A Robust Proportional Integral Sliding Mode Controller Synthesis Applied on Buck-Boost DC-DC converter for Electric Vehicle Application

Ms.K.M.Priya* [1], Dr.T.Balakumaran [2]

[1,2]*Coimbatore Institute of Technology, Electronics and communication Engineering,*

Coimbatore- 641014, Tamilnadu, India.

Abstract

Battery fed electric drives are mostly used for Electric vehicle applications. A various advantages of EV Compared to Hybrid such as emission, it decreases the petroleum resources, waste oil dumping decreases, provide good performance in acceleration and braking conditions. Electric vehicle consists of Dc-Dc converter and electric motor drive system. It is operating in three modes (i) Acceleration mode (ii) Normal steady state (iii) Regenerative braking mode. In acceleration, the power flow from battery to electric motor. In normal steady state converter output maintains in steady state value. In regenerative braking mode the power flows from electric motor to battery. If any variations occur in the battery and the motor side the converter output not maintain in steady state, the converter output produces variable output voltage. Nonlinear control of power converters is an active area of research in the fields of power electronics. This proposed work focuses on Proportional Integral Sliding Mode Control (PISMC) for Buck-Boost DC-DC converter power supply to maintain the constant output voltage. The performance of the proposed proportional integral sliding mode controller is compared to classical PI, PID and SMC controllers. The proposed controller has certain merits like less rise time, maximum peak over shoot, settling time and steady state error.

Keywords: *Batteries, Converters, Controllers and Electric vehicles*

1.Introduction

Electric vehicles power management has a very important role, as it has the adaptability to make a decision of electrical vehicle power remaining in conservative economy. A several powerful methods of energy optimization for Hybrid Electric vehicle is described in [1, 2]. All batteries do not have correct autonomous that rely upon their specific energy storage (state of charge and depth of discharge) wherever the output voltage is not constant. For this reason, tend to use the DC –DC converter with an effect strategy to assure the energy requirement for the electrical vehicle and therefore the system. Consequently, the projected management strategy applied on DC -DC converter assures and maintains the DC output voltage constant against load variations. Energy storage or power provide devices vary their output voltage with load or state of charge, and this creates major challenges for electrical vehicle. DC-DC converters will be wont to interface the elements within the power train by boosting or chopping the voltage levels. A non-isolated universal bidirectional DC-DC converter are studied and analyzed in [3]. The presented power converter in [3] is capable of operating in all power transferring directions in buck/boost mode. However, their use is prescribed because of the size, weight, efficiency, and price of DC-DC converter. Recent applications within the style of power supply use Buck Boost DC-DC converter as a result of the specified output is inverted directly from the input voltage, and the output voltage are often either higher or below the input voltage. A novel buck–boost converter circuit is presented in [4]. The proposed converter in [4] has higher voltage gain in step-up mode in comparison with Cuk converter. The buck-boost power converters are wide employed in applications like automotive and marine. A buck -boost DC-DC converter with robust control strategy used in battery electric vehicles must provide a regulated DC output voltage when varying load, or when the input voltage varies and if the battery state of charge varies. Generally, the linear conventional control solutions applied to power electronic system, especially for buck boost DC-DC converter, failed to accomplish robustness under nonlinearity, parameter variation, load disturbance, and input voltage variation as a result, there's a lot of interest in developing a lot of nonlinear and advanced nonconventional sturdy management structures to improve the performance of the buck -boost device. From the survey, A PI controller is designed and analyzed for a buck-boost converter and Closed loop provides high stable with high efficiency in [5]. To reduce the harmonics in the boost converter circuit using PI control algorithm was explained in [6]. A robustness of PID controller tuning methods to step changes in the set point and disturbance rejection in power converter control is described in [7]. A simple PID (Proportional, Integral and Derivative) controller has been applied to a conventional Boost converter and tested in MATLAB-Simulink environment achieving improved voltage regulation in [8]. The fast reference tracking capability with small overshoot and robustness to the disturbances of the SMC controller is verified with the experimental result in [9]. The photovoltaic powered buck-boost DC/DC converter with Sliding Mode Controller has been presented in [10]. A second-order sliding-mode (SOSM) control method is developed for the regulation problem of a dc–dc buck converter in [11]. The design, control and implementation of a non-isolated low voltage DC/DC converter with a high voltage ratio coupled to fuel cell stack and the control of the converters is ensured by a dual loop control that contains PI controller and a fast current loop using a non-linear sliding controller is described in [12]. The buck–boost converter is controlled using different algorithms like voltage mode control, current mode control, V2 control, enhanced V2 control, Sliding Mode Control (SMC), and Proportional Integral (PI) control. In all these algorithms the steady state error is more[13]. The more no of converters and controllers are reported in the Literature can be effectively used for Electric vehicle and various applications. The drawback of the controllers is more rise time, peak overshoot, settling time and steady state error. The proposed Proportional Integral sliding mode Control (PISMC) produces improved dynamic response of the converter. The PISMC (Proportional Integral Sliding Mode controller) could be a management approach, which complies with the nonlinear nature of switch-mode power supplies. This control technique offers several advantages compared to traditional control methods: stability, even for large line a load variation, robustness, and good dynamic response. This paper has been organized as follows: Section 2 describes the DC /DC converters model. Section 3 describes the Control Strategy for Buck-Boost DC/DC Converters**.** Section 4 presents Results and Discussions. Finally, a conclusion of the proposed PISMC controller is presented in Section 5.

