Design and Analysis of Sliding Mode Control for Battery Charging Applications

P Sivaraman1*, T Logeswaran2, J S Sakthi Surya Raj3 and S Boopathimanikandan4

1Associate Professor, Bannari Amman Institute of Technology, Department of Electrical and Electronics Engineering, Erode, Tamilnadu, India. 
2Assistant professor (Sr.G), Kongu Engineering College, Department of Electrical and Electronics Engineering, Erode, Tamilnadu, India. 
3Research Scholar, Bannari Amman Institute of Technology, Department of Electrical and Electronics Engineering, Erode, Tamilnadu, India. 
4PG Scholar, Bannari Amman Institute of Technology, Department of Electrical and Electronics Engineering, Erode, Tamilnadu, India.
sivaramanpsr@bitsathy.ac.in, logeskongu@gmail.com, sakthisuriyaraj@bitsathy.ac.in, boopathimanikandan.pe18@bitsathy.ac.in

Abstract. In Electric Vehicle (EV) charging stations connected loads are intermittent due to continuous variation of charging level battery. In this situation, the linear controller like P, PI, and PID does not offer a quick and good transient response to the EV charging converter. In some cases, EV charging stations push to instability region for abrupt change in loads. Therefore, this research work focused on investigation of non-linear controllers for EV battery charging station. This paper investigates the performance of Hysteresis Controller (HC) and Sliding Mode Controller (SMC) for EV charging station under dynamic load conditions. The hysteresis controller and sliding mode controller are developed for buck converter fed EV charging stations and its performance is analyzed using pole zero plot and bode plot methods. From the investigation it is found that SMC offer optimum gain margin and phase margin under dynamic load condition for EV charging station.

Keywords: Hysteresis Controller, Sliding Mode Controller, Electric Vehicle, Charging Station and Dynamic Controller.

1. Introduction

Among the various categories of power conversion operations, DC-DC converters are well known for maximum power point tracking [1], DC bus integration, and battery charging application [2]. Due to the transient switching action DC-DC converters are nonlinear in nature [3,4]. Most of the design, controllers are using Linear controller like PID based controllers. In some cases, due to nonlinear change in loads, the transient response of linear controller has peak overshoot, oscillations in the output before settles to final value [5]. There are two categories of control in DC-DC Converters namely, Voltage Mode (VM) and Current Mode (CM) control [6]. The voltage mode control detects the output voltage and compared with a reference voltage to generate error voltage signal. In Current Mode control, both the output voltage and inductor current are sensed. Due to the non-linear and time varying nature of DC-DC converters, the designer controls the output voltage by directly controlling the inductor current (CM) [7]. A fixed-frequency pulse width modulation based Sliding-Mode Controllers (SMC) developed for dc–dc converters that operates in the continuous conduction mode is proposed in [8]. However, the PWM based SMC has transient parameters with high voltage ripples. This type of nonlinear controllers is used to support the converters that needs high dynamic response for a wide range of operating conditions [9]. To
improve the performance of the converter in terms of its transient response an nonlinear hysteresis controller for DC-DC converter is proposed in [13]. However, the attenuation of disturbances in the power supply and sensitivity to unknown loads are need to be analysed [10]. To reduce the overshoot in output voltage a combination of linear and non-linear parts consisting of PID and hysteresis controller is proposed in [11]. Though, the settling time is drastically reduced, there is a negligible amount of overshoot in output voltage during load variation [12]. Hence for Battery Charging Applications, linear controller generates peak overshoot voltages that results increase in charging current will leads to damage the battery. Some nonlinear behaviour of Battery, will results in system instability. The system will operate in unstable condition, which causes unbounded output generated by DC-DC converter [13]. Thus a new controller designed that includes both hysteresis controller and Sliding mode controller to improve the charging of battery.

In this paper the methodology of hysteresis controller and SMC and the design is studied in section 2. The section 3 and 4 gives the control algorithm of PI controller and proposed SMC. In section 5 the results obtained by implementing PI, SMC and hysteresis controller on buck converter for battery charging is analyzed based on the current and voltage wave form. Finally, the comparison is made based on the results obtained.

