FLC-based, PV-fed interleaved dual buck-boost converter for EV battery charging applications

S. Krithiga,*, N. Sujitha, G.J.S.M. Sandeep, R. Gokulnath, Partha Sarathi Subudhi

School of Electrical Engineering, Vellore Institute of Technology, Chennai, Tamilnadu, India
Department of Electrical Engineering, Bajaj Institute of Technology, Wardha, India
Department of Electrical and Electronics Engineering, Faculty of Engineering and Architecture, Nisantasi University, Istanbul, Turkey

ARTICLE INFO

Keywords:
Renewable energy
Electric vehicle battery charging system
Photovoltaic array
Fuzzy logic controller
Interleaved dual buck-boost converter

ABSTRACT

Fuzzy logic controller is developed for PV array fed interleaved dual buck-boost (IDBB) converter for EV battery charging applications. The inner dynamics of the IDBB converter is improved using the damping network. Irrespective of the change in solar insolation conditions, the developed fuzzy logic controller adjusts the duty ratio of the converter to obtain constant output voltage. Simulation studies have been carried out using MATLAB/Simulink software and Fuzzy Logic Controller modelled in MATLAB/Simulink software was interfaced with dSPACE1103 to carry out the experimental investigation in Hardware-in-loop methodology in dSPACE workstation. The experimental results are on-par with the simulated results validating the proposed system.

1. Introduction

Vehicle electrification has been expedited due to the increase of conventional energy usage for transportation which causes the environmental pollution. As a result, electric vehicles (EV) are expected to evolve all over the world as a commonly used transportation in the near future [1, 2]. Electric vehicle uses a rechargeable battery pack which is powered from the utility grid. Electric vehicles increase the load demand on the utility grid during peak demand duration, which eventually escalates the electricity bills on the EV users [3]. Hence, there is need for alternative source of energy to charge the EV batteries. Renewable energy sources like Photovoltaic (PV) array can be used as an alternative energy source due to its profusion availability and easy installation process which makes the system to be termed as “green transportation” [4, 5].

The intermittent nature of PV array necessitates intermediate power electronic interface to attain the desired voltage to charge EV battery. Conventional dc-dc converters like buck-boost, SEPIC, Cuk, Flyback converters are used as power electronic interface in the PV applications. In addition to these converters, boost and buck converters are cascaded to obtain single inductor based buck-boost converter for low voltage applications. All the aforementioned converters have the drawback of current ripples. As the current is divided into more than one path, conduction loss is reduced which in turn increases the overall efficiency compared to the conventional converter [13]. The two phases are merged at the output capacitor resulting in doubled effective ripple frequency, and hence, the voltage ripples are reduced. Some of the advantages of this technique are harmonic cancellation, better efficiency, reduction in component stress and high current capability [14]. Hence, the dual...
Figure 2. Schematic diagram of IDBB converter adapted from [15].

Figure 3. Schematic diagram of IDBB converter operating in (a) boost mode (b) buck mode, adapted from [15].
buck-boost converter with interleaving technique is used in the proposed PV array system which can be utilised as an EV battery charger [15].

The proposed system requires a voltage controller to maintain output voltage constant irrespective of solar irradiation conditions. Conventional voltage controllers are reported in the literature [16, 17]. Also, artificial intelligence controllers have been explained in the recent papers [18, 19, 20]. The Fuzzy logic controller (FLC) is more precise in tracking the PV array voltage and controls the duty ratio of the converter for maintaining constant output voltage compared to the conventional

![Figure 4. Flow chart of the controller.](image)

![Figure 5. Controller diagram of the proposed system.](image)

![Figure 6. Membership function plots of (a) error, e (b) change in error, de and (c) change in duty ratio, del_d](image)

| Change in error (de) | Error (e) |
|---------------------|-----------|
| NM                  | NM        |
| NS                  | NS        |
| ZO                  | ZO        |
| PS                  | PS        |
| PM                  | PM        |

| Change in error (de) | Error (e) |
|---------------------|-----------|
| NB                  | NB        |
| NM                  | NM        |
| NS                  | NS        |
| ZO                  | ZO        |
| PS                  | PS        |
| PM                  | PM        |
| PB                  | PB        |
controllers. Hence, FLC is implemented in the proposed PV array system. Contributions of this article are as follows:

