Design of Fuzzy Sliding Mode Controller for DC-DC Converter used in Enhanced Fast Charging of Electric Vehicle

[1]Balakrishna Nallamothu, [2] B.Santhana Krishnan, [3]Ravindra Janga

[1]Research Scholar,

Department of Electrical Engineering, Annamalai University, Annamalai nagar -608002 TamilNadu, India

[2]Associate Professor,

Department of Electrical Engineering, Annamalai University, Annamalai nagar-608002,TamilNadu, India

[3]Assistant Professor,

Department of Electrical & Electronics Engineering, Bapatla Engineering College, Bapatla, Andhra Pradesh, India

Abstract

In the current automotive landscape, the increasing adoption of electric vehicles (EVs) over traditional fossil fuel vehicles has significantly influenced charging time and infrastructure. Enhancements in the control systems for DC-DC off-board fast charging have become a key area of research in EV technology. These improvements not only boost the overall efficiency of fast charging but also reduce charging time, which consequently enhances the market share of EVs compared to fossil fuel vehicles. The control strategy proposed in this model aims to enhance the performance of the DC-DC converter. Although many conventional controllers are available, they often fall short in providing optimal control for high-frequency switching DC-DC converters in off-board chargers. The advanced fuzzy-based controller is designed to manage the dynamic behaviour and nonlinear characteristics of the converter. Initially, a sliding mode controller was developed using a small-signal state space average model. Based on the converter's behaviour, a fuzzy-based sliding mode controller was introduced to achieve superior performance by mitigating the chattering effect. Finally, the simulation results for the proposed controller, applied in a 400V/120A DC-DC off-board fast charger for an electric vehicle, were analysed and evaluated.

Keywords: DC-DC Converter; Electric Vehicles; Fast Charging; Fuzzy Sliding Mode Controller;

1. Introduction

The market share of battery Electric vehicles (EVs) has grown rapidly due to its high reliability and green energy usage. This leads to the requirement of technically advancements in the off board fast charging facilities in the form of charging stations [1-2]. Due to the sudden growth of EVs impact the existing conventional grid setup. As a result all the charging facilities has to rely on the integration of renewable energy sources with the off board chargers. One of the economic integration is PV solar system.

In contrast, the output voltage from PV solar systems is non-linear in nature, which leads to the need for controlling of high switching frequency DC–DC converter effectively to maintain the output voltage linear with change in the source voltage [3]. The control loop design becomes more complex at higher frequencies, requiring precise tuning and often more sophisticated control algorithms to maintain stability and performance[4-5]. The precise control of the DC-DC converter can be achieved by advanced digital controllers over conventional controllers [6]. Programing of advanced digital controllers provides an extra edge over conventional controllers.

This proposed work emphasis on fuzzy sliding mode controller which has positive edge over analog controllers in controlling high switching converters used in achieving fast charging. Conventional controllers lack in removal or reduction in chattering effect of the control signal to converter. Whereas fuzzy sliding eliminates chattering effect of the signal fed to the DC-DC converter [8]. Also, the proposed controllers boost the efficiency of the basic DC-DC converter.

This proposal led to the design of an advanced fuzzy sliding mode controller, which controls the basic DC-DC converter of an off board charger of a charging station. The robustness of Sliding mode control and precise feature of fuzzy logic provide more control of high frequency DC-DC converters in achieving fast charging [6-8]. The non-linear nature of PV system can easily addressed by the controlling capability of fuzzy based sliding mode controller. The complex nature in designing mathematical model of the EV charging system coupled with PV system can easily resolved by the proposed controller. Sudden change in the source voltage can easily sense by the fuzzy model to deal with the charging demand. Fuzzy based sliding mode controllers facilitate fast chagrining of electric vehicles [12-15]. The robustness reduced chattering, efficiency, dynamic response to source input change and flexible control to various battery load best suites the need for the fast charging of electric vehicles.

In section 2, Selection of solar panels and modeling of converter is presented. In section 3, controller design issues were presented in detail. Simulation outcomes for the proposed system presented in section 4. Depended on the achieved simulation results, inferences were made in Section 5. Acquired results affirm the proposed controller design for the considered converter. The Off-Board charging system for electric vehicles (EVs) is modeled and simulated in MATLAB, as depicted in Figure 1.

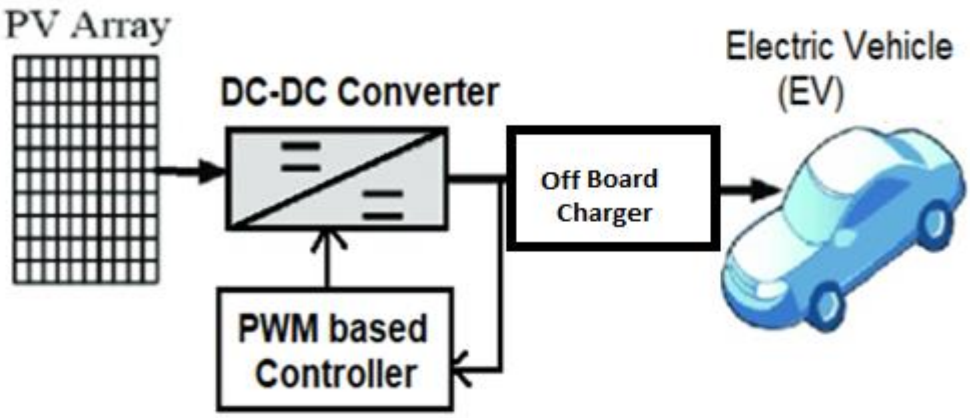

Fig. 1: Proposed EV Charging System with Fuzzy Sliding Mode Controller

2. Modeling Of The Converter

Before designing of a controller in a physical system, the working principle & mathematical model of the system is derived. Section 2.1 represents solar panel modeling and its ratings. The working principle & the mathematical model of the system presented in section

2.1 SOLAR PANELS SELCTION

To meet the requirements of load with 310 Wp, mono crystalline with a voltage of 33V and a maximum peak current of 9.37A was selected. After that, A total number of 156 number of solar panels was calculated with 48KWp and Two numbers 24KW inverters was selected.

2.2 WORKING PRINCIPLE OF THE CONSIDERED DC-DC CONVERTER

To obtain fast charging of EV’s, a high current at low voltage is imperative. This can be achieved by using DC-DC step-down converter into account, as indicated in Fig.2. The output generated by this converter is primarily utilized to charge the EV's battery. Based on this setup, the Continuous Conduction Mode (CCM) of the converter circuit is examined, which operates in two distinct modes: the switch ON state and the switch OFF state, as depicted in Figures 3 and 4. The switching characteristics of the converter are analyzed based on the waveforms presented.in Fig.5.

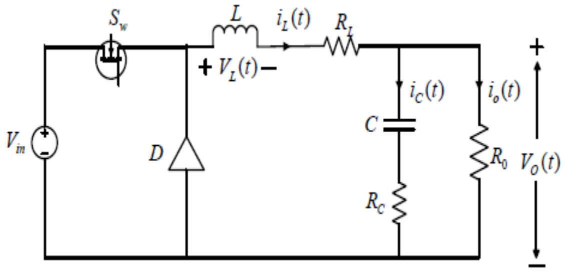

Fig. 2: Considered DC-DC Converter

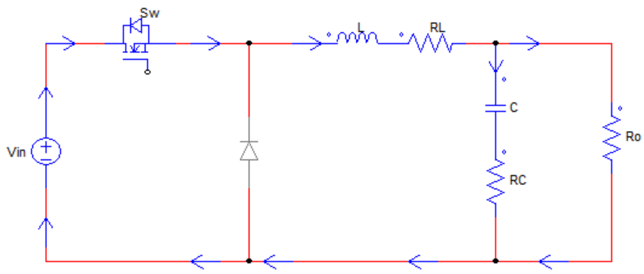

Fig. 3: Turn ON Mode of Main Switch

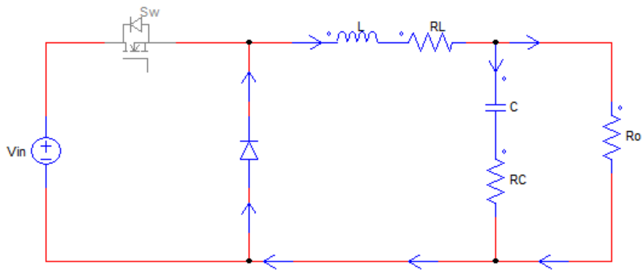

Fig. 4: Turn OFF Mode of Main Switch

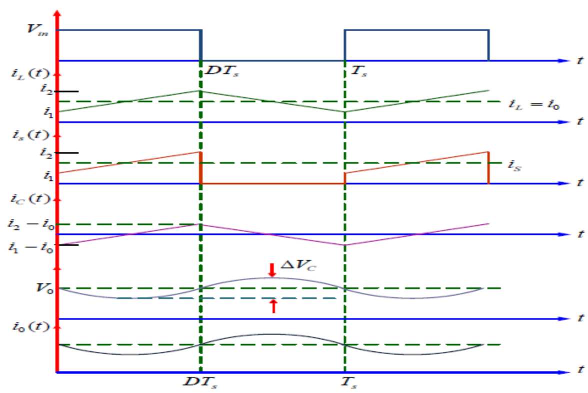

Fig. 5: Charactestics of considered Converter

The relation between the output & input Voltage is given by,

$$d = \frac{V_0}{V_{in}} \quad (1)$$

By considering required values from converter, capacitance and Inductance values are calculated by using Equations (2) & (3).

$$L_{min} = \frac{(1-D)R}{2f} \quad (2)$$

$$L = 1.25\ times\ Lmin \quad (3)$$

$$C = \frac{(1-D)}{8L(^{\Delta V_0}/_{V_0})f^2} \quad (4)$$

2.3 MATHEMATICAL MODELING OF THE DC-DC CONVERTER

The state space averaging mathematical model is well-suited for designing a sliding mode controller (SMC) for DC-DC converters. Given that the DC-DC converter operates in Continuous Conduction Mode (CCM), it generates two distinct state equations. One equation corresponds to the ON state of the main MOSFET, while the other represents the OFF state. These state equations are provided in equations (5) and (6).

$$\begin{bmatrix} \dot{i} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}\left(\frac{R_0R_c}{R_0+R_c}+R_l\right) & \frac{-1}{L}\left(\frac{R_0}{R_0+R_c}\right) \\ \frac{1}{C}\left(\frac{R_0}{R_0+R_c}\right) & \frac{-1}{C}\left(\frac{1}{R_0+R_c}\right) \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} [v_{in}]$$

$$[y] = \begin{bmatrix} \frac{R_0R_c}{R_0+R_c} & \frac{R_0}{R_0+R_c} \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} \dot{i} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}\left(\frac{R_0R_c}{R_0+R_c}+R_l\right) & \frac{-1}{L}\left(\frac{R_0}{R_0+R_c}\right) \\ \frac{1}{C}\left(\frac{R_0}{R_0+R_c}\right) & \frac{-1}{C}\left(\frac{1}{R_0+R_c}\right) \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} [v_{in}]\ [y] = \begin{bmatrix} \frac{R_0R_c}{R_0+R_c} & \frac{R_0}{R_0+R_c} \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} \quad (6)$$

By taking the weighted average over a complete cycle of equations (5) and (6), the averaged model is derived and presented as equation (7).

$$\dot{x} = Ax + Bu$$

(7)

Where A= d A_{ON} + (1- d) A_{OFF}

B= d B_{ON} + (1 – d) B_{OFF}

$$\begin{bmatrix} \dot{i} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L}\left(\frac{R_0R_c}{R_0+R_c}+R_l\right) & \frac{-1}{L}\left(\frac{R_0}{R_0+R_c}\right) \\ \frac{1}{C}\left(\frac{R_0}{R_0+R_c}\right) & \frac{-1}{C}\left(\frac{1}{R_0+R_c}\right) \end{bmatrix} \begin{bmatrix} i \\ v \end{bmatrix} + \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix} [v_{in}]$$

The Linearized model is given by perturbing & linearizing the variables in equation (8)

$$x = X + \hat{x}$$

$$u = U + \hat{u}$$

$$d = D + \hat{d}$$

$$\hat{x} \prec\prec X$$

$$\hat{u} \prec\prec U$$

$$\hat{d} \prec\prec D \qquad (8)$$

After neglecting Higher terms & by substituting the Eq.(8) in Eq (7) we get

$$\dot{\hat{x}} = A\hat{x} + B\hat{u} + (A_{ON} - A_{OFF})\hat{d}X + (B_{ON} - B_{OFF})\hat{d}U$$

$$\dot{\hat{x}} = A\hat{x} + B\hat{u} + E\hat{d} \qquad (9)$$

Where

$$E = (A_{ON} - A_{OFF})X + (B_{ON} - B_{OFF})U$$

$$E = \begin{bmatrix} \frac{Vin}{L} \\ 0 \end{bmatrix}$$

The block diagram of the converter, based on the designed model, is illustrated in Figure 6. The system parameters used in this model are listed in Table 1

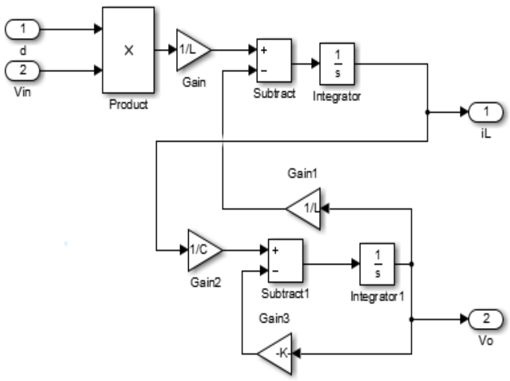

Fig. 6: Block diagram representation of converter

Table 1: Design Parameters

Parameters	Values
DC Bus Voltage	800V
Output Voltage	400V
Output Power	48KW
Switching Frequency	100KHz
Battery Nominal Voltage	300V
Battery Capacity	12KWh
Battery State of Charge	50%
Battery Time Constant	2 Sec

By the given parameters, considered system is simulated and Response of converter without any controller is shown in Fig.7.it shows the necessity of the controller.