2. Methodology

A new control design has proposed to improve the design includes both hysteresis controller and SMC. SMC changes the dynamics of the system by applying a discontinuous control signal. This discontinuous signal forces the system to slide along a sector of the system’s normal function. The proposed method used Hysteresis based SMC to reduce the transient parameters and improves the stability of the system during nonlinear conditions. Buck Converters are used for low power battery charging applications [14]. Hence, buck converter is used for the proposed methodology. The designed proposed controlled is shown in figure 1.

![Figure 1. Proposed controller.](image1)

2.1. Hysteresis Controller

Hysteresis controller are used to control the converter that has faster load transients [15]. It is also called as ripple control method since it controls by detecting the ripples in the output voltage. Further, the output voltage is monitored directly only with the help of a comparator without an error amplifier. The comparator directly turns on/off the switch by detecting the level of output voltage that exceeds or falls below the threshold value at an instant. Fixed on-time and fixed off-time control scheme are used for detecting the voltage that falls below and above the threshold level respectively [16]. The hysteresis controller to fed buck converter is presented in figure 2.

![Figure 2. Hysteresis controller block diagram.](image2)
Generator [18]. By applying threshold limits Variable Switching Frequencies (VSF) can be achieved with less ripples on output voltage.

2.2. Sliding Mode Controller

Sliding Mode Controller (SMC) is a nonlinear controller it overcomes the slow response and transient oscillation caused by dynamic change in load. The output of SMC is a discontinuous signal that drives the converter to slide in the cross section of the operating region of converter [19]. The trails always slide towards an adjacent section designed with multiple control structures so that the entire trail will not occur with single control structure. Hence, the trail slides along the borders of the control system [20]. This motion of the system is called sliding mode and the locus consisting of the borders is called the sliding surface. This methodology is used to force the system to reach towards a normal operation or its desired final value by sliding on the surface. This nonlinear dynamic nature of the controller and its robustness against the disturbance makes it an ideal choice for battery charging application.

2.2.1. Design of Sliding Mode Control Equations. To design a SM controller, the first step is to develop a state space model of the converter with desired control variables [21]. The controller designed for the study is a PID sliding mode voltage controller. This controller overcomes the steady state DC error prevailed in the conventional controller by including additional voltage error value in the calculation. The principle of operation of sliding mode is given in figure 3.

\[
U = \begin{cases} 
1 & \text{when } L > 0 \\
0 & \text{when } L < 0 
\end{cases}
\]  

(1)

Where L is the immediate state variable’s trail, and is described as

\[L = \alpha_1 x_1 + \alpha_2 x_2 + \alpha_3 x_3\]

Where \(\alpha_1, \alpha_2, \alpha_3\) are sliding coefficients and \(x_1, x_2, x_3\) are voltage error respectively. During SM operation the dynamic response of the converter and the equation relating to the sliding co-efficient are obtained by solving \(L=0\). This effects in second order linear equations and produces over-damped, critically damped and under-damped responses. The SMC block diagram is illustrated in figure 4.

\[
\frac{\alpha_1}{\alpha_2} = \frac{10 \alpha_3}{T_s \alpha_2} = \frac{2.5}{\epsilon^2 T_s^2}
\]

(2)

where \(T_s\) and \(\epsilon\) are settling time and damping co-efficient respectively.

The control voltage (\(V_c\)) equations are essential for the application of buck or Hysteresis-based SMVC converters is given by

\[V_C = -K_{p1} i_c + K_{p2} (V_{ref} - \beta V_o) + \beta V_o\]

(3)

Where \(K_{p1} = \frac{1}{R_L C}\) and \(K_{p2} = \frac{\beta}{C} \frac{V_{ref}}{V_{out}}\). \(K_{p1}\) and \(K_{p2}\) are the constant gain factors for the feedback signals \(i_c\) and \(V_{ref} - \beta V_o\) respectively.
3. Control algorithm using PI controller

DC Link Controller is to design to maintain output voltage. Controller measures the output voltage and compares it with the reference voltage given and the error signal generated is fed to PI controller [22]. Low pass filter (PI) is used to regulate error to generate pattern voltage to generate pulses. The DC link controller block diagram is represented in Figure 5.