- In this paper, unique Fuzzy logic controller is developed for stand-alone PV array system.
- Developed PV array system is capable of charging EV battery.
- The proposed fuzzy logic controller is used along with interleaved dual buck-boost (IDBB) converter and provides constant output voltage irrespective of the change in solar irradiation conditions.
The proposed system is experimentally verified using Hardware-in-loop mode in dSPACE workstation and dSPACE1103 interfaced Fuzzy Logic Controller modeled in MATLAB/Simulink software.

2. Proposed FLC based PV array system

The proposed Fuzzy Logic Controller based PV array system comprises of PV array, Interleaved Dual Buck-Boost converter, FLC and load is shown in Figure 1. Generated power from PV array is fed to load through IDBB converter. Based on the PV array voltage, IDBB converter works either in boost or buck mode by appropriately turning on the switches depending on solar irradiation conditions. Further, the duty ratio of the gate pulses supplied to the switches is adjusted appropriately by the Fuzzy logic controller to provide constant output voltage.

2.1. Interleaved dual buck-boost converter

IDBB converter shown in Figure 2 operates in two modes viz boost mode and buck mode depending on the PV array voltage.

The voltage transfer ratio of IDBB converter is as follows [15]:

\[
\frac{V_o}{V_{PV}} = \frac{\delta_{34}}{1 - \delta_{12}}
\]

(1)

Where, \(V_o\) is the output voltage \\
\(V_{PV}\) is the PV array voltage \\
\(\delta_{12}\) & \(\delta_{34}\) are the duty ratio of gate pulses provided to the switches \(S_1, S_2, S_3, S_4\) respectively.

In boost mode, switches \(S_3\) & \(S_4\) conduct continuously as depicted in Figure 3(a) and the switches \(S_1\) and \(S_2\) are operated with duty ratio, \(\delta_{12}\) as per the Eq. (1). The generated gate pulses of \(S_3\) is 180° phase shifted from that of gate pulses of \(S_1\) for obtaining the interleaved operation. The duty ratio is tuned in order to obtain the desired reference voltage, \(V_{ref}\) at the output terminals.

In buck mode, switches \(S_1\) & \(S_2\) are in off state continuously as depicted in Figure 3(b) and the switches \(S_3\) & \(S_4\) are operated with duty ratio, \(\delta_{34}\) as per Eq. (1). Similar to the boost mode, the generated gate pulses of \(S_4\) is 180° phase shifted from that of gate pulses of \(S_3\) for obtaining the interleaved operation. The duty ratio of the gate pulses are adjusted in order to obtain the desired reference voltage, \(V_{ref}\) at the output terminals. The damping network, \((C_d & R_d)\) plays a key role in decaying the oscillation of input voltage during buck mode where switches \(S_1\) & \(S_2\) are continuously in off state. The inductors are designed using the Eqs. (2), (3), (4), and (5) [15]:

\[
L_a = \frac{V_{PV}(V_o - V_{PV})}{\Delta I_{o} V_0 T_S}
\]

(2)

\[
L_b = \frac{V_{PV}(V_o - V_{PV})}{\Delta I_{o} V_0 T_S}
\]

(3)

\[
L_c = \frac{V_{PV}(V_o - V_{PV})}{\Delta I_{o} V_0 T_S}
\]

(4)

\[
L_d = \frac{V_{PV}(V_o - V_{PV})}{\Delta I_{o} V_0 T_S}
\]

(5)