2. DC/DC Converter Model

2.1 DC/DC Converters for Electric Vehicles

The different configurations of EV power supply show that at least one DC/DC converter is necessary to interface the Battery or the Super capacitors module to the DC-link. A DC to DC converter is a category of power converters which converts a source of direct current (DC) from one voltage level to another, by storing the input energy temporarily and then releasing that energy to the output at a different voltage. The storage may be in either magnetic field storage component (inductors, transformers) or electric field storage component (capacitors). DC/DC converters can be designed to transfer power in only one direction, from the input to the output. However, almost all DC/DC converter topologies can be made bi-directional. A bi-directional converter can move power in either direction, which is useful in applications requiring regenerative braking. The amount of power flow between the input and the output can be controlled by adjusting the duty cycle (ratio of on/off time of the switch). Usually, this is done to control the output voltage, the input current, the output current, or to maintain a constant power. Transformer based converters may provide isolation between the input and the output. The main drawbacks of switching converters include complexity, electronic noise and high cost for some topologies. Many different types of DC/DC power converters are proposed in literature. The most common DC/DC converters can be grouped as follows: Non-isolated converters, isolated converters. There are five main types of converter in this non-isolated group, usually called the buck, boost, buck-boost, Cuk and charge-pump converters. The buck converter is used for voltage step-down, while the boost converter is used for voltage step-up. The buck-boost and Cuk converters can be used for either stepdown or step-up. The charge-pump converter is used for either voltage step-up or voltage inversion, but only in relatively low power applications.

2.2 Buck-Boost DC/DC Converters for Electric Vehicles

The main objective of a buck-boost converter is to receive an input DC voltage and output a different level of DC voltage, either lowering or boosting the voltage as required by the application. The design of a buck-boost converter is similar to a buck converter and boost converter. The buck-boost converter circuit as shown in Figure.1

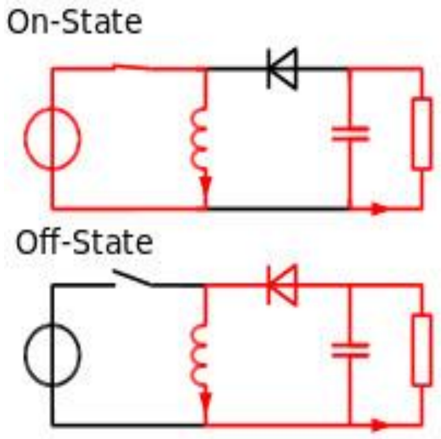

Figure 1. Buck-Boost converter circuit

The working operation of the DC to DC converter is the inductor in the input resistance has the unexpected variation in the input current. If the switch is ON, then the inductor feed the energy from the input and it stores the energy. If the switch is closed it discharges the energy. There are two different types of working principles in the buck boost converter.

- Buck converter.
- Boost converter.

A Buck Boost converter is a switch mode DC to DC converter in which the output voltage can be transformed to a level less than or greater than the input voltage. The magnitude of output voltage depends on the duty cycle of the switch. It is also called as step up/step down converter. By law of conservation of energy, the input power has to be equal to output power (assuming no losses in the circuit), Input power (Pin) = output power (Pout).

In step up mode Vin < Vout in a Buck Boost converter, it follows then that the output current will be less than the input current therefore for a Buck Boost converter in step up mode. In step down mode Vin > Vout in a Buck Boost converter, it follows then that the output current will be greater than the input current.