The plant transfer function is found by control to input voltage
\[ T(s) = \frac{D_o(s)}{V_i(s)} \]  \hspace{1cm} (4)
\[ T(s) = \frac{a(Cs + 1)}{s^2 + bS + c} \]  \hspace{1cm} (5)

Where
\[ a = \frac{V_{in}}{L_C} \hspace{1cm} b = \frac{1}{RC} + \frac{1}{L} \hspace{1cm} c = \frac{1}{LC} \]  \hspace{1cm} (6)

The open loop transfer function with PI Compensator is \( H(s) = T(s) \ast G_{PI} \). By proper tuning PI Controller, it can able to operate the controller in stable region. By choosing \( K_p=0.5, \) \( K_i=0.01 \) controller enter into stable operating region. The Bode and Pole Zero plot of DC converter with compensator is shown in Figure 6.
From the plot, the positive values of Gain margin and Phase margin shows that Controller is in stable region. From the pole zero plot, All the poles are lying in LHS of S-plane and two complex poles are lying in the imaginary axis indicate output voltage have minimum ripples.

4. Control algorithm of proposed SMC

DC Link Controller is to design to maintain output voltage. Controller senses the output voltage is fed to SMC. SMC will regulate the output within the sliding surface which chosen and make the system to operate in desired level. Hysteresis controller is used to regulate output voltage within threshold limit and generate pulses according to output voltage ripples. The DC link controller with SMC is presented in figure 7 and the corresponding bode plot and pole zero plot of open loop DC link controller is shown in figure 8.

![Figure 7. Open loop DC link controller fed SMC.](image)

All the poles are lying in left of S plane. This shows the controller will be always operates in stable region. From the bode plot, the gain margin and phase margin is 7.09dB and 36.78 degree respectively which is optimised value.

5. Result and discussion

The Buck converter is designed for 7V(output) with 12V (Input Voltage). The Inductance and Capacitance values of Buck converter is designed by assuming current ripple of 1% and Voltage ripple of 1% and operated in Continuous Conduction mode. The battery chose for this simulation is Lithium-ion battery [23,24]. The voltage and capacity of the battery is 6V and 5Ah respectively. Efficiency of Buck converter in this design is around 97.35%.

5.1. Buck Converter with PI Controller

In this method Voltage mode control method is used. It involves sensing of output voltage, which is compared with the reference voltage to generate error voltage signal. The error signal is fed to PI controller and its output is compared with a saw tooth waveform, which generates a Pulse Width Modulated (PWM) signal that is fed back to the converter as gate pulse. The output waveform of linear controller fed Buck converter is shown in figure 9.
5.2. Buck Converter with Hysteresis Controller

In this method Voltage mode control method is used. The error signal is generated by sensing and comparing the voltage obtained with the reference voltage. The obtained error signal is fed to the Hysteresis Controller. The comparator generates the pulse to turn on/off the switch when the output voltage level has exceeded or fallen below a set threshold level. The hysteresis level set for this design is 0.01. The output voltage is oscillating between 6.99V-7.01V. The output waveform of hysteresis controller fed buck converter is presented in figure 10. The peak overshoot is completely eliminated and settling time obtained is 0.05sec.
Figure 11 Displays the output voltage ripple band of hysteresis controller. It shows the output voltage is oscillating between 6.99V to 7.01 V with ripple of 0.02V.

5.3. Buck Converter with proposed Non-Linear Controller

In this method both Voltage control mode method current control mode is used. The nonlinear converter used in this design is Hysteresis based SMC. The simulation model figure of buck converter with SMC is given in figure 12.

Figure 12. Buck converter fed SMC controller.

Figure 13. Output Voltage and Current waveform of SMC controller fed Buck converter.

This proposed controller merges the hysteresis band for PWM generation and regulating error using Sliding mode design. The output waveform of non-linear controller fed buck converter is presented in figure 13. The peak overshoot and oscillations is eliminated shown in the output voltage waveform. An Comparative Analysis of PI, Hysteresis and SMC is made and tabulated in table 1.

Table 1. Comparison of various controller parameters

| Parameters     | PI Controller | Hysteresis Controller | Sliding Mode Controller |
|----------------|---------------|-----------------------|-------------------------|
| Output Voltage | 7.1 V         | 7.007 V               | 6.88 V                  |
| Voltage Ripples| 0.2 V         | 0.02 V                | 0.004 V                 |
| Peak Overshoot | 0.03%         | 0                     | 0                       |
| Settling Time  | 0.1 sec       | 0.05 sec              | 0.04 Sec                |
The output voltage from SMC is slightly less than the reference voltage. But voltage ripples are very low compared to PI controller and Hysteresis Controller. PI Controller has peak to peak ripple voltage of 0.2 V with peak overshoot of 0.03% with settling time of 0.1 seconds. Compared to all converter, SMC has low settling time around 0.04 sec with zero peak overshoot, i.e. Peak overshoot is completely eliminated in SMC and hysteresis controller. Hysteresis controller operating at 2.5kHz for the threshold voltage of 0.01 V. The PI Controller and SMC are operating at 50kHz. So switching losses will be more for SMC and PI controller. Hysteresis controller will not able to perform correct control action for nonlinear change in load. For the case of nonlinear control action, SMC will behave smooth operations.

6. Conclusion
Buck Converter for battery charging application was designed. The performance of converter is analyzed with three different control techniques like PI, hysteresis controller and SMC. Hysteresis controller monitors the output voltage and maintained within threshold limits and also eliminates peak overshoot and oscillations generated while transient state. The performance of Hysteresis based SMC is efficient that maintains the converter to be operated in designed sliding surface. Current mode control method is used for design SMC which regulates the output voltage by regulating inductor current. The results confirm that the proposed controller has less ripple, fast settling time and zero peak overshoot.

References
[1] Sivaraman P 2015 A New Method of Maximum Power Point Tracking for Maximizing the Power Generation from a SPV Plant Journal of scientific and Industrial Research Vol 74 No 3 pp 411 – 415.
[2] Prem P Sathik J Sivaraman P Matheswaran A Abdel Aleem S.H.E 2019 A new asymmetric dual source multilevel inverter topology with reduced power switches Journal of Chinese Institute Engineering Vol 42 No 5 pp 460–472.
[3] Kim K Lee H Hong S and Cho G A 2019 Noninverting Buck–Boost Converter with State-Based Current Control for Li-ion Battery Management in Mobile Applications IEEE Transactions on Industrial Electronics Vol 66 No 12 pp 9623-9627.
[4] Ponnumasy V Velliangiri S Ali J.S.M 2020 A Hybrid Switched Capacitor Multi-Level Inverter with High Voltage Gain and Self-Voltage Balancing Ability Electric Power Components System pp 1–14.
[5] Sivaraman P and Prem P 2017 PR Controller Design and Stability Analysis of Single Stage T-Source Inverter Based Solar PV System in Journal of Chinese Institute of Engineers Vol 40 No 3 pp 235 - 245.
[6] Chuang Y and Ke Y 2007 A Novel High-Efficiency Battery Charger with a Buck Zero-Voltage-Switching Resonant Converter in IEEE Transactions on Energy Conversion Vol 22 No 4 pp 848-854.
[7] Chuang Y and Ke Y 2008 High efficiency battery charger with a buck zero-current-switching pulse-width-modulated converter IET Power Electronics Vol 1 No 4 pp 433-444.
[8] Siew-Chong Tan Lai Y M and Chi K Tse 2016 A Uniﬁed Approach to the Design of PWM-Based Sliding-Mode Voltage Controllers for Basic DC-DC Converters in Continuous Conduction Mode IEEE Transactions on circuits and systems Vol 8 No 08.
[9] Tan C Lai Y M Cheung M K H and Tse C K 2005 On the practical design of a sliding-mode voltage controlled buck converter IEEE Trans. Power Electronics Vol 20 No 2 pp 425–437.
[10] Escobar G Ortega R Sira-Ramirez H Vilain J and Zein I 1999 An experimental comparison of several nonlinear controllers for power converters IEE Control Systems Magazine Vol 19 No 1 pp 66-82.
[11] van der Broeck C H De Doncker R W Richter S A and Bloh J V 2015 Uniﬁed Control of a Buck Converter for Wide-Load-Range Applications IEEE Transactions on Industry Applications Vol 51 No 5 pp 4061-4071.
[12] Kim T Kim D Shin H Lee S Suh J and Yang B 2019 Low Power Digital PWM Buck Converter With a Clock-Gating Shift-Register International Conference on Electronics Information and Communication (ICEIC) Auckland New Zealand 2019 pp 1-3.
[13] Schild A Lunze J Krupa J and Schwarz W 2009 Design of Generalized Hysteresis Controllers for DC–DC Switching Power Converters IEEE Transactions on Power Electronics Vol 24 No 1 pp 138-146.
[14] Prem P Sivaraman P Sakthi Suriya Raj J S Sathik M J Almakhles D 2020 Fast charging converter and control algorithm for solar PV battery and electrical grid integrated electric vehicle charging station Automatika Vol 61 No 4 pp 614–625.

[15] Zheng Y Chen H and Leung K N 2012 A Fast-Response Pseudo-PWM Buck Converter with PLL-Based Hysteresis Control IEEE Transactions on Very Large Scale Integration (VLSI) Systems Vol 20 No 7 pp 1167-1174.

[16] Chincholkar S H Jiang W and Chan C 2018 A Modified Hysteresis-Modulation-Based Sliding Mode Control for Improved Performance in Hybrid DC–DC Boost Converter IEEE Transactions on Circuits and Systems II: Express Briefs Vol 65 No 11 pp 2048-2061.

[17] Lekić A and Stipanović D M 2016 Hysteresis Switching Control of the Ćuk Converter IEEE Transactions on Circuits and Systems I: Regular Papers Vol 63 No 11 pp 2048-2061.

[18] Deshmukh M 2017 A constant frequency second order sliding mode controller for buck converter 2017 Second International Conference on Electrical Computer and Communication Technologies (ICECCT) Coimbatore 2017 pp 1-5.

[19] Guo S Lin-Shi X Allard B Gao Y and Ruan Y 2010 Digital Sliding-Mode Controller for High-Frequency DC/DC SMPS IEEE Transactions on Power Electronics Vol 25 No 5 pp 1120-1123.

[20] Chuang Y 2010 High-Efficiency ZCS Buck Converter for Rechargeable Batteries in IEEE Transactions on Industrial Electronics Vol 57 No 7 pp 2463-2472.

[21] Sivaraman P 2012 Dynamic modeling and analysis of T-source electronic inverter using state space technique Sci. Res. Essays Vol 7 No 38 pp. 3269–3280.

[22] Tsang K M Chan W L and Wei X L 2008 Robust DC/DC buck converter using conditional integrator compensator in Electronics Letters Vol 44 No 2 pp 152-153 17.

[23] Raviraj V S C and Sen PC Comparative study of proportional-integral sliding mode and fuzzy logic controllers for power converters in IEEE Transactions on Industry Applications Vol 33 No 2 pp 511-524 March-April 1997.

[24] Prem P Sivaraman P Almakhles Dhafer Sanjeevikumar P Leonowicz Zbigniew Matheswaran A and Mohamed Ali Jagabar S 2020 A New Multilevel Inverter Topology with Reduced Power Components for Domestic Solar PV Applications. IEEE Access.