2.2. Controller

Fuzzy logic controller in the proposed system acts as a voltage controller to provide constant output voltage irrespective of the change in solar irradiation conditions by adjusting the duty ratio of the gate pulses provided to the IDBB converter. Initially, controller senses the PV array voltage, \(V_{PV}\) and compares with the reference voltage, \(V_{ref}\) and also
senses output voltage, $V_0$. Based on the sensed voltages, controller selects the operating mode using two control signals, $S_{\text{boost}}$ and $S_{\text{buck}}$ as shown in Figure 4. If $V_{PV} > V_{\text{ref}}$, buck mode is selected by setting $S_{\text{boost}} = 0$ & $S_{\text{buck}} = 1$. Whereas if $V_{PV} < V_{\text{ref}}$, boost mode is selected by setting $S_{\text{boost}} = 1$ & $S_{\text{buck}} = 0$. After the selection of modes, controller compares the output voltage, $V_0$ and the reference voltage, $V_{\text{ref}}$ and computes the error, $e$ and change in error, $de$ as per the following Eqs. (6) and (7) [21]:

$$e(k) = V_{\text{ref}} - V_0$$  \hspace{1cm} (6)

$$de(k) = e(k) - e(k-1)$$  \hspace{1cm} (7)

Error, $e$ and change in error, $de$ are the inputs to the FLC and change in duty ratio, $del_d$ is the output of FLC. Fuzzy membership functions of Error, $e$ is chosen such that, error is positive in buck mode whereas, in boost mode, error is negative. As, same FLC is used for both buck and boost mode, negative of computed error is provided as one of the inputs to the FLC during boost mode while, in buck mode, computed error itself is provided as input to FLC as shown in Figure 5. The FLC output, change in duty ratio, $del_d$ is added with the previous duty ratio in the integrator to generate the control signal, $V_{\text{control}}$. This control signal is compared with 50 kHz ramp signal to generate the pulse width modulated (PWM) signals, $X$ and $Y$. The PWM signal, $Y$ is 180° phase shifted from that of $X$ signal. In order to compensate the negative of error provided as input to FLC during boost mode, the PWM signals $X$ and $Y$ are inverted and provided as gate pulses to the Switches $S_1$ & $S_2$ respectively after logical
“AND” operation with the Sboost variable. Whereas the PWM signals, X and Y are provided as gate pulses to the Switches S3 & S4 respectively after the logical “OR” operation with the Sboost variable as shown in Figure 5. Explanation on the FLC is elaborated in the next section.

3. Fuzzy logic controller

FLC comprises of three key components viz fuzzification, inference engine, and defuzzification. In fuzzification process, error, e & change in error, de are the crisp inputs and they are converted into fuzzy quantity using the membership functions [21]. The triangular membership functions for inputs, error, e, change in error, de and output, change in duty ratio, del_d are shown in Figure 6. Rule base of the proposed FLC is presented in Table 1. For locating the region of output, del_d, “MIN” implication method is employed. Then, the actual change in duty ratio, del_d is obtained from the FLC output using “Centroid” defuzzification method.

4. Simulation studies of the proposed system

The proposed FLC system is simulated in MATLAB/simulink software by modeling PV array, MOSFETs, inductors, diodes, capacitors and resistor available in the software. Controller is developed using FLC, logical & relational operators, delay, repeating sequence and discrete time integrator existing in the software.

The proposed system is simulated in boost and buck mode corresponding to the PV array (series connected two panels each with, Voc of 37.25 V & Isc of 8.75 A) irradiation of 600 W/m² & 400 W/m² respectively. In boost mode, the PV array voltage, V PV of 29.12 V is boosted to the output voltage, V0 of 36 V as shown in Figures 7 and 8 and the corresponding PV array current, IPV of 5.45 A and output current, I0 of 4.24 A is also depicted respectively in Figures 7 and 8. The fuzzy logic controller tuned the duty ratio of 50 kHz gate pulses to 22 % and provided to the switches of IDBB converter as presented in Figure 9. From Figure 9, we can observe that the gate pulses to the switches S1 & S2 are pulse width modulated and the switches S3 & S4 are turned on continuously.

In buck mode, the output voltage, V0 of 36 V is obtained by stepping down the PV array voltage, V PV of 44 V as shown in Figures 10 and 11 and corresponding PV array current, IPV of 3.6 A and output current, I0 of 4.24 A is also depicted in Figures 10 and 11 respectively. The fuzzy logic controller tuned the duty ratio of 50 kHz gate pulses to 84 % and provided to the switches of IDBB converter as presented in Figure 12. From Figure 12, we can observe that the gate pulses to the S3 & S4 switches are pulse width modulated and the switches S1 & S2 switches are turned off in this mode.

5. Experimental results

The Experimental prototype of the proposed system was fabricated and tested in the laboratory. MOSFET IRF540N (100V, 30A), Diode MUR860 (200V, 30A), inductors 100μH, 10A, capacitors of 68 μF, 100V and 47 μF, 100V and damping resistor of 10 Ω and damping capacitor of 470 μF, 100 V are used to fabricate the IDBB converter as shown in
the switches S3 duty ratio and switching frequency of 50 kHz are shown in Fig. 16(a) and (b) depicts that S1 and 50 kHz switching frequency are shown in Fig. 18(a) and (b). The corresponding input and output currents are shown in Fig. 17(a) (b). The generated gate pulses to the switches S3, S4 with 85% duty ratio the corresponding waveforms are presented in Fig. 20. Figure 20, transitions from boost mode to buck mode and then to boost mode and current waveforms are shown in Fig. 19.

The authors would like to thank Mr. Anupam Anand, B. Tech. Student, School of Electrical Engineering, Vellore Institute of Technology, Chennai, India, for his contributions in testing of laboratory prototype.

6. Conclusion

This paper presents a FLC based PV fed IDBB converter, which can be used as an efficient EV battery charger. The input & output current ripples of the IDBB are reduced due to the input and output interleaved inductors respectively. Irrespective of the changes in solar irradiation conditions, the proposed fuzzy logic controller controls the duty ratio of the gate pulses to the switches of IDBB converter to deliver the constant output voltage. Solar irradiation of 200 W/m² is considered as the lower limit for the boost mode operation of the system. Using MATLAB/Simulink software, the FLC system is simulated and the experimental study is carried out in Hardware-in-loop mode in dSPACE workstation by developing a laboratory prototype of the converter and dSPACE1103 interfaced FLC modeled in software. The dynamic response of the developed system validates the efficacy of the proposed fuzzy logic controller. The simulation studies and experimental results validate the proposed system. MPPT technique can be adopted in the proposed system in future.

Declarations

Author contribution statement

Krithiga S.: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Sujitha N.: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Sandeep G.J.S.M., Gokulnath R.: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Partha Sarathi Subudhi: Performed the experiments; Contributed reagents, materials, analysis tools or data, Wrote the paper.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

No data was used for the research described in the article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Krithiga S. was Associate Professor in School of Electrical Engineering, Vellore Institute of Technology (VIT), Chennai. Research work presented in this paper was carried out by the authors when they were in Vellore Institute of Technology (VIT), Chennai, Tamil Nadu, India.

Acknowledgements

The authors would like to thank Mr. Anupam Anand, B. Tech. Student, School of Electrical Engineering, Vellore Institute of Technology, Chennai, India, for his contributions in testing of laboratory prototype.

References

[1] Byung-Kwon Lee, Jong-Pil Kim, Sam-Gyun Kim, Jun-Young Lee, An Isolated/ Bidirectional PWM resonant converter for V2G(H) EV on-board charger, IEEE Trans. Veh. Technol. 66 (9) (2017) 7741–7750.
[2] J.G. Pinto, V. Monteiro, H. Goncalnas, J.L. Afonso, Onboard reconfigurable battery charger for electric vehicles with traction-to-auxiliary mode, IEEE Trans. Veh. Technol. 63 (30) (2014) 1104–1116.
[3] H.H. Eldeeb, S. Faddel, O.A. Mohammed, Multi-objective optimization technique for the operation of grid tied PV powered EV charging station, Elec. Power Syst. Res. 164 (2018) 201–211.
[4] N. Sujitha, S. Krithiga, Grid tied PV- electric vehicle battery charger using bidirectional converter, Int. J. Renew. Energy Res. 9 (4) (2019) 1873–1881.
[5] D. Van Der Meer, G.R. Chandra Mouli, G. Morales-Espana Mouli, L.R. Elizondo, P. Bauer, Energy management system with PV power forecast to optimally charge EVs at the workplace, IEEE Trans. Ind. Inf. 14 (2018) 311–520.
[6] Abdelhakim Belkaid, Ilhami Colak, Korhan Kayisi, Ramazan Bayindir, Design and implementation of a Cak converter controlled by a direct duty cycle INC-MPPT in PV battery system, Int. J. Smart Grid 3 (1) (2019) 19–25.
[7] W. Li, X. He, Review of non-isolated high step-up DC/DC converters in photovoltaic grid-connected applications, IEEE Trans. Ind. Electron. 58 (4) (2011) 1239–1250.
[8] P.S. Shenoy, M. Amaro, J. Morroni, D. Freeman, Comparison of a buck converter and a series capacitor buck converter for high-frequency, high-conversion-ratio voltage regulators, IEEE Trans. Power Electron. 31 (10) (2016) 7006–7015.
[9] M.R. Banaei, S.G. Sani, Analysis and implementation of a new SEPIC-based single switch buck-boost DC-DC converter with continuous input current, IEEE Trans. Power Electron. 33 (12) (2018) 10317–10325.
[10] G. Chu, H. Wen, L. Jiang, Y. Hu, X. Li, Bidirectional flyback based isolated-port submodule differential power processing optimizer for photovoltaic applications, Sol. Energy 158 (2017) 929–940.
[11] N. Sujitha, S. Krithiga, RES based EV battery charging system: a review, Renew. Sustain. Energy Rev. 75 (2017) 978–988.
[12] Y.-J. Lee, A. Khaligh, A. Emadi, A compensation technique for smooth transitions in a non-inverting buck-boost converter, IEEE Trans. Power Electron. 24 (6) (2009) 1002–1015.
[13] M. Hwu, T.J. Peng, A novel buck-boost converter combining boost and buck converters, IEEE Trans. Power Electron. 27 (5) (2012) 236–241.
[14] Y.-J. Lee, A. Khaligh, A. Chakraborty, A. Emadi, Digital combination of buck and boost converters to control a positive buck-boost converter and improve the output transients, IEEE Trans. Power Electron. 24 (5) (2009) 1267–1279.
[15] Vahid Samavatian, Radan Ahmad, A novel low-ripple interleaved buck-boost converter with high efficiency and low oscillation for fuel-cell applications, Elect. Power and Energy Systems 63 (2014) 446–454.
[16] J. Chiang, H.J. Shieh, M.C. Chen, M.R. Banaei, S.G. Sani, M.O. Badawy, Y. Sozer, A high efficiency non-isolated bidirectional DC-DC converter with zero-voltage-transition, Comput. Electr. Eng. 7 (2) (2018) 1659–1666.
[17] T. Arunkumari, V. Indragandhi, A novel single switch high step up DC-DC converter for PV based application, Int. J. Renew. Energy Resour. 8 (2) (2018) 1085–1097.
[18] T.-F. Wu, C.-H. Chang, Y.-H. Chen, A fuzzy-logic-controlled single-stage converter for PV-powered lighting system applications, IEEE Trans. Ind. Electron. 47 (2) (2000) 287–296.
[19] S. Krithiga, D.R.B.B. Jose, H.R. Upadya, N.A. Gounden, Grid-Tied photovoltaic array using power electronic converters with fuzzy logic controller for maximum power point tracking, Aust. J. Electr. Electron. Eng. 9 (4) (2012) 393–406.
[20] M. Shariief Islam, N. Mithilasaranthan, D. Qoew Hung, Coordinated EV charging for correlated EV and grid loads and PV output using a novel, correlated, probabilistic model, Int. J. Electr. Power Energy Syst. 104 (2019) 335–348.
[21] N. Ammasai Gounden, Sabitha Ann Peter, Himaja Nallandula, S. Krithiga, Fuzzy logic controller with MPPT using line-commutated inverter for three-phase grid-connected photovoltaic systems, Renew. Energy 34 (2009) 909–915.