© June 2026 | IJIRT | Volume 13 Issue 1 | ISSN: 2349-6002

Intelligent Controller for A Bi Directional Converter

Dineep S[1], Dr.SG Srivani[2]
[1,2]EEE Dept, RVCE, Bengaluru-560059

***Abstract*—The rapid proliferation of Electric Vehicles (EVs) has given rise to the need of highly efficient and smart power management system. The bidirectional DC-DC converters play an important role in managing power transfer between battery and DC bus in charging, discharging and regenerative braking. However, the traditional control approaches are generally insufficient to effectively manage varying dynamic operations, parameter variations, instantaneous load changes and fault situations to enhance efficiency, stability and reliability. A Digital Twin based control framework is adopted to provide real-time virtual copy of the physical converter system. Real-time synchronized communication of physical and virtual models helps in the real-time monitoring, forecasting, adaptive control, and fault detection. Integration of battery modeling, PWM control, regenerative braking and the converter behavior in both buck and boost operation modes are carried out in MATLAB/Simulink. The simulation results confirm the perfect tracking of the converter operation at different circumstances. Voltage regulation and dynamic response improvement, improved fault tolerance and higher energy efficiency over traditional controllers are observed.**

***Index Terms*—Digital Twin, Electric Vehicles, Bi-directional DC-DC Converter, Energy Management system, Regenerative Braking, Fault Detection, Predictive Maintenance, Real-Time Monitoring.**

I. INTRODUCTION

Due to rapid development of EVs and intelligent energy systems, the need for an efficient, reliable and intelligent power management system is increased. A critical role in all kinds of power electronic interfaces of EVs is played by bi-directional DC-DC converter enabling the bi-directional power flow from the battery and DC bus, during charging, discharging and regenerating braking operations. Although many controller approaches are used in convention converter control, such as PI, SMC and MPC, their performances are severely limited under nonlinear operating condition, parameter changing, abrupt load variations and failure condition etc. [1] [2]. The use of Digital Twin (DT) technology is being identified as a favorable option for the intelligent monitoring and control of power electronic systems. DT represents real-time virtual copy of a physical system which continuously interacts with its physical counterparts exchanging operating information. This enables real-time monitoring, prediction, optimization, fault diagnosis and adapt control of the system [3]. Numerous studies have confirmed the suitability of using DT for manufacturing, transportation, smart grid and power electronic systems that can improve system reliability, decrease maintenance cost and enhance performance [4] [5] [6]. As the integration of AI/ML, IoT and cloud with DT framework, it brings advanced prediction capability and intelligent decision to converter control [7] [8]. It has also been found that DT based converter system achieve better fault detection, prediction maintenance and adaptive control compared to conventional method [9]. For EV system, the DT technology is able to provide energy management, optimal control for regenerating braking, and real-time monitor of critical parameters such as V, I, T, SOC etc. [10] [11]. It also supports predictive maintenance by comparing the real-time operating data with virtual model prediction for abnormal phenomena [12]. The seamless synchronization between physical and virtual systems by sophisticated communication technology and embedded system makes the real-time control and operation optimize possible [13]. Furthermore, the recent work of HIL and virtual prototyping shows effective performance and control for the validation of the converter control strategy [14]. With inspiration from the above points, this work proposed a Digital Twin Based Controller for Bi-Directional DC-DC converter in EV applications aiming to enhance its efficiency, reliability, fault tolerance and energy management using real time monitoring, predictive analyzing and intelligent control.

II. LITERATURE SURVEY

Recent works by researchers on the power electronic converter intelligent controller and Electric Vehicle (EV) energy management system have been examined. Artificial Intelligence (AI), Machine Learning (ML) and Internet of Things (IoT) technologies have improved adaptive control, real-time monitoring and better decision-making processes [1]-[3]. Most of the recent work presented focuses on the bi-directional DC-DC converter which has an application in EV systems to charge, discharge battery and in regenerative braking [4], [5]. Controllers like PI, SMC, and MPC have been commonly utilized but cannot give satisfactory response under varying and nonlinear conditions or load change. Studies have shown that intelligent controller approaches achieve better dynamic response, efficiency, fault detection and reliability [6]-[9]. In some works, regenerative braking strategies and intelligent energy management strategies are used to optimize energy regeneration and battery usage [10], [11]. The application of communication on cloud, hardware in loop (HIL) and virtual prototyping for controller validation and verification is also observed in [12]-[14].

However, few works are available regarding the all-inclusive intelligent controller for bi-directional DC-DC converter used in EV systems. An intelligent controller is proposed in this work for Bi-Directional Converter for effective power management and control of the system. However, there are still few works for applying the total digital twin based intelligent controller on bidirectional DC-DC converter for EV energy management. So, this paper is proposed as a Digital Twin Based Controller that allows real time monitoring, adaptive control, predictive analyses and intelligent energy management to achieve high efficiency, robustness and fault-tolerant.

