PERFORMANCE ANALYSIS OF PI AND FUZZY LOGIC CONTROLLED BIDIRECTIONAL DC-DC CONVERTER WITH DUAL-BATTERY STORAGE FOR HYBRID ELECTRIC VEHICLES

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ABSTRACT

Hybrid Electric Vehicles (HEVs) demand highly efficient and reliable power electronic interfaces to manage multiple energy storage systems and ensure stable operation under various driving conditions. In this work, a bidirectional DC-DC converter interfacing a dual-battery energy storage system is designed and simulated for HEV applications. The proposed topology employs two batteries with different voltage levels (96 V and 48 V) and enables controlled power flow in both motoring and regenerative braking modes. A comparative performance evaluation is carried out between a conventional PI controller and a Fuzzy Logic Controller (FLC) for regulating the converter. The simulation is implemented in MATLAB/Simulink, and the results demonstrate that while the PI controller ensures basic voltage regulation, the FLC achieves faster settling time, improved DC-link voltage stability, and better dynamic response under varying load conditions. The results confirm that FLC-based control enhances overall system efficiency and reliability, making it a more suitable choice for modern hybrid electric vehicle powertrains.

Key Words: Bidirectional dc/dc converter (BDC), dual battery storage, hybrid electric vehicle, PI Controller, Fuzzy Logic Controller.

1. