.6228, ki = 1.0392e+03, kd = 0.0041 and filter co-efficient ‘N’=1.7031e+06.It is obtained for transfer function of BBC shown in eqn (13).It’s ideal PID control function. This results in ripple in the out signal as shown Fig. 11.1 and also it results in lower bandwidth and system gain that in turn results in slow dynamic response. Therefore to improve bandwidth and system gain, filter co-efficient to be considered to develop transfer function. So by considering value of 'N' which is obtained from tuning process i.e. N=1.7031e+04 the transfer function of PIDN is obtained as shown in the equation 15.

$$\text{PID}=\frac{6947\,s^2+7.874e^6\,s+1.77e^9}{s^2+1.703e^6\,s}\;\ldots.(14)$$

$$\text{PIDN}=C(s)=\frac{74.05\,s^2+7.977e^4\,s+1.77e^7}{s^2+1.703e^4\,s}\;\ldots.(15)$$

b. Buck Mode

During ON state of S1 ,state variables Vc *and* i_L *are defined in (16) and (17).*

$$V_C=V_{bus}-L\frac{di_L}{dt}\ldots\ldots(16)$$

$$i_L=C_0\frac{dV_C}{dt}+\frac{V_C}{R_{batt}}\ldots\ldots..(17)$$

Derivatives of state variables Vc *and* i_L *are given in (18) and (19)*

$$x1'=-\frac{1}{L}x_2+\frac{1}{L}V_{bus}\ldots\ldots(18)$$

$$x_2'=\frac{1}{C_0}x_1-\frac{1}{R_{batt}C_0}x_2\ldots..(19)$$

The state space matrix A and B are formulated using (18) and (19) in (20).

$$\begin{bmatrix}x_1'\\x_2'\end{bmatrix}=\begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C_0} & -\frac{1}{R_{batt}C_0}\end{bmatrix}\begin{bmatrix}x_1\\x_2\end{bmatrix}+\begin{bmatrix}\frac{1}{L}\\0\end{bmatrix}V_{bus}\ldots\ldots\ldots\ldots.(20)$$

During OFF state of S1 , Vbus=0 therefore, the derivatives x1' and x2' are given in (21) and (22).

$$x1'=-\frac{1}{L}x_2\ldots\ldots\ldots\ldots\ldots\ldots(21)$$

$$x_2'=\frac{1}{C_0}x_1-\frac{1}{R_{batt}C_0}x_2\ldots\ldots\ldots.(22)$$

The state space matrix A and B are formulated using (21) and (22) in (23)

$$\begin{bmatrix}x_1'\\x_2'\end{bmatrix}=\begin{bmatrix}0 & -\frac{1}{L}\\ \frac{1}{C_0} & -\frac{1}{R_{batt}C_0}\end{bmatrix}\begin{bmatrix}x_1\\x_2\end{bmatrix}+\begin{bmatrix}0\\0\end{bmatrix}V_{bus}\ldots\ldots\ldots.(23)$$

The average of buck mode state space matrix *A* and *B* for its 'ON' and 'OFF' states can be formulated along with duty cycle '*d'* and is given in (24)

To obtain the output state of Vc and i_L, the output state space for C and D matrix is shown in (25).

$$\begin{bmatrix} x_1' \\ x_2' \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C_0} & -\frac{1}{R_{batt}C_0} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} Vbus.....(24)$$

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{bus}....(25)$$

Continuous-time transfer function *obtained from eqn (24) and (25) by considering the design specifications and parameters of BBC given in table II, is shown in eqn (26)* .

$$TF = \frac{2*10^6}{S^2 + 400S + 1*10^6}.....................(26)$$

$$PID = \frac{-3135\ s^2 + 2.443e^6\ s + 7.167e^8}{s^2 + 7.78e^5\ s}\ ....(27)$$

Equation 27 represents transfer function of PID control with gains of kp = 3.1393, ki = 921.1756, kd = -0.0040 and filter co-efficient 'N'=778000.31. It is obtained for transfer function of BBC in buck mode as shown in eqn (26).It's ideal PID control. This results in ripple in the out signal as shown Fig. 11.2 and also it results in lower bandwidth and system gain that in turn results in slow dynamic response. Therefore to improve bandwidth and system gain, filter co-efficient to be considered to develop transfer function. So by considering value of 'N' which is obtained from tuning process i.e. N=778.31 the transfer function of PIDN is obtained as given in the equation(28).

$$\text{PIDN=C(s)=}\frac{3.793e^{-9}\ s^2 + 3364\ s + 7.169e^5}{s^2 + 778.3\ s}\ ...(28)$$