III. BLOCK DIAGRAM & METHODOLOGY

3.1. Block Diagram

Fig. 3.1 describes the proposed Intelligent Controller-Based Bi-Directional DC-DC Converter for the EV application. The whole system contains the input sources, bi-directional DC-DC converter, STM32 controller, sensing unit, battery, and intelligent control block. Voltage, current, and temperature sensors keep monitoring the parameters of the system and send feedback to the STM32 controller in real-time. Controller works based on the intelligent control strategy and closed-loop technique to make PWM signal for controlling the converter working in buck and boost modes.

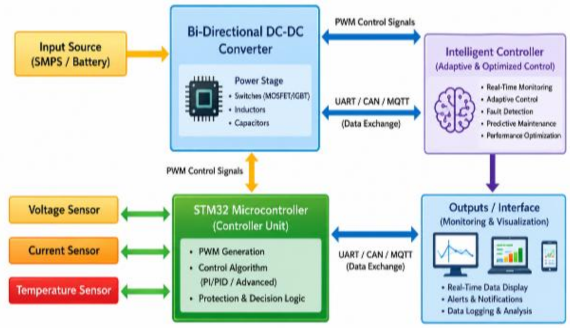

Fig. 3.1 Block Diagram of Intelligent Controller-Based Bi-Directional DC-DC Converter

Intelligent controller continuously monitors the converter operation, battery conditions and operating parameter to make the control adaptively and to detect faults and increase performance, efficiently and it will also enhance EV power system performance.

3.2. Methodology

The Intelligent Controller-Based Bi-Directional DC-DC Converter is designed and simulated as stated in the following points:

Fig.3.2 shows the workflow diagram of implementation for the Intelligent Controller-Based Bi-Directional DC-DC Converter. Start from the literature review and problem statement by reviewing existing studies and its limitations, after that design the converter topology and the system based on the specified requirement and an intelligent PWM-based closed loop controller system is design and programmed by using STM32 microcontroller. Based on a dynamic model of converter in Matlab/Simulink and test the performance in different operating modes and finally test and validate the system performance to enhance the efficiency, stable, reliability, and intelligent operation.

Step 1: System Analysis and Converter Design:

the EV energy management system is analyzed and converter parameters are design such as the operating voltage, current, switching frequency and also the battery parameters and operating condition. Bi-directional DC-DC converter is design to provide Buck operation to charge the battery from the source or Boost operation for the battery discharging for EV acceleration and also regenerative braking for EV braking condition.

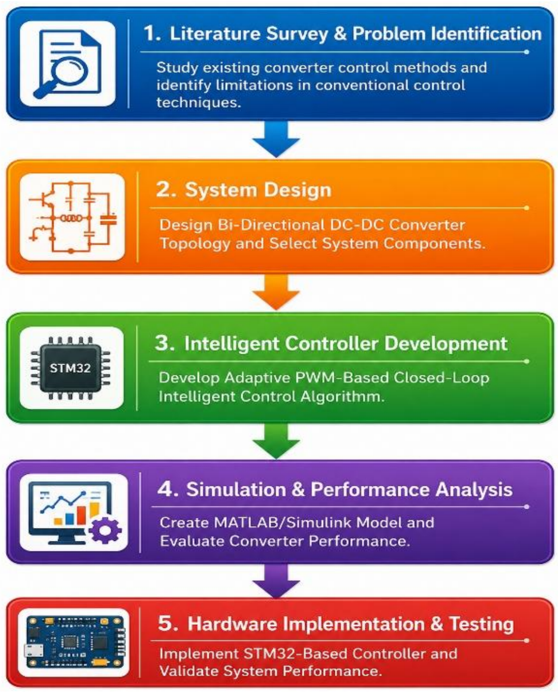

Fig. 3.2 Design Flow

Step 2: Control System Design:
a closed loop intelligent controller system is design to regulate the bi-directional power flow in the converter and keep stable the DC bus voltage by monitoring the battery State of Charge, battery terminal voltage and battery current for enhancing the efficiency by reducing the switching losses.

Step 3: Implementation of Intelligent Controller:
Intelligent Controller is designed in the STM32 microcontrollers, STM32 controller takes all sensed value and by calculating from controller algorithm to provide PWM duty ratio to control the MOSFET of the converter, and controller used Matlab/Simulink platform, it takes sensor data in real-time to optimize the converter, it makes the dynamic of controller more efficient and reliable and it detects abnormal behavior for EV management.

Step 4: Simulation and Performance Analysis:
The developed intelligent control system model for bi-directional DC-DC converter is simulated under several conditions for EV operation such as the buck mode, boost mode, regenerative braking condition, load variations and transient disturbance. Voltage regulation, current ripple and also transient performance of the converter are analyzed.

Step 5: Validation and Performance Evaluation: The designed controller is compared to the conventional control method in order to evaluate its performance. Efficiency, dynamic response, transient behavior, fault detecting and energy management characteristic of the proposed intelligent control strategy are evaluated.

IV. Mathematical Modelling of Digital Twin Based Bi-Directional DC-DC Converter

Mathematical Modelling

The mathematical model of the proposed Digital Twin-based bidirectional DC–DC converter is developed to analyze converter behavior, design the control system, and support real-time monitoring and prediction. The model describes the relationship between voltage, current, duty cycle, and power flow during charging and discharging operations in EV applications.

4.1. Battery Model

The battery supplies the major energy source of the system.

Battery Voltage Equation

$$V_{battery} = V_{oc} - I_{battery}R_{internal}$$

Buck Converter Output Voltage

$$V_o = D \times V_{in}$$

Inductor Current Equation

$$L\frac{di_L}{dt} = V_{in} - V_o$$

Boost Converter Output Voltage

$$V_o = \frac{V_{in}}{1 - D}$$

Boost Mode Inductor Equation

$$L\frac{di_L}{dt} = V_{in}$$

Duty Cycle Equation

$$D = \frac{T_{on}}{T}$$

Switching Frequency

$$f_s = \frac{1}{T}$$

Transfer function of PI controller.

$$G(s) = K_p + \frac{K_i}{s}$$

Error Signal

$$e(t) = V_{ref} - V_{actual}$$

Power Equation

$$P = VI$$

Converter Efficiency

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

Thermal Equation

$$T = T_{ambient} + P_{loss}R_{th}$$

State Space Representation

$$\dot{x}(t) = Ax(t) + Bu(t)$$

Output Equation

$$y(t) = Cx(t) + Du(t)$$

Clarke Transformation Equation

$$I_\alpha = I_a$$

$$I_\beta = \frac{1}{\sqrt{3}}(I_a + 2I_b)$$

Park Transformation Equation

$$I_d = I_\alpha \cos\,\theta + I_\beta \sin\,\theta$$

$$I_q = -I_\alpha \sin\,\theta + I_\beta \cos\,\theta$$

Regenerative Power Equation

$$P_{regen} = T\omega$$

4.2. System Design

MATLAB/Simulink was used for the simulation design of proposed Digital Twin Based Bi-Directional DC-DC Converter for EV Applications in which MATLAB/Simulink was used for simulation and Visual Studio Code (VS Code) was used for coding the simulation. The designed simulation model was used to investigate the bidirectional power flow, converter performance, battery charging/discharging, PMSM motor operation, ripple analyses, and Digital Twin monitoring under various operating conditions. The simulation environment allows a real-time monitoring scenario, fault analysis, performance optimization and dynamic validation of the converter system without having to implement the physical system.

4.2.1.Simulation Platform

The adequate development and validation of the designed Digital Twin Based Bi-Directional DC-DC Converter require usage of both simulation and control, and software development tool. The tools will help to build converter models, create control algorithm, implement Digital Twin and the monitoring of real time. MATLAB/Simulink has been adopted to build the system model and validation while Visual Studio Code has been employed to develop the Digital Twin platform and monitoring dashboard. Summary of the used simulation platform is listed in Table 4.1.

Table 4.1 Simulation Platform

Software Tool	Purpose
MATLAB/Simulink	Converter and motor simulation in MATLAB/Simulink
Embedded MATLAB Functions	Control algorithm implementation
MATLAB Scope & Analysis Tools	Ripple and performance analysis

4.2.2.Battery Simulation Model

The EV energy storage system was modeled with 24 V battery in MATLAB/Simulink.

The battery model is capable of: Charging operatio, Discharging operation, SOC estimation, Regenerative energy storage

The Digital Twin is continuously monitoring the battery voltage, current, and SOC during Simulation.

Table 4.2 Battery Parameters

Parameter	Values
Nominal Voltage	24 V
Battery Capacity	10 Ah
Internal Resistance	0.08 Ω
Initial SOC (Boost Mode)	85%
Initial SOC (Buck Mode)	35%

4.2.3.Bi-Directional Converter Simulation

The bi-directional converter was modeled by using MOSFET switches, inductors, capacitors and PWM control blocks.

Table 4.3 Bi-Directional Converter Parameters

Parameter	Value
Back EMF Constant	0.20 V/rad/s
Torque Constant	0.20 N.m/A
Stator Resistance	0.8 Ω
Stator Inductance	5 mH
Rotor Inertia	0.002 kg.m²
Pole Pairs	2

The Converter runs in:
Selects the Boost mode when the vehicle is being driven.
Buck mode during regenerative braking
The simulation evaluates: Voltage regulation, Current response, Converter efficient.

4.2.4.PMSM Motor Simulation

The PMSM motor model has been connected to the converter for the purpose of the EV drive simulation. It can also perform the below mentioned operations. Motoring operation, Torque analysis, Speed analysis, Regenerative braking, the motor model is integrated with both the converter as well as Digital Twin.

Table 4.4 PMSM Parameter

Parameter	Value
Inductance (L)	200 µH
Capacitance (C)	470 µF
Inductor ESR	0.05 Ω
Capacitor ESR	0.02 Ω
Switching Frequency	50 kH
Diode Voltage Drop	0.7 V

4.2.5.PWM Control Simulation

PWM control blocks were implemented to control MOSFET switching.
PWM Features: Variable duty cycle operation, High-frequency switching, Converter regulation, Ripple reduction

The PWM switching frequency used in simulation is:
$f_s = 50kHz$
PWM duty cycle varies dynamically according to: Load condition, Battery voltage, Reference voltage, Motor demand.

4.2.6.Digital Twin Simulation Design

The Digital Twin was developed using:
- MATLAB/Simulink
- VS Code

The Digital Twin is basically a virtual representation of the converter system and PMSM motor.
It is designed for the following tasks: Real-time monitoring, Dynamic analysis, Ripple analysis, Fault prediction, Converter efficiency estimation, Predictive maintenance, Performance optimization.
The Digital Twin continuously checks its actual values from the actual system and its virtual models for prediction and adaptation.

4.2.7.Dynamic Analysis and Validation

The designed model is tested at different operating conditions such as:
- Boost mode operation
- Buck mode operation
- Battery charging/discharging
- Regenerative braking
- Load variation
- Fault conditions

The following performance parameters were analysed:
- Converter efficiency
- Output voltage regulation
- Current response
- Torque response
- Battery SOC variation
- Dynamic stability

The analysis of the simulation results shows that the designed Digital Twin Based Converter system for EVs is efficient and it will perform as expected.

4.2.8.Torque Ripple Minimization Calculation

The torque ripple in the proposed Digital Twin Based Bi-Directional DC-DC Converter for EV Applications has been minimized using PWM switching operation, current ripple and by implementing closed loop PI control along with the Clarke and Park transformation. Digital Twin constantly monitors converter current, motor torque and switching characteristic.

Torque Ripple Factor (TRF)
The torque ripple factor is evaluated using:

$$TRF = \frac{T_{max} - T_{min}}{T_{avg}} \times 100\%$$

Where:
- T_{max}= Maximum torque
- T_{min}= Minimum torque
- T_{avg}= Average torque

The TRF parameter determines the electromagnetic torque variation. Low values of TRF leads to smooth torque, reduced vibration, lower acoustic noise, increased efficiency and improved accuracy of position.

Current Ripple Reduction

Torque Ripple factor is also dependent on the current ripple at the PMSM Motor. The inductor current ripple can be minimized using high switching frequency of the PWM signals and optimum values for the converter parameters.

Inductor Current Ripple

$$\Delta I_L = \frac{V_{in} D}{L f_s}$$

Where:

- ΔI_L= Inductor current ripple
- V_{in}= Input voltage
- D= Duty cycle
- L= Inductance
- f_s= Switching frequency

Increasing switching frequency and appropriate choice of inductor inductance will result in the reduction of current ripple to some extent.

V. SIMULATION AND ANALYSIS

An Intelligent Controller based bidirectional DC-DC converter combined with the PMSM drive was simulated in MATLAB/Simulink to analyze the performances in different electric vehicle (EV) operating conditions. Both boost mode (power delivery from battery to motor) and buck mode (power delivery from motor to battery (regenerative braking and battery charging)) were simulated.

The intelligent control strategy always tried to maintain steady and efficient system by controlling many parameters: output voltage, inductor current, battery SoC, electromagnetic torque, and power transfer (from/to battery). The converter was modeled to investigate the converter operations, ripple deduction ability, and dynamics and stability behavior under dynamic changing input voltage and load conditions. The controller was designed in such way that it adapts to the changes in input voltage, load demand, and regenerative energy flow, thus improves the performance of the converter. The simulation performances were tested using voltage regulation ability, transient response, converter efficiency, and power transfer ability.

5.1. Intelligent Controller Design

The intelligent controller is designed using the developed mathematical model of the bidirectional DC-DC converter. The intelligent controller supervises parameters such as output voltage, inductor current, duty cycle, power flow and ripple component of converter. Feedback signals are compared in real-time and the switching pulses to switches are generated. Through this type of control action, good voltage regulation, low ripple value, better dynamic performance and stability of converter can be achieved.