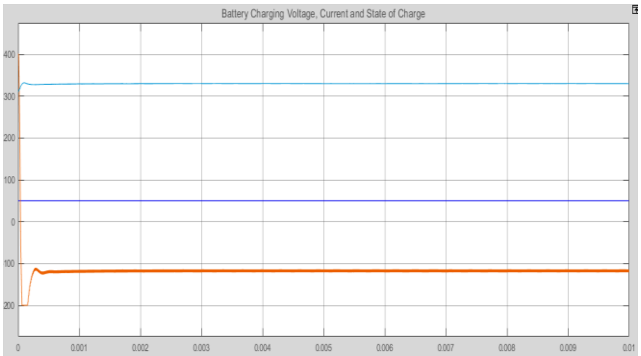

Fig. 7: Response of converter without any controller

3. Controller Design Issues

The converter must need a controller to get a steady response Hence PI Controller is designed first and then to get a better performance a FSMC is designed.

3.1 DESIGN OF PI CONTROLLER

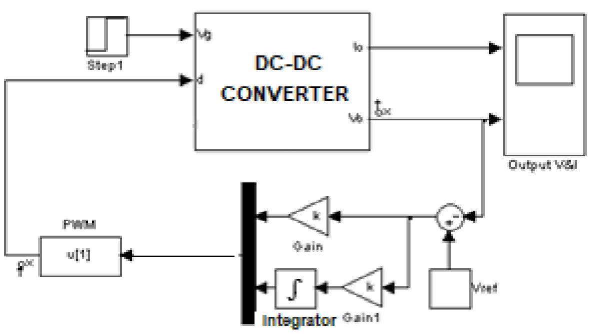

Fig. 8: PI controller for the Converter

Figure 8 depicts the PI controller for the converter. The transfer function of the controller is expressed as

Kp+Ki/S. This controller is simulated in MATLAB, as illustrated in Figure 9, with the outputs displayed in Figure 10.

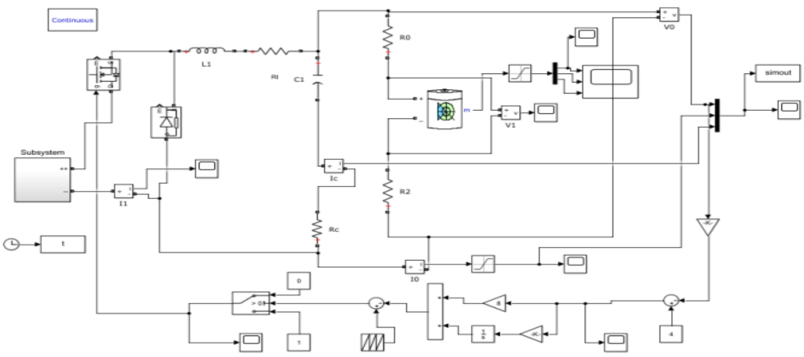

Fig. 9: Simulation diagram of proposed system with PI Controller

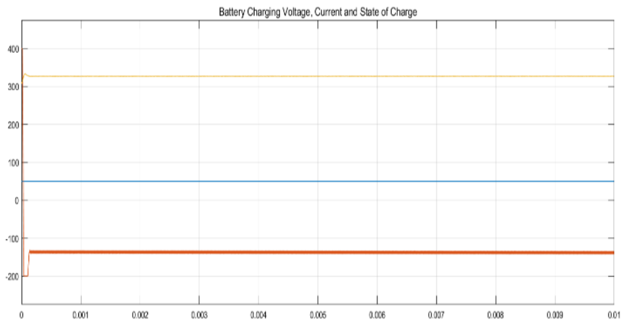

Fig. 10: Outputs of System with PI Controller

3.2 CONVERTER WITH FSMC CONTROLLER

A schematic representation of FSMC for Considered DC-DC Converter is shown in Fig.11.