3. SIMULATION

MATLAB R13a tool was used for simulating the controller with Bidirectional buck-boost converter (BBC) as shown in the figure.4 and it is having the specification shown in the table II. Simulation is used for verifying the controller characteristics of generating PWM pulses for switch (S1) and switch (S2) of BBC based on status of DC bus voltage and ensuring stable DC voltage of 24V over DC Bus[11]. This involves auto transition of buck mode to boost mode and vice versa. Such auto transition offered by the controller is as shown in figure.5 and it is made up of PWM circuit, PIDN control law, comparator and mode selection logic.

a. Power stage

The power converter 'BBC' is half bridge converter as shown in Fig.3.It has two switches. In this BBC topology, MOSFET is used as switch. In each direction of power flow, one particular switch is operating with different duty cycle of control signal therefore each particular switch is driving with separate PIDN control law and hence separate PWM block is designated for it.In addition BBC consists of filter section where one inductor (L) and two capacitors; one is at battery side called as C_{batt} and another one is at load side called as Cbus. BBC pumps the power from DC bus side to battery to charge it with constant current and voltage when sufficient power is available at DC bus side for load (R)[12]. When there is no sufficient power for load from DC bus, then BBC pumps power from battery to load with constant current and voltage. The BBC which is single converter works as a two converter therefore its compact and efficient. But the difficult part is the design of controller for such converter.

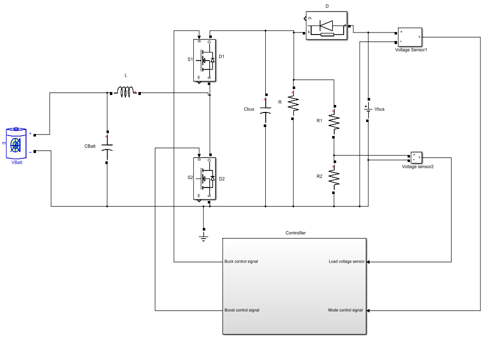


Fig.3. Power stage of BBC with closed loop control

b. Controller

The controller circuit designed for bidirectional buck-boost converter is as shown in Fig.4 .The BBC shown in Fig.2 works in two modes for bidirectional power flow. For each direction of power flow, one particular switch has to operate with particular control signal[13].Therefore to generate such particular control signal, separate PIDN control logic with designated PWM circuit is required and it is as shown in Fig.2 for each mode of operation. Since voltage mode control is used in closed loop control to regulate battery charging and discharging as well as to regulate DC bus voltage, load voltage is sampled using voltage divider circuit shown in Fig.3.By using comparator circuit shown in Fig.5 ,the sampled load voltage is compared with reference voltage(3V) which is a scaled down version of load voltage. This is made so since digital controller works in low voltage in the range of 1.8V to 5V.Further it is scaled down to 1/reference voltage since control logic i.e. PIDN works in the bandwidth of ‘0’ to ‘1’ unit. The error signal produced by the comparator is used in PIDN control logic circuit shown in Fig.6 for buck mode control and Fig.7 for boost mode control. Each PIDN control logic circuit has different gains with filter co-efficient (N).The output of PIDN control signal is fed to the PWM circuit shown in Fig.8 for buck mode control and figure.9 for boost mode control. These PWM signals which are generating upon load voltage fed to the gateway called as mode selection circuit as shown in Fig.10. It is logic circuit which transfers PWM signals for switches in BBC based on DC bus voltage. It transfers PWM signal from PWM system1 shown in Fig.4 to switch ‘s1’ to operate BBC in buck mode to charge the battery when DC bus voltage ≥ 24V.In case DC bus voltage < 24V,It transfers PWM signal from PWM system2 shown in Fig.4 to switch ‘s2’ to operate BBC in boost mode to discharge the battery in order to regulate DC bus voltage at 24V where load is connected and hence load gets the stable voltage.

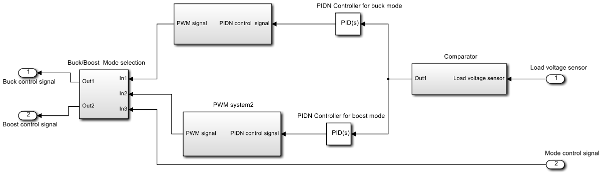


Fig.4. Controller for power stage of BBC

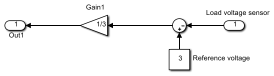
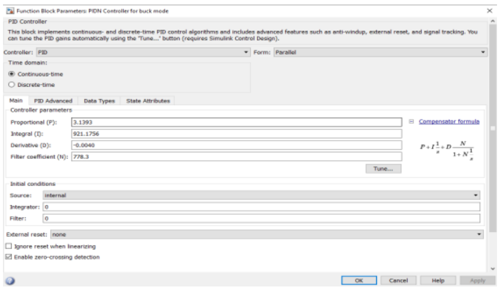


Fig. 5. Logical block of comparator


Function Block Parameters: PIDN Controller for buck mode

PID Controller

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: PID
Form: Parallel

Time domain:
● Continuous-time
○ Discrete-time

Controller parameters
Proportional (P): 3.1393
Integral (I): 921.1756
Derivative (D): -0.0040
Filter coefficient (N): 778.3

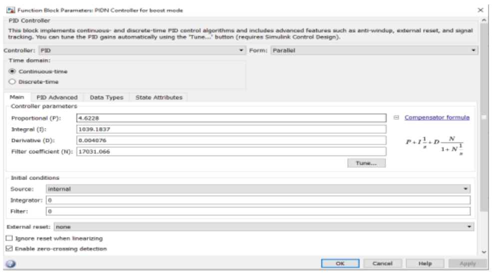
Compensator formula

$$P+I\frac{1}{s}+D\frac{N}{1+N\frac{1}{s}}$$

Initial conditions
Source: internal
Integrator: 0
Filter: 0

External reset: none
☐ Ignore reset when linearizing
☑ Enable zero-crossing detection

Fig.6.Functional block of PIDN controller for buck mode control


Function Block Parameters: PIDN Controller for boost mode

PID Controller

This block implements continuous- and discrete-time PID control algorithms and includes advanced features such as anti-windup, external reset, and signal tracking. You can tune the PID gains automatically using the 'Tune...' button (requires Simulink Control Design).

Controller: PID
Form: Parallel

Time domain:
● Continuous-time
○ Discrete-time

Controller parameters
Proportional (P): 4.6228
Integral (I): 1039.1837
Derivative (D): 0.004076
Filter coefficient (N): 17031.066

Compensator formula

$$P+I\frac{1}{s}+D\frac{N}{1+N\frac{1}{s}}$$

Initial conditions
Source: internal
Integrator: 0
Filter: 0

External reset: none
☐ Ignore reset when linearizing
☑ Enable zero-crossing detection

Fig.7.Functional block of PIDN controller for boost mode control

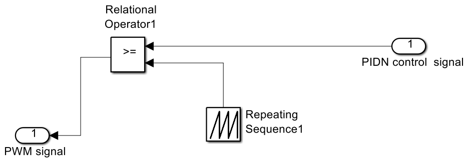


Fig. 8. Logical bock of PWM for buck mode control signal

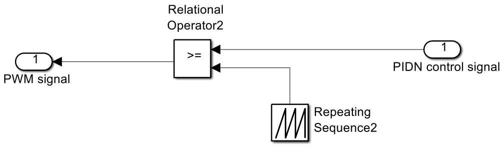


Fig. 9. Logical bock of PWM for boost mode control signal

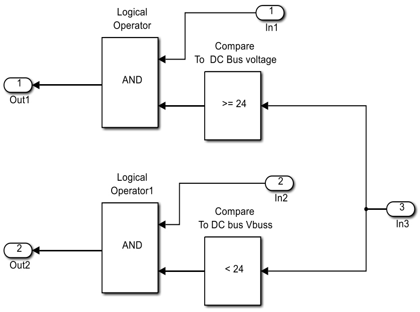


Fig. 10. Logical block of mode selection

4. RESULTS AND DISCUSSION

Simulation and hardware results of BBC are presented in this section.BBC works in two modes like Boost mode and buck mode. Controller determines the mode of operation based on DC bus voltage. This controller contains PIDN control law for boost and buck modes. The impact of PID control and PIDN control on load voltage during boost mode of operation of BBC is shown in Fig. 11.1.Similarly The impact of PID control and PIDN control on load voltage during buck mode of operation of BBC is shown in Fig. 11.2

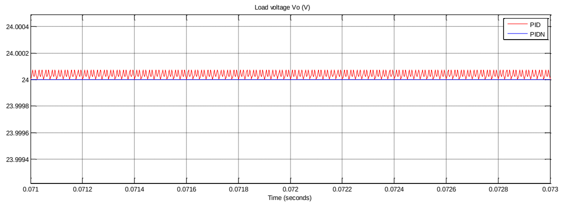


Fig.11.1 Simulation output of BBC with PIDN and PID control in boost mode

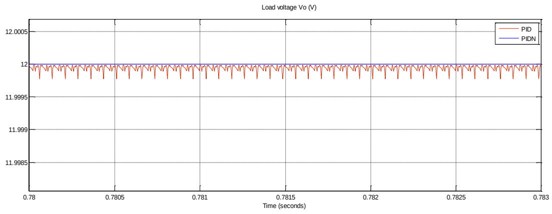


Fig.11.2 Simulation output of BBC with PIDN and PID control in buck mode

a. Boost Mode

The BBC works in boost mode when DC bus voltage < 24V.In boost mode ,control circuit generates PWM signal for the switch‘S2’ therefore battery as source voltage starts discharging and hence BBC boosts the battery voltage(12V) to the level of DC bus voltage (24V). Fig.12 represents battery characteristics in boost mode of operation where state of charge (SOC) of the battery is falling .This clearly indicates that the battery is discharging to boost up the voltage by the BBC [9].Battery with 12V pumps the current of 5A to maintain 24V across load of 10Ω with 2.4 A.

Fig.13 represents dynamic and steady states of BBC in boost mode at DC bus voltage of 15V.Since DC bus voltage is < 24V ,the controller stops generating PWM signal for the switch ‘s1’ and starts generating PWM signal for the switch ‘s2’ as shown in Fig.13.

Fig.14 represents steady state of BBC in boost mode. Wherein control signals, inductor voltage and current, load voltage and battery voltage are depicted. According to the waveforms in Fig.14, when switch ‘s2’ is ON with control signal ON, inductor current increases with battery voltage and hence inductor stores the energy by the virtue of current through it.When the switch ‘s2’ is OFF with control signal OFF, voltage across inductor (12V) and battery voltage (12V) adds up and fed to the DC bus to maintain 24V for load. As it is seen in Fig.14,duty cycle of the control signal is less than 50% since fully charged battery voltage is 13.9V therefore 5.3A of current is forced for load to maintain 24V across it.In the same way as it is seen in Fig.14.1, duty cycle of the control signal is more than 50% since fully charged battery voltage is 10.7V therefore 7.1A of current is forced for load to maintain 24V across it.From this it is clear that system is working in closed loop control with control logic of PIDN and PWM.

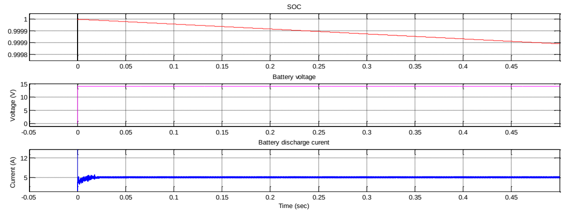


Fig.12

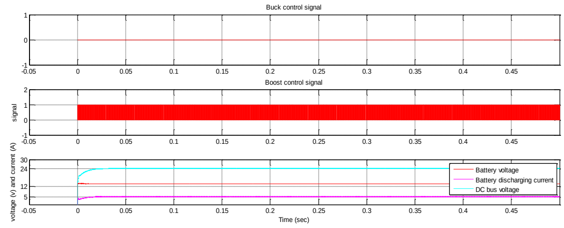


Fig.13

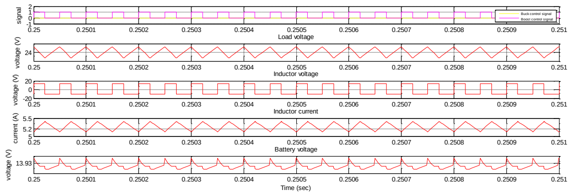


Fig. 14

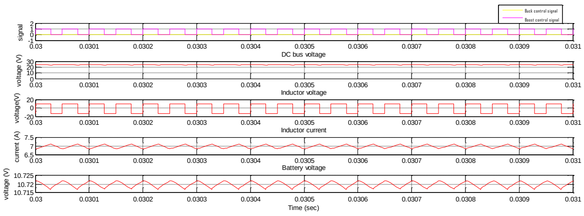


Fig. 14.1

b. Buck Mode

The BBC works in buck mode when DC bus voltage is ≥ 24V. In buck mode ,control circuit generates PWM signal for the switch‘S1’ therefore battery as load starts charging and hence BBC step down the DC bus voltage(24V) to the level of battery voltage (12V). Figure.15 represents battery a characteristic in buck mode of operation where SOC of the battery is increasing .This clearly indicates that the battery is charging by the BBC from the DC bus as voltage source. Battery with 12V receives the current of 0.25A shown in Fig.15 to charge itself while load (R) receives current of 2.4 A from DC bus.