When switch in ON for a time t_{on},

The current through the inductor is given as

$$I_L = \left(\frac{1}{L}\right) * \int V * dt$$

Since the input voltage is constant

$$I_{L,on} = \left(\frac{1}{L}\right) * \int V_{in} * dt + I'_{L,on}$$

Assume the switch is open for t_{on} seconds which is given by $D*T_s$ where D is duty cycle and T_s is switching time period. The current through the inductor at the end of switch on state is given as

$$I_{L,on} = \left(\frac{1}{L}\right) * V_{in} * D * T_S + I'_{L,on} \quad (1)$$

$$\Delta I_{L,on} = \left(\frac{1}{L}\right) * V_{in} * D * T_S$$

When switch is off

The inductor now discharges through the diode and RC combination. Assume that prior to the closing of switch the inductor current is $I''_{L,off}$. The current through the inductor is given as

$$I'''_{L,off} = -\left(\frac{1}{L}\right) * \int V_{out} * dt + I''_{L,off}$$

Assume the switch is open for t_{off} seconds which is given by (1-D) *T_s where D is duty cycle and T_s is switching time period. The current through the inductor at the end of switch off state is given as

$$I'''_{L,off} = -\left(\frac{1}{L}\right) * V_{out} * (1-D) * T_S + I''_{L,off} \quad (2)$$

In steady state condition as the current through the inductor does not change abruptly, the current at the end of switch on state and the current at the end of switch off state should be equal.

Hence

$$I'''_{L,off} = I_{L,on} \;\; , on\ also\ I'''_{L,off} = I''_{L,off}$$

Using the equations 1 and 2 we get

$$\left(\frac{1}{L}\right) * V_{in} * D * T_S = \left(\frac{1}{L}\right) * V_{out} * (1-D) * T_S$$

$$V_{in} * D = V_{out} * (1-D)$$

$$\frac{V_{out}}{V_{in}} = \frac{D}{(1-D)}$$

Since D < 1, V_{out} can be greater than or less than V_{in}. For D>0.5 the Buck boost converter acts as boost converter with V_{out} >V_{in}. For D<0.5 the Buck boost converter acts as buck converter with V_{out} >V_{in}.

3.Control Strategy for Buck-Boost DC/DC Converters

3.1 PI control of Buck–Boost Converter:

A PI controller fuses the properties of P and I controllers and the algorithm provides a balance of complexity and capability to be widely used in process control applications. Eq. (3) describes P controller.

$$u(t) = k_p * e(t) \quad (3)$$

Where K_p is the proportional gain, e(t) is the error and u(t) is the perturbation in output signal of PI controller from the base value corresponding to normal operating conditions. It with no integration property always exhibit static error in the presence of disturbances and changes in set-point and shows a relatively maximum overshoot and long settling time. To remove steady-state offset in controlled variable of a process, an extra intelligence is added to the P controller and this intelligence is the integral action. The controller is a PI controller whose mathematical notation is depicted in Eq. (4)

$$u(t) = k_p * e(t) + k_I \int e(t)dt \quad (4)$$

3.2 PID control of Buck–Boost Converter:

A Proportional–Integral–Derivative controller (PID controller)is a control loop feedback mechanism widely used in industrial control systems and a variety of other applications. A PID controller continuously calculates an error value as the difference between a desired set point (SP) and a measured process variable (PV) and applies a correction based on proportional, integral, and derivative terms . The overall control function can be expressed mathematically in Eq. (5),

$$u(t) = k_p * e(t) + k_I \int e(t)dt + k_d \frac{de(t)}{dt} \quad (5)$$

3.3 Sliding mode control of Buck–Boost Converter:

In SMC, a controller is forcing the system states to reach, and remain on, a predefined switching surface within the state space. This motion to a predefined switching surface is known as sliding motion. The advantages of this type of motion or control are reduction in system order and control is insensitive to parameter variations. Due to these advantages, the buck–boost converter is controlled using SMC. The buck–boost converter output voltage error and rate of change of voltage are both selected as state variables. The SMC is simulated using two control loops and they are inner current loop and the outer voltage loop. These two loops are combined in series to achieve SMC for buck–boost converter. The equations used in SMC are explained as follows. Let us consider voltage error as X, rate of change of voltage error as Y and integral of voltage error as Z. For the buck–boost converter the sliding mode control adopts a switching function such as

$u = 1 \; when \; s > 0$

$u = 0 \; when \; s < 0$

$$u = \frac{1}{2(1+sgn\, s)} \quad (6)$$

Where s is the instantaneous state variable trajectory and is described as

$$s = \alpha 1X1 + \alpha 2X1 + \alpha 3X1 = J^T X \quad (7)$$

Where

$J^T = [\propto 1 \propto 2 \propto 3]$

Where $\propto 1 \propto 2 \; and \; \propto 3$ represents control parameters and these known as sliding coefficients. A sliding surface is obtained by substituting S=0.