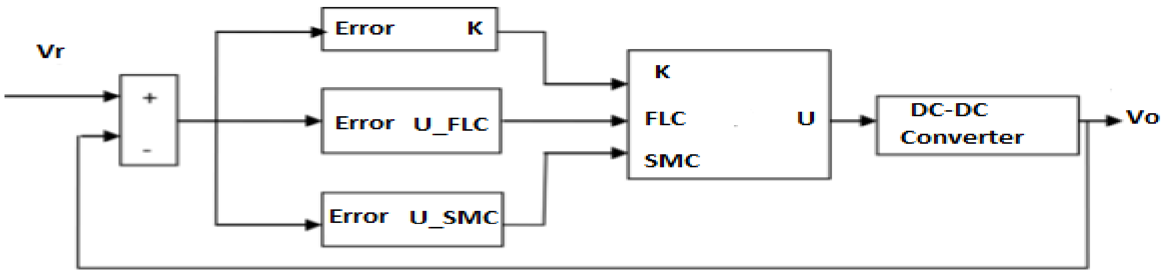

Fig. 11: Simulation Model of FSMC for DC-DC Converter

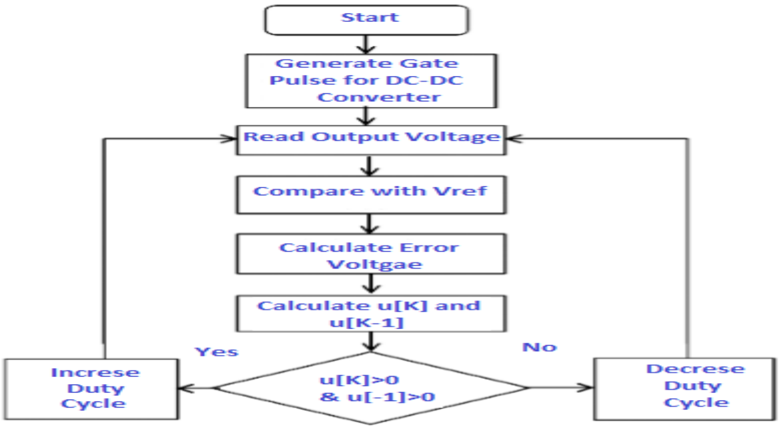

Fig. 12: Flow Chart for the controller design using FSMC

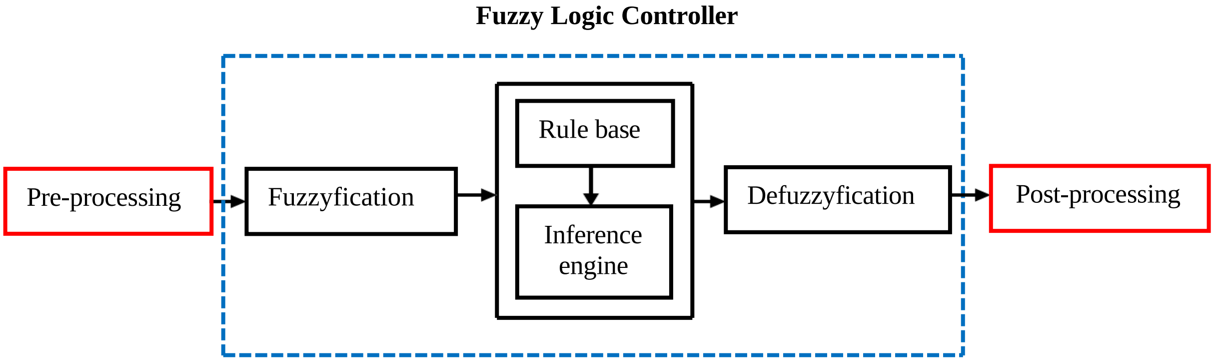

Fig. 13: Structure of Fuzzy Logic Controller

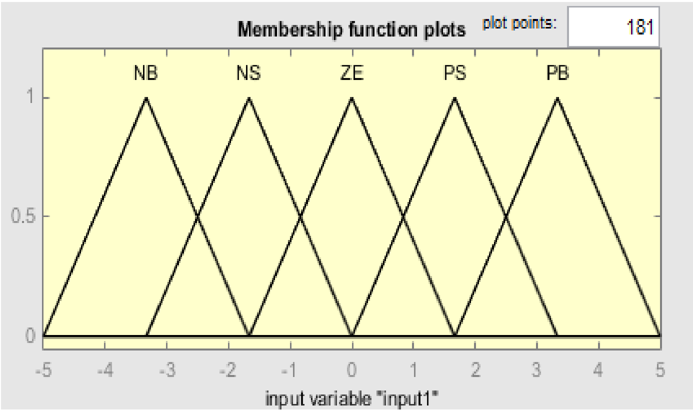

Fig. 14: Error & Change in Error signal functions

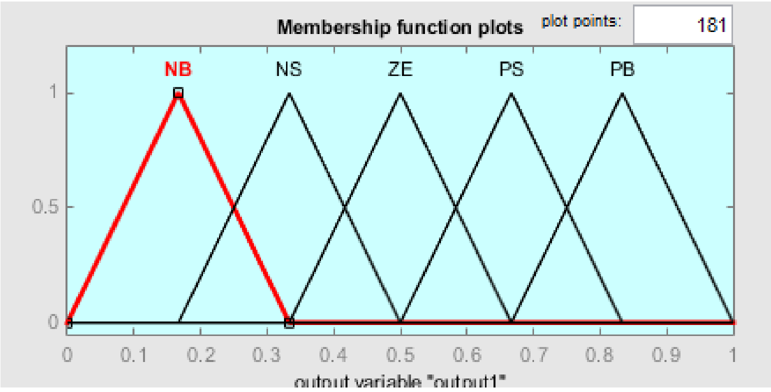

Fig. 15: output Membership functions

Table.2 Membership Rules

E\CE	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	PB	PB	PS	PS	ZE
NS	PB	PS	PS	ZE	NS
ZE	PB	PS	ZE	NS	NB
PS	PS	ZE	NS	NS	NB
PB	ZE	NS	NB	NB	NB