Fig.16 represents dynamic and steady states of BBC in buck mode at DC bus voltage of 24V.When DC bus voltage is ≥24V ,the controller starts generating PWM signal for the switch ‘s2’ and stops generating PWM signal for the switch ‘s1’ as shown in Fig.13.

Fig.17 represents steady state of BBC in buck mode. Wherein control signals, inductor voltage and current, load voltage and battery voltage are depicted. According to the waveforms in Fig.17, when switch ‘s1’ is ON with control signal ON, inductor current increases in the negative direction with DC bus voltage of 24V and hence inductor stores the energy by the virtue of current through it.When the switch ‘s1’ is OFF with control signal OFF, voltage across inductor (-12V) and DC bus voltage (24V) adds up and fed to the battery of 12V.From the waveform it is observed that the battery is already charged to its fully charged voltage level of 12.95V and further it doesn’t receive power from BBC therefore battery current reaches zero even if BBC is trying to supply power to it due to inductor voltage. This state results in ringing effect in inductor voltage and hence causes heat in the inductor. This deteriorates the efficiency of the system. Further if DC bus voltage is increased, the ringing effect in inductor voltage increases with PWM action shown in Fig.18. In buck mode also close loop is working however this is happening because it is feedforward closed loop action i.e. source voltage (Vbus) is taken for control action but not the load voltage (Vbatt).This ringing effect doesn’t appear if battery is able charge complete power supplied by BBC from DC bus as it is shown in Fig.19 .Another way of avoiding ringing effect is feedback control loop where battery voltage supposed to be taken for control action.

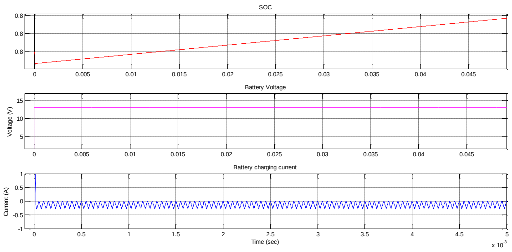


Fig. 15

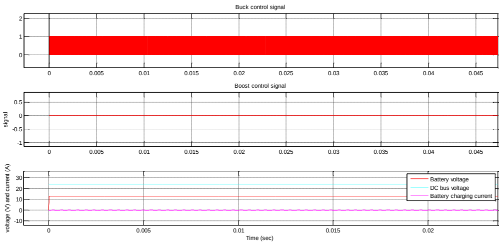


Fig.16

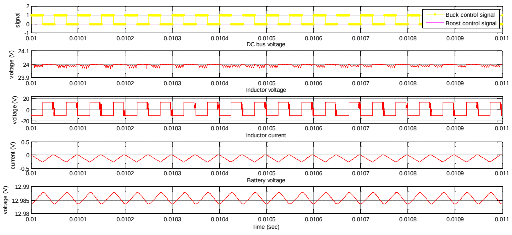


Fig. 17

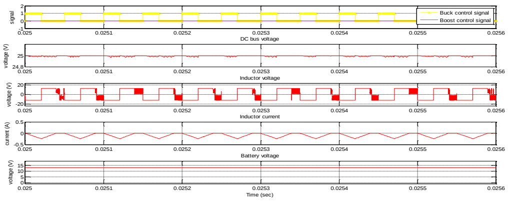


Fig.18

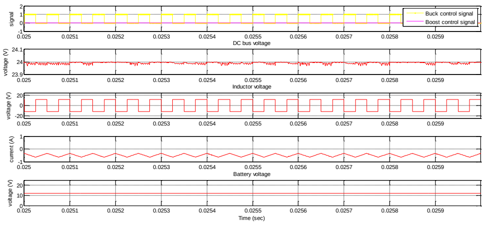


Fig. 19

5. CONCLUSION

The design of control logic with bidirectional buck-boost converter for 12V/24V automotive systems fulfils the typical operating voltage requirements for 12V/24V automotive systems. In buck mode: 24V- port voltage range 3V to 35V; 12V-port voltage regulated at 14.5V.In boost mode: 12V-port voltage range 3V to 48V; 24V-port voltage regulated at 24.V.Maximum dc current into or out of the 12V- port is 30A. It accepts analog voltage loop control. While it also accept microcontroller Digital voltage loop control. The control logic uses PIDN control law which reduces output ripple and thus electromagnetic interference (EMI). The complete system uses two voltage mode control loops which benefits good noise immunity for all load conditions.

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