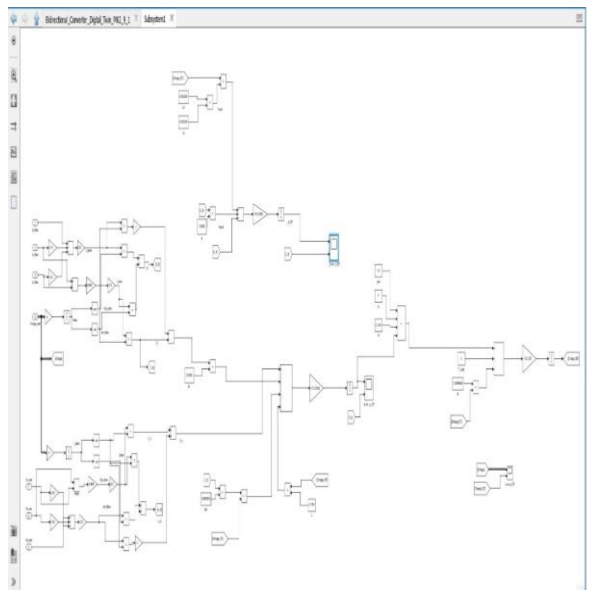

Fig. 5.1 Intelligent Control Architecture of the Bidirectional DC–DC Converter

5.2. Simulation Results at Load Side

Fig. 5.4 shows the load-side response of the conventional bidirectional DC-Dc converter integrated with the PMSM drive. The output gradually reaches steady state with small ripples and a relatively longer settling time. Although continuous power is supplied to the load, the absence of Digital Twin-based monitoring and adaptive control limits the dynamic performance. The simulation result shows that the performance is satisfactory and can be improved with faster dynamic response, less ripple and increased stability.

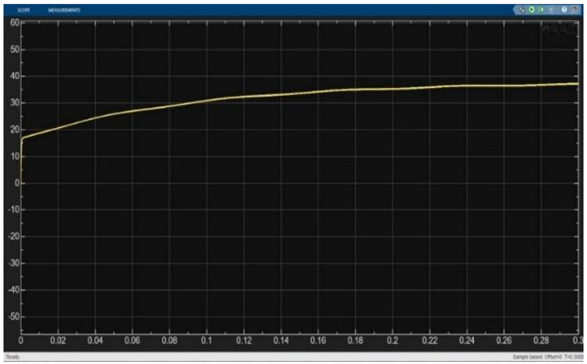

Fig. 5.4 Simulation results at load side.

5.3. Simulation Results at Battery Side

The simulation performance of battery side operation during the buck mode operation is shown in Fig. 5.5. The battery voltage shows very small ripple during charging period and the State of Charge (SoC) has steadily increased over the entire charging duration. From these two simulation results, it proves that battery can be charged steadily and the regenerative power can be transferred to the battery with well converter behavior in EV application.

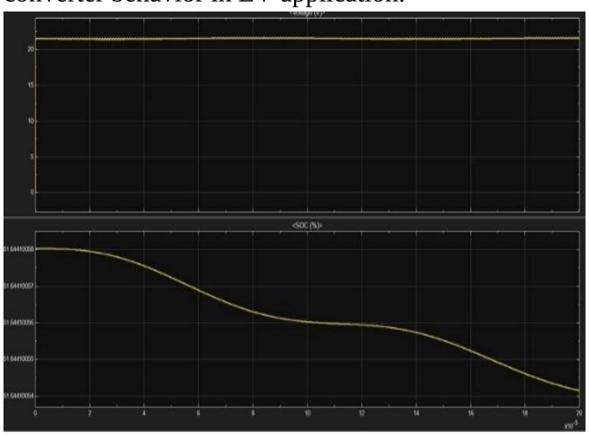

Fig. 5.5 Simulation results at Battery side

5.4. Mathematical Modelling and Digital Twin Validation

The developed Digital Twin based bidirectional DC-DC converter with the PMSM drive is modeled in MATLAB/Simulink to evaluate the converter dynamics and power flow and to determine the real-time estimation capability.

Boost Mode (Motoring Operation):

The battery voltage was stepped up during the motoring operation, so the battery voltage should increase in boost mode and it was represented in boost mode dynamics and it shows that the Digital Twin matches perfectly to the converter output voltage, inductor current and the torque produced by the motor. The converter has operated in CCM with the low voltage and current ripple so it shows a stable converter performance with high efficiency.

Buck Mode (Regenerative Braking):

During the regenerative braking process the power flow will be from the motor back to the battery and it can be verified from these two simulation results, the reverse power flow was detected and it can be noted that the conduction modes were changed and dynamic transient variations of voltage and current are shown. The ripple in the charging stage was increased. However, the behavior of the converter was well represented by the model.

The simulation results prove that the proposed intelligent controller can effectively control the bidirectional DC-DC converter. Voltage regulation, ripple elimination, fast dynamic response and steady performance with varying load were all realized with this controller, indicating its effectiveness for electric vehicle applications.

Fig. 5.6–5.8 illustrate the boost mode performance, buck mode performance, and overall system summary, respectively in the below Table 5.1.

Table 1: Simulation Results Summary

Parameter	Boost Mode (Motoring)	Buck Mode (Regeneration)
Operating Mode	PWSM Motoring	PWSG Generating
Input Voltage (V)	24 V	48 V
Output Voltage (V)	34.96 V	-25.08
Target Voltage (V)	36 V	24 V
Speed (RPM)	1432 RPM	2292 RPM
Converter Efficiency (%)	99.67 %	99.90 %
Battery SoC Initial (%)	85 %	35 %
Battery SoC Final (%)	85 %	35 %
Current Ripple / DT Error (RMS)	0.2751 A	102.2230 A
Voltage Ripple / DT Error (RMS)	0.0948 V	83.0203 V

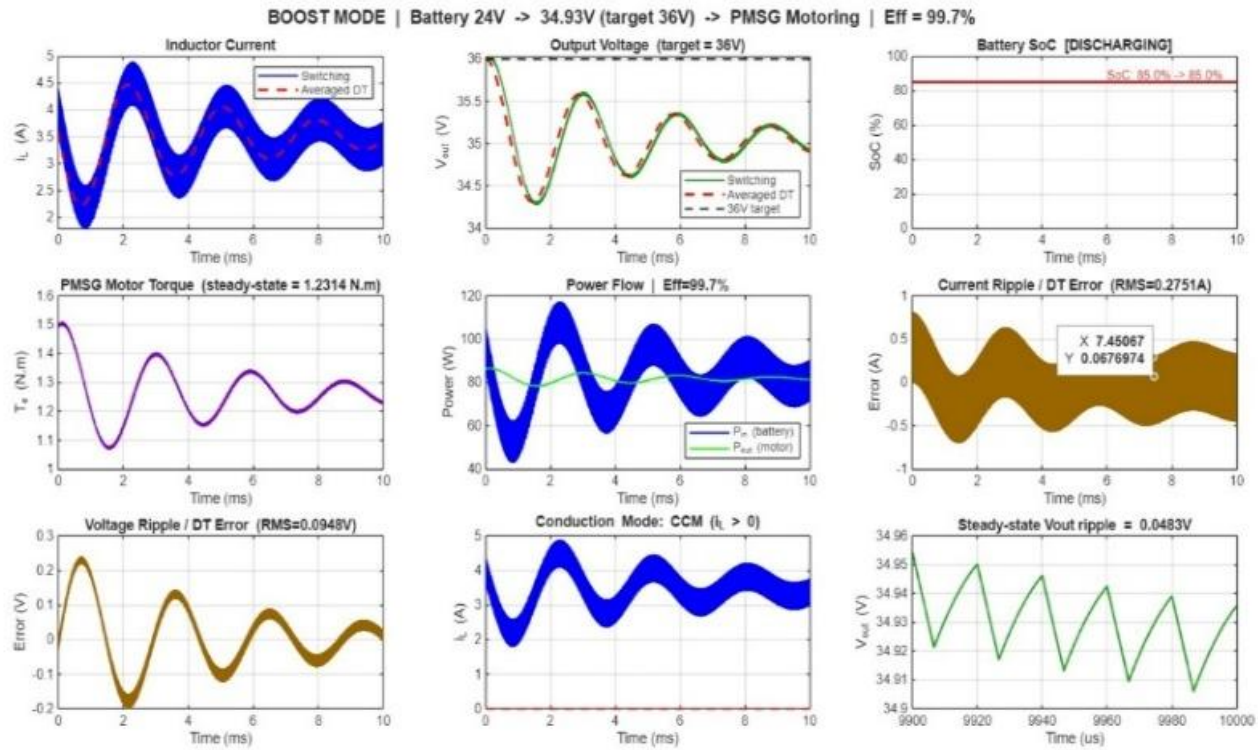

Fig. 5.6 Simulation Results of Mathematical modelling during Boost Mode

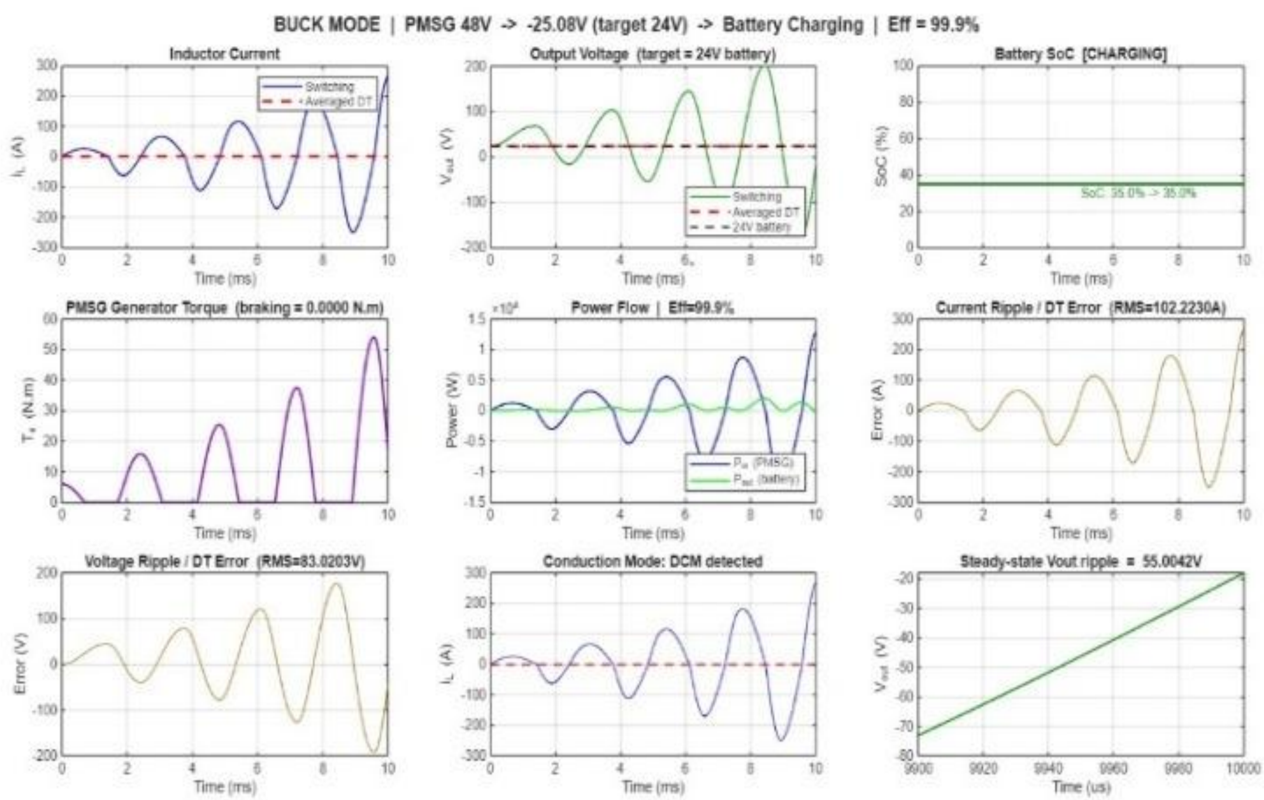

Fig. 5.7 Simulation Results of Mathematical modelling during Buck Mode

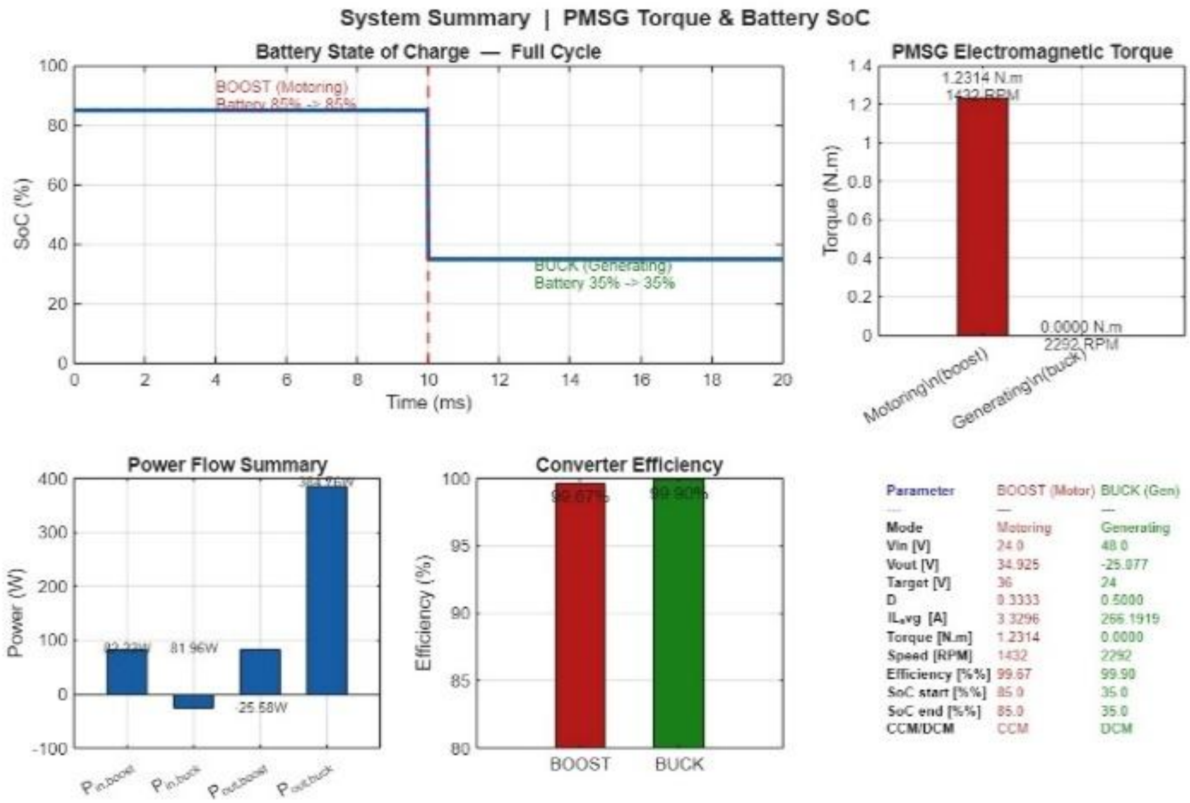

Fig. 5.8 System Summy

VI. CONCLUSION

The results from the simulation indicate that the proposed intelligent controller-based bidirectional DC-DC converter can meet efficient and reliable requirements for electric vehicle application. It can efficiently control output voltage and current of the converter and stable operating during both motoring and regeneration braking processes. Lower output ripple and better dynamic performance, precise power flow and better energy transfer characteristics were found compared with the other traditional control strategies.

In addition, the controller based on MATLAB/Simulink also showed its adaptive performance during various operating condition and load variation to keep converter stable and efficient. According to the simulation results, the intelligent control strategy is suitable for modern electric vehicle energy management systems and contribute to the improvements in power electronic control, system stability and vehicle performance.

REFERENCES

[1] S. Kouro, M. Malinowski, K. Gopakumar, J. Pou, L. G. Franquelo, B. Wu, J. Rodriguez, M. A. Perez, and J. I. Leon, "Recent Advances and Industrial Applications of Multilevel Converters," *IEEE Trans. Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, 2010.

[2] J. Rodriguez, M. P. Kazmierkowski, J. R. Espinoza, P. Zanchetta, H. Abu-Rub, H. A. Young, and C. A. Rojas, "State of the Art of Finite Control Set Model Predictive Control in Power Electronics," IEEE Trans. Ind. Informatics, vol. 9, no. 2, pp. 1003–1016, 2013.

[3] H. Komurcugil, S. Biricik, and N. Bayhan, "Sliding Mode Control: Theory and Applications in Power Electronics," IEEE Access, vol. 8, pp. 199682–199693, 2020.

[4] S. Li and C. C. Mi, "Wireless Power Transfer for Electric Vehicle Applications," IEEE J. Emerg. Sel. Topics Power Electron., vol. 3, no. 1, pp. 4–17, 2015.

[5] M. Yilmaz and P. T. Krein, “Review of Battery Charger Topologies, Charging Power Levels and Infrastructure for Plug-In Electric and Hybrid Vehicles,” IEEE Trans. Power Electron., vol. 28, no. 5, pp. 2151–2169, 2013.
[6] A. Khaligh and Z. Li, “Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid Electric Vehicles: State of the Art,” IEEE Trans. Veh. Technol., vol. 59, no. 6, pp. 2806–2814, 2010.
[7] B. K. Bose, “Artificial Intelligence Techniques in Smart Grid and Renewable Energy Systems—Some Example Applications,” Proc. IEEE, vol. 105, no. 11, pp. 2262–2273, 2017.
[8] A. M. Howlader, N. Urasaki, A. Yona, T. Senjyu, and A. Y. Saber, “A Review of Intelligent Control Strategies for Electric Vehicle Applications,” IEEE Access, vol. 9, pp. 139590–139607, 2021.
[9] A. Sharma, Design, Analysis and Implementation of Bidirectional DC–DC Converter, Ph.D. dissertation, Dept. Elect. Eng., Indian Institute of Technology Delhi, New Delhi, India, Jul. 2022.
[10] A. Kalra, S. Sarkar, and N. Sagar, “Design and Simulation of DC Microgrid with DC–DC Bi-Directional Converter,” Int. Res. J. Eng. Technol. (IRJET), vol. 9, no. 7, pp. 2452–2457, Jul. 2022.
[11] D. Ravi, B. M. Reddy, S. L. Shimi, and P. Samuel, “Bidirectional DC to DC Converters: An Overview of Various Topologies, Switching Schemes and Control Techniques,” Int. J. Eng. Technol., vol. 7, no. 4.5, pp. 360–365, 2018.
[12] R. Gebreil, T. Elferjani, S. Borghed, A. Hammoda, M. T. Elrais, M. Albarassi, and R. Elzwawi, “Practical and Simulation Implementation of Bi-Directional DC/DC Converter Controlled by Arduino Using MATLAB-SIMULINK,” 2023.
[13] S. Manjare, S. Saraf, and C. Rajeshwari, “Design and Control of Bidirectional Converter for EV Application,” in Proc. IEEE Renewable Energy and Sustainable E-Mobility Conf. (RESEM), 2023.
[14] D. Raveendhra, P. Ridwanulzaman, and K. Govind, “FPGA Controlled High Gain Bi-Directional DC–DC Converter (BDC) for Energy Storage of Solar Power,” 2023.