$$0 < d = \frac{v_c}{v_{ramp}} < 1$$

This gives the following relationship for the control signal v_c and v_{ramp} where,

$$v_c = -k_{p1} i_c + k_{p2}(v_{ref} - \beta v_{0)}) + \beta(v_0 - v_i) \quad (8)$$

Where

$v_{ramp} = \beta(v_0 - v_i)$

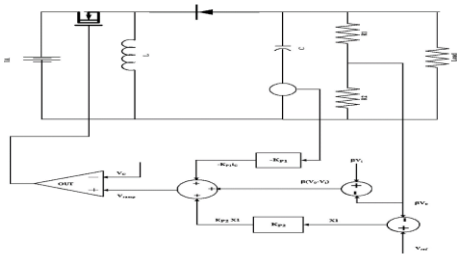

Figure 2. SMC for Buck Boost converter model

SMC for buck boost converter is modeled as shown in Figure.2. The capacitor current i_c is measured and multiplied with a constant Kp_1. The output voltage is measured from a voltage divider circuit to get βV_o, where $\beta=\frac{R2}{R1+R2}$.

The voltage βV_o is compared with reference voltage V_{ref}, the output of which is multiplied with a constant Kp_2. The input voltage is also multiplied with β and compared with βV_o. The outputs $Kp_1 i_c$, $\beta (V_o\text{-}V_i)$ and K_{p2x1} are added to get a signal V_c. Using comparator, output signal V_c and ramp signal V_{ramp} are compared to get PWM signal to trigger the MOSFET switch in a buck–boost converter. The model developed for sliding mode control algorithm is simulated using Simulink. The ADD blocks and Gain blocks from Simulink library are used for comparators and multipliers respectively.

3.4 Proportional Integral Sliding mode control of Buck–Boost Converter:

In this control algorithm the advantages of PI control and sliding mode control methods are combined. For developing simulation diagram the equations and models derived in PI control and sliding mode control of buck boost converters are used. The output of the PI controller is applied as input to the sliding mode control to obtain a PWM wave. The advantage of the PISMC is that steady state error and maximum overshoot are minimized.

4.Results and Discussions

In this paper, MATLAB/SIMULINK is applied to verify the feasibility of the proposed Buck Boost DC to DC converter and controllers. The specifications and circuit parameters are used in the simulation circuit are listed in Table.1

Table .1 Specifications and parameters settings of the DC/DC converters

Type of converter	Input voltage	Inductor	capacitor	Output voltage
Boost	100V	1 mH	30uF	200V
Buck	100V	1 mH	30uF	37.2V
Buck Boost (Boost mode)	100V	1 mH	30uF	233.9V
Buck Boost (Buck mode)	100V	1 mH	30uF	44.24V
Cuk	100V	1 mH	30uF	232V

Figure 3-7 shows the simulated circuit and results of different types of DC –DC converters. Figure 3. (a) shows the circuit diagram of Boost converter. The design of the boost converter is similar to a buck boost converter. If the switch is on, then the inductor feed the energy from the input and it stores the energy. If the switch is closed it discharges the energy. Figure 3. (b) shows the output response of the Boost Converter. The boost converter output voltage can be transformed to a level of greater than the input voltage. The magnitude of output voltage depends on the duty cycle of the switch. It is also called as step up converter.

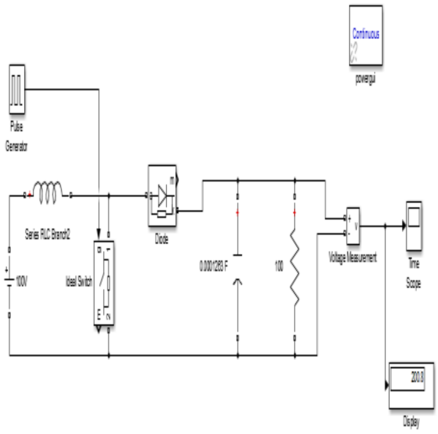

Figure 3. (a)Boost converter

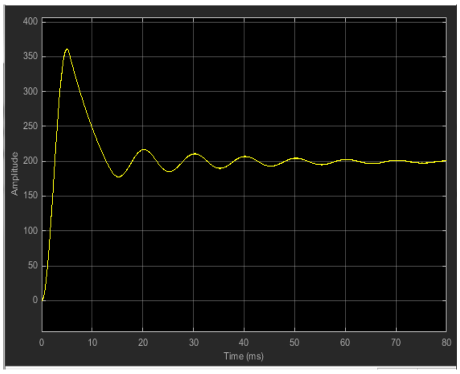

Figure 3. (b)Simulated response of Boost converter

Figure 4. (a) shows the circuit diagram of Buck converter. The design of the buck converter is similar to a buck boost converter. switch turns on and lets current flow to the output capacitor, charging it up. Since the voltage across the capacitor cannot rise instantly, and since the inductor limits the charging current, the voltage across the capacitor during the switching cycle is not the full voltage of the power source. The switch now turns off, Since the current in an inductor cannot change suddenly, the inductor creates a voltage across it. This voltage is allowed to charge the capacitor. Figure 4. (b) shows the output response of the Buck Converter. The buck converter output voltage can be transformed to a level of less than the input voltage. The magnitude of output voltage depends on the duty cycle of the switch. It is also called as step down converter.

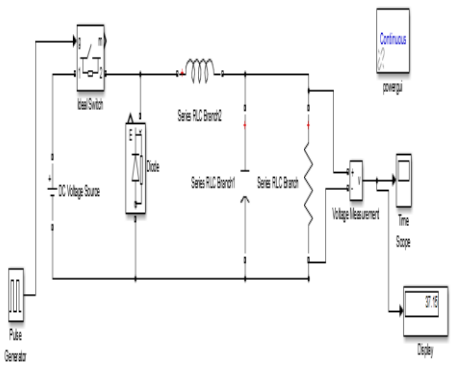

Figure 4. (a) Buck converter

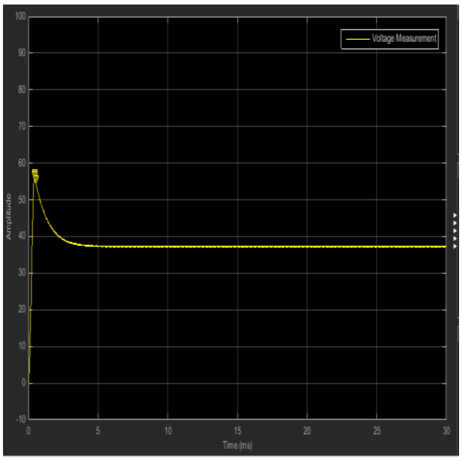

Figure 4. (b) Simulated response of Buck converter

Figure 5. (a)& (b) shows the circuit diagram and response of the Buck Boost converter in boost mode. The design and operation of the buck boost converter was mentioned already in section 2.2. A Buck Boost converter is a switch mode DC to DC converter in which the output voltage can be transformed to a level less than or greater than the input voltage. The magnitude of output voltage depends on the duty cycle of the switch. It is also called as step up/step down converter. Figure 6. (a)& (b) shows the circuit diagram and response of the Buck boost converter in buck mode.

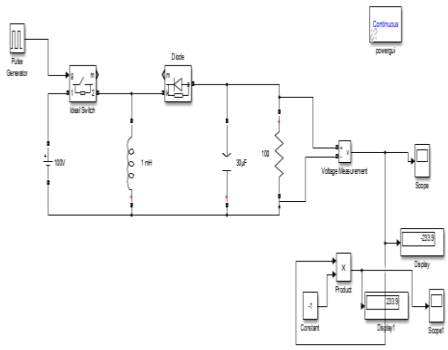

Figure 5. (a) Buck Boost converter circuit in Boost Mode

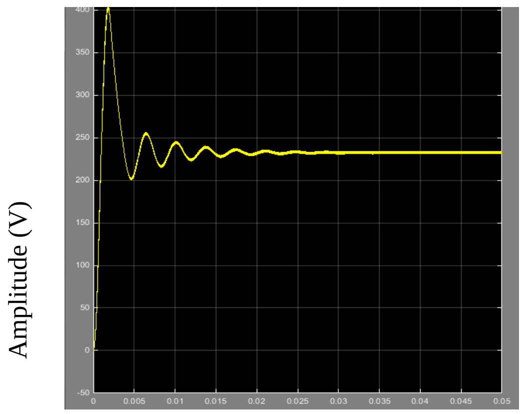

Figure 5. (b) Simulated response of Buck Boost converter in Boost Mode

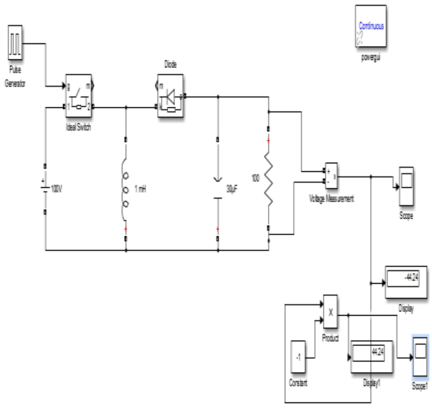

Figure 6. (a) Buck Boost converter circuit in Buck Mode

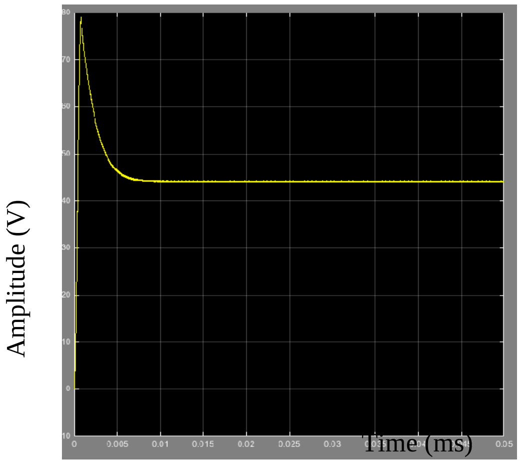

Figure 6. (b) Simulated response of Buck Boost converter in Buck Mode

Figure .7 (a) shows the circuit diagram of Cuk converter. when the switch S is turned on, the input source charges the inductor as a result, the current through the inductor L rises. The current through Vs, L forms a current loop. Meanwhile, since $V_C > V_O$, the capacitor C discharge and the diode D has the inverse voltage which is regarded as open circuit. The energy stored in the capacitor was transferred to capacitor and load and inductor. In the other words, the voltage of capacitor C_o increases and the current of inductor rises. Figure .7 (b) shows the output response of the Cuk Converter.

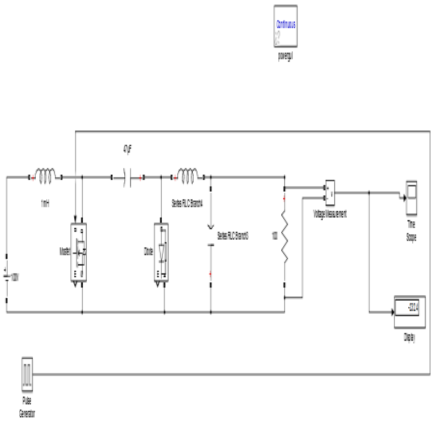

Figure 7. (a) Cuk converter

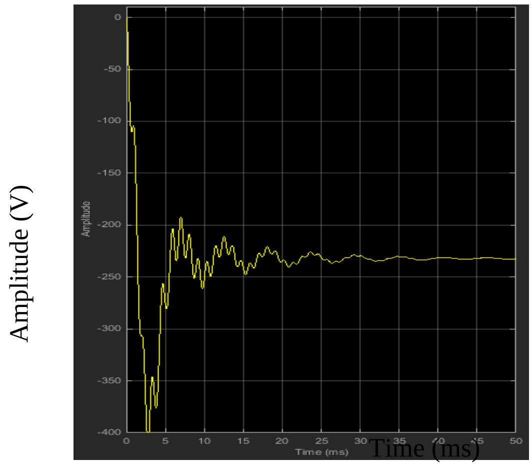

Figure 7. (b) Simulated response of Cuk converter

From the simulation results Buck-Boost converter gives higher output voltage compared all other types of converters so control solution applied to Buck- Boost converter circuit.

Figure.8 (a)& (b) shows the circuit diagram and response of PI control with Buck–Boost converter is simulated using Simulink. output voltage of the buck boost converter is compared with a reference source of 240 V and the error signal generated is applied to PI controller. Controller obtain PWM wave so as to trigger the MOSFET switch. The PI controller with buck boost converter has the output voltage of 222.5V. so the steady state error is 17.5V. The Rise time, Maximum over shoot, settling time of PI controller is 0.006sec,13.5% and 0.014 sec.

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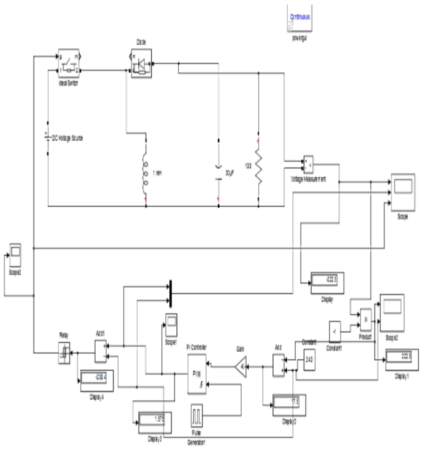

Figure 8. (a) Buck Boost converter with PI Controller

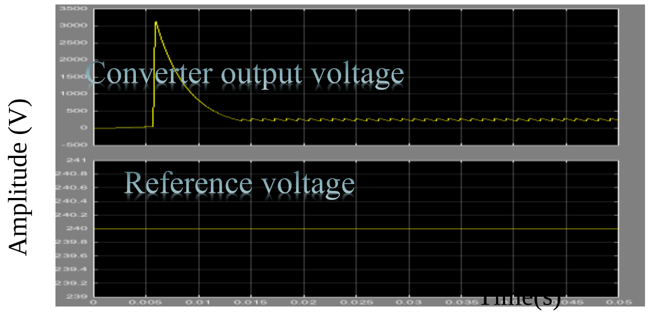

Figure 8. (b)Simulated response of the PI Controller

Figure 9. (a)& (b) shows the circuit diagram and response of PID control with Buck–Boost converter is simulated using Simulink. output voltage of the buck boost converter is compared with a reference source of 240 V and the error signal generated is applied to PID controller. Controller obtain PWM wave so as to trigger the MOSFET switch. The PID controller with buck boost converter has the output voltage of 227.6V. so the steady state error is 12.4V. The Rise time, Maximum over shoot, settling time of PID controller is 0.005sec,10.5% and 0.013 sec.

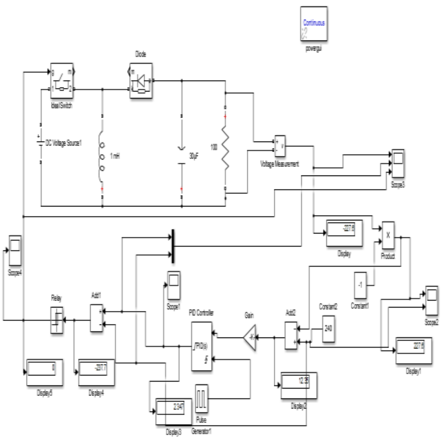

Figure 9. (a) Buck Boost converter with PID Controller

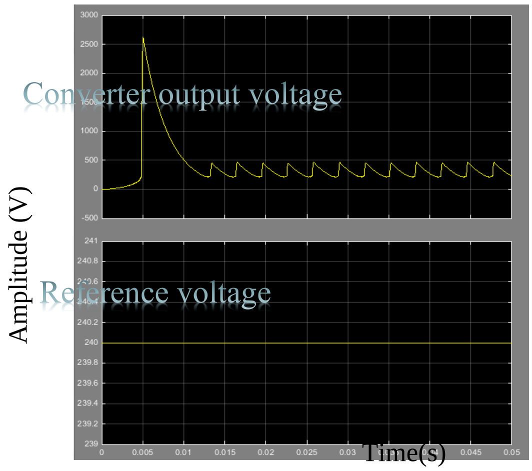

Figure 9. (b)Simulated response of the PID Controller

Figure 10. (a)& (b) shows the circuit diagram and response of SMC with Buck–Boost converter is simulated using Simulink. output voltage of the buck boost converter is compared with a reference source of 240 V and the error signal generated is applied to SMC controller. Controller obtain PWM wave so as to trigger the MOSFET switch. The SMC controller with buck boost converter has the output voltage of 232.6V. so the steady state error is 7.4V. The Rise time, Maximum over shoot, settling time of SMC controller is 0.001sec,0.38 % and 0.0025 sec.

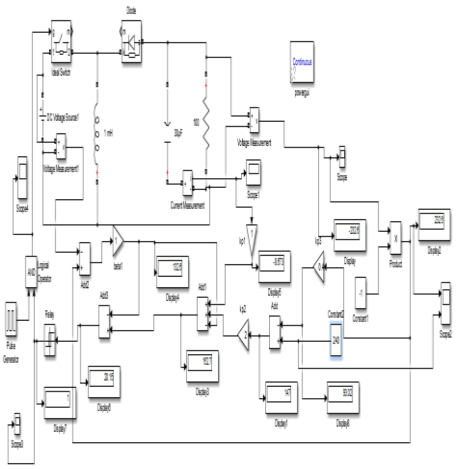

Figure 10. (a) Buck Boost converter with SMC Controller

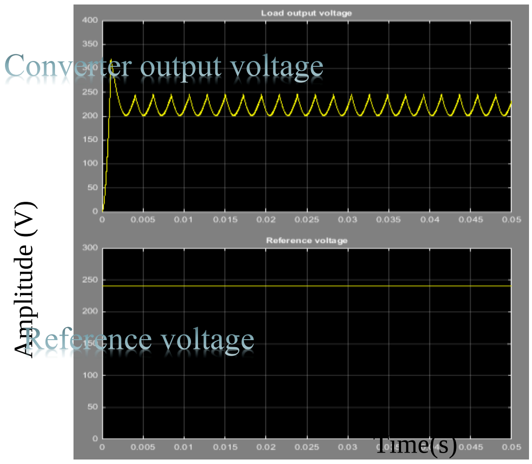

Figure 10. (b)Simulated response of the SMC Controller

Figure 11. (a)& (b) shows the circuit diagram and response of PISMC with Buck–Boost converter is simulated using Simulink. output voltage of the buck boost converter is compared with a reference source of 240 V and the error signal generated is applied to PISMC controller. Controller obtain PWM wave so as to trigger the MOSFET switch. The PISMC controller with buck boost converter has the output voltage of 241.9V. so the steady state error is 1.9V. The Rise time, Maximum over shoot, settling time of PISMC controller is 0.001sec,0.38 % and 0.0025 sec. PISMC controller has less steady state error value as compared to SMC.

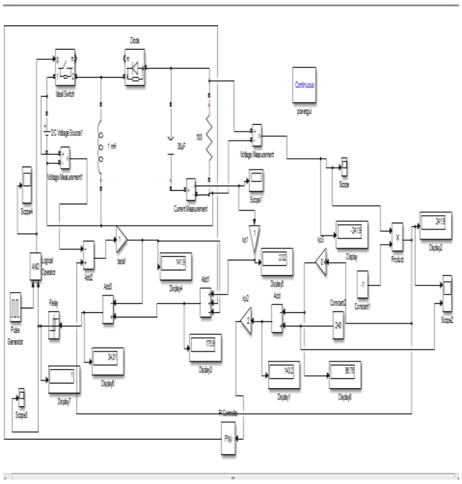

Figure 11. (a) Buck Boost converter with PISMC Controller

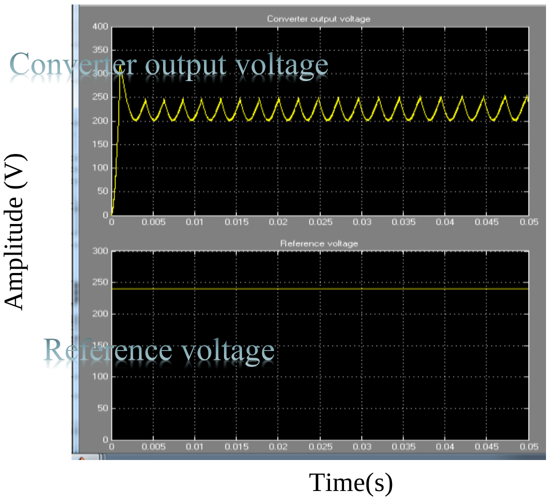

Figure 11. (b)Simulated response of the PISMC Controller

In this proposed work a robust Proportional Integral Sliding Mode controller(PISMC) strategy is applied to the buck -boost DC-DC converter and the results are compared with classical PI, PID and SMC controllers. The comparison of control algorithms with respect to maximum overshoot, rise time, settling time and steady state error. The comparison of control algorithms is tabulated in Table 2.

Table .2 Performance and Analysis of Buck Boost converter with PI, PID, SMC and PISMC

Type of Controller	Rise Time in Sec	Maximum overshoot (%)	Settling Time in Sec	Steady State error
PI	0.006 sec	13.06	0.014 sec	17.5 V
PID	0.005 sec	10.5	0.013 sec	12.4 V
SMC	0.001 sec	0.38	0.0025 sec	7.4 V
PISMC	0.001 sec	0.38	0.0025 sec	1.9V

Performance and analysis of Buck Boost converter with PI, PID, SMC and PISMC are compared in terms of Rise Time, Maximum overshoot, Settling Time and Steady State error as shown in figure.12.

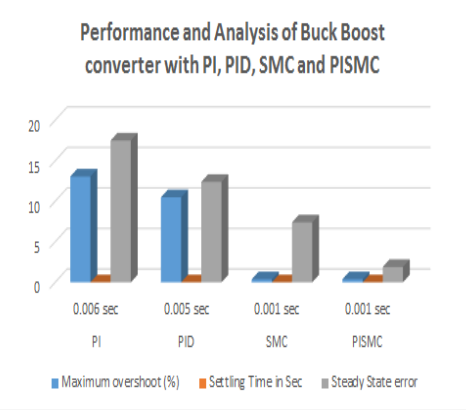

Figure 12. Performance and Analysis of Buck Boost converter with PI, PID, SMC and PISMC

5.Conclusion

The control algorithms such as PI, PID, SMC control and PISMC controllers are applied to the buck boost converter. From the results PISMC has less steady state error, less maximum overshoot and Quick settling time. The proposed study of PISMC with buck boost converter provides improved results in terms of regulation and also it is best suitable for Electric vehicle application.

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