The FLC output is used to tune the gain K adaptively in the SMC control law. As most of Converters have non-liner nature due to high frequency of operation. A SMC is able to address the most of these issues but it was having a problem with chattering effect. By combining both Fuzzy and SMC more robust controller were designed to get good performance. A detailed step-by-step design procedure for the Fuzzy Sliding Mode Controller (FSMC) is outlined for the specified system. The control variables used in the Sliding Mode Controller (SMC) are defined as follows:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} (V_{ref} - \delta V_o) \\ \frac{d}{dt}(V_{ref} - \delta V_o) \\ \int (V_{ref} - \delta V_o)\, dt \end{bmatrix} \tag{10}$$

The control variables are error, change in error and integral of error. By substituting designed State model in (10) We get,

$$x_{buck} = \begin{bmatrix} x_1 = \boldsymbol{\Upsilon}_{\boldsymbol{p2}}(V_{ref} - \delta V_o) \\ x_2 = \frac{\delta V_o}{RC} + \int \frac{\beta(V_o - V_g u)}{LC} dt \\ \int (V_{ref} - \delta V_o)\, dt \end{bmatrix} \tag{11}$$

On Differentiation of eq. (11) we get,

$$\begin{bmatrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-1}{R_0 C_0} & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ -\frac{\delta V_g}{LoCo} \\ 0 \end{bmatrix} u + \begin{bmatrix} 0 \\ \frac{\delta V_0}{LoCo} \\ 0 \end{bmatrix} \tag{12}$$

It is represented as: $\dot{x} = Ax + Bu + D$. The Designed sliding surface must satisfy the hitting, existence and stability conditions.

i.Hitting condition

A control law is designed as

$$u = \frac{1}{2}\left(1 + sgn(S)\right) \tag{13}$$

& u= 1,0 when S>0 & S<0.

Here, S represents the trajectory reference path, which is designed using the sliding coefficients λ1, λ2, λ3 as follows:

$$S = \lambda_1 x_1 + \lambda_2 x_2 + \lambda_3 x_3 = I^T x \tag{14}$$

ii.Existence condition

To verify the existence of trajectory ranges, the sliding coefficients are determined using the following approach:

$$\lim_{s \to 0} S\,\dot{S} < 0 \tag{15}$$

By solving the equation above and setting it equal, we can express it as

$$\dot{S} = I^T A x + I^T B u_{eq} + I^T D = 0.$$

consequently, the control law is calculated as follows:

$$0 < -\delta Lo\left(\frac{\lambda_1}{\lambda_2} - \frac{1}{R_0 C_0}\right) i_C + L_0 C_0 \frac{\lambda_3}{\lambda_2}\left(V_{ref} - \delta V_o\right) + \delta V_o < \delta V_g \tag{16}$$

iii.Stability condition derivation

Using the trajectory, we can assess the stability of the system, and the sliding coefficients were determined using equation (17).

$$\lambda_1 x_1 + \lambda_2 \frac{dx_1}{dt} + \lambda_3 \int x_1 dt = 0. \tag{17}$$

On rearranging eq.(17)

$$\frac{d^2 x_1}{d^2 t} + \frac{\lambda_1}{\lambda_2}\frac{dx_1}{dt} + \frac{\lambda_3}{\lambda_2} x_1 = 0 \tag{18}$$

By comparing it with the standard form, we obtain:

$$\omega_n = \sqrt{\frac{\lambda_3}{\lambda_2}} \;\&\; \xi = \frac{\lambda_1}{2}\sqrt{\lambda_2 \lambda_3} \tag{19}$$

Using the desired response, the sliding coefficients were calculated based on the parameters listed in Table 1 and simulated in MATLAB.

$$\omega_n = 4K\frac{rad}{sec}, T_s = 250\mu sec, \frac{\lambda_1}{\lambda_2} = 8000, \frac{\lambda_3}{\lambda_2} = 16000 \textit{ and hence } \boldsymbol{\Upsilon_{p1}} \& \boldsymbol{\Upsilon_{p2}}$$

4. Simulation Results

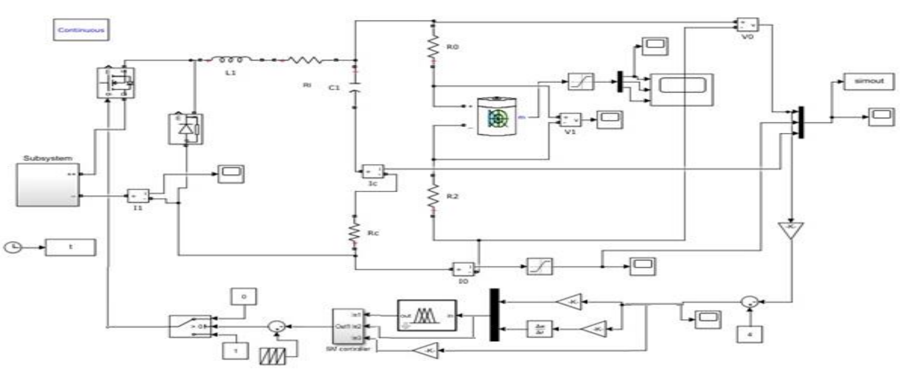

Fig. 16: Considered system with FSMC

The output voltage of the solar system is depicted from the Fig.17, which translates to output voltage of 800V at 60A. Step-Down DC-DC voltage of 340V is illustrated in fig.18, which is slightly higher than the rated battery voltage of 320V, as labeled in Fig.19. To facilitate fast charging capability, a charging current of 120A is achieved over entire operating time, as evident in Fig. 20 and the battery state of charge (SOC) is shown in Fig. 21. The results obtained in both the time and frequency domains confirm the effectiveness of the DC-DC converter.

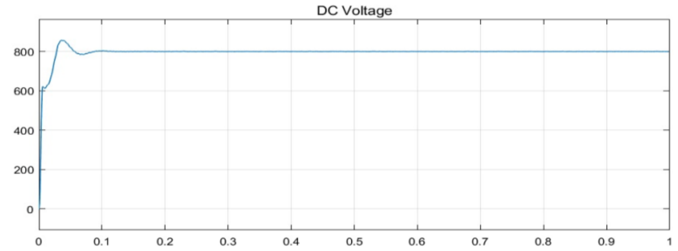

Fig. 17: DC Voltage from Solar Panels

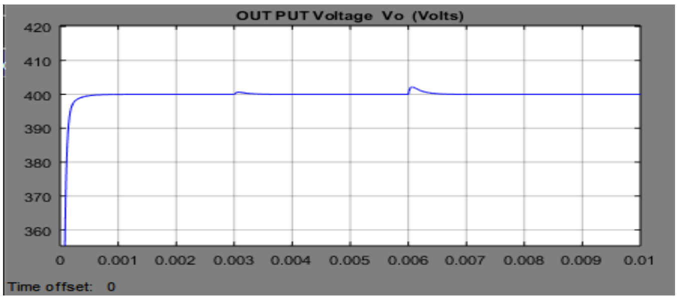

Fig. 18. DC-DC Converter Output Voltage

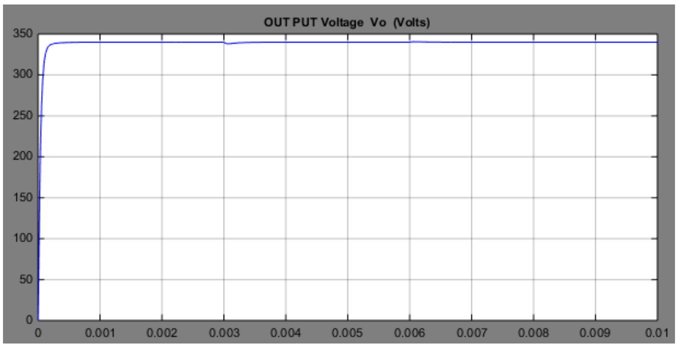

Fig. 19: Charging Voltage of EV Battery

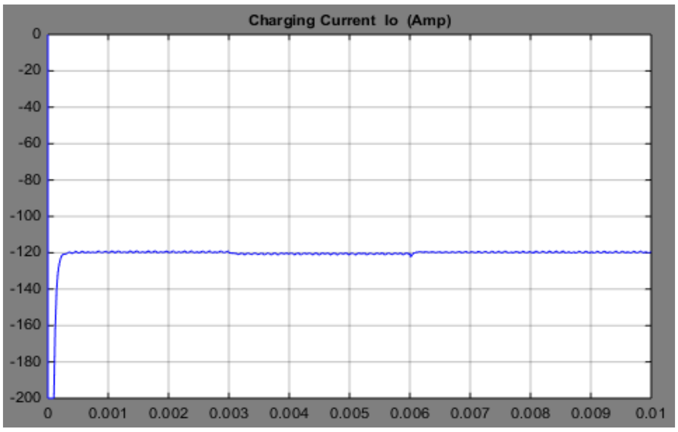

Fig. 20: Charging Current of EV Battery

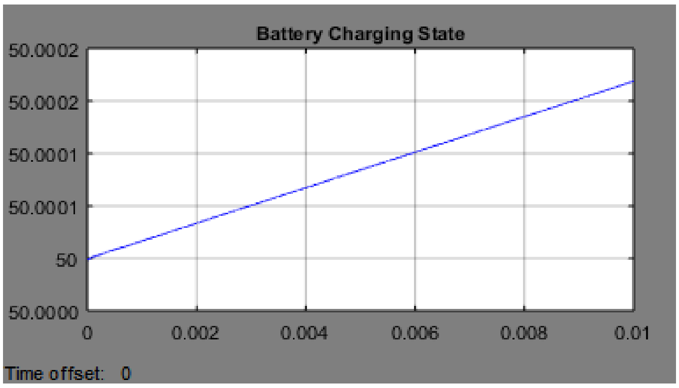

Fig. 21: Battery State of Charge

Disturbances may occur at the source or at the load end. The trustworthiness of the proper controller depended on the steady state response even with source and load end disturbances. To validate, the same 20V of voltage at the source is injected at 0.003 sec, and 5A of current is injected at 0.006 sec. It is evident from Fig. 19. and Fig. 20, even with both cases of disruptions, the system is able to output the desired steady state response without effecting the charging pattern, this confirms the validity of the proposed controller.

5. Conclusion

This paper presents a fuzzy-based sliding mode controller designed to manage fluctuations in input voltage when integrating a PV system with off-board electric vehicle charging. The proposed controller effectively handles the nonlinear characteristics of the DC-DC converter. Initially, a standard sliding mode controller (SMC) was developed, and to mitigate chattering effects, a more robust fuzzy sliding mode controller (FSMC) was designed. The complete design process is detailed for an 800V solar-integrated off-board charging system for electric vehicles, including MATLAB simulations. The performance of the designed model outperforms that of a PI controller, validating the effectiveness of the proposed controller.

References

1. Un-Noor F, Padmanaban S, Mihet-Popa L et al (2017) A comprehensive study of key electric vehicle (EV) components, technologies, challenges, impacts, and future direction of development. Energies. 10(8), 1217-1301.
2. Sidharthan Panaparambil V, Kashyap Y, Vijay Castelino R (2021) A review on hybrid source energy management strategies for electric vehicle. International Journal of Energy Research 45:19819–19850.
3. K. Vibha , Kishore Bala K (2024) Half Bridge LLC DC-DC Converter for EV Battery Charger Tuijin

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Jishu/Journal of Propulsion Technology ISSN: 1001-4055 Vol. 45 No. 2 (2024) 4646 – 4655.

4. BalaKrishna Nallamothu, B. Santhana Krishnan, Ravindra Janga (2020) :“ Performance Evolution of Small Signal Model based Peak Current Mode Controller for Off-board Fast Charging DC-DC Converter” 2020 IEEE 17th India Council International Conference (INDICON), 10-13 December 2020.
5. P. Goli and W. Shireen (2014) "PV Integrated Smart Charging of PHEVs Based on DC Link Voltage Sensing," IEEE Transactions on Smart Grid, vol. 5, pp. 1421-1428.
6. Nethaji G, Kathirvelan J (2024) “Performance comparison between PID and Fuzzy logic controllers for the hardware implementation of traditional high voltage DC-DC boost converter –Heliyon.
7. AHMED, HUSAIN and RAJORIYA, ABHA (2017) "A hybrid of sliding mode control and fuzzy logic control using a fuzzy supervisory switched system for DC motor speed control," Turkish Journal of Electrical Engineering and Computer Sciences: Vol. 25: No. 3, Article 30.
8. J. P. Leo Arokia Raj, S. Padma, R. Kannan (2023) “Pi And Fuzzy Logic Controlled Multiple Lift Push-Pull Switched Capacitor Luo Converter. Tuijin Jishu/Journal of Propulsion Technology ISSN: 1001-4055 Vol. 44 No. 3 1774 – 1784.
9. Hammed Olabisi Omotoso, Saad M. Alghuwainem, Irfan Ahmad (2019)“Constant Current Fuzzy Logic Controller for Grid Connected Electric Vehicle Charging” 8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO)15-17 April 2019, pp.1-5.
10. Ravindra Janga, Sushama Malaji (2019) “Design of PWM based Sliding Mode Controller for an Active Clamp Forward Converter with Current Doubler Rectifier” International Journal of Engineering and Advanced Technology (IJEAT),ISSN: 2249 – 8958.Volume-8 Issue-5, June 2019, p.p. 1070-1075.
11. Dr. M. Balakrishnan, R. Satheesh, S. Selvam, V. Raja Subramanian, R. Masilamani, G. Nirmal Kumar, (2024) “A Study of Barrier and Challenges of Electric Vehicle in India and Vehicle to Grid Optimization” Tuijin Jishu/Journal of Propulsion Technology ISSN: 1001-4055 Vol. 45 No. 1 4387 – 4401.
12. A. Verma, B. Singh, (2019)”An implementation of renewable energy based grid interactive charging station” in IEEE Transportation Electrification Conference and Expo (ITEC), Detroit
13. V.T. Tran, K.M. Muttaqi, D. Sutanto (2019) A robust power management strategy with multi-mode control features for an integrated PV and energy storage system to take the advantage of ToU electricity pricing, in IEEE Transaction on Industry Application, vol. 55, no. 2, March-April 2019, pp. 2110–2120.
14. M.F. Shaaban, S. Mohamed, M. Ismail, K. Qaraqe, E. Serpedin(2024) “Joint planning of smart EV charging stations and DGs in eco-friendly remote hybrid microgrids” in IEEE Transaction on Smart Grid, Early Access.
15. A. Meintz, J. Zhang, R. Vijayagopal, C. Kreutzer, S. Ahmed, I. Bloom, et al.(2017), "Enabling fast charging – Vehicle considerations," Journal of Power Sources, vol. 367, pp. 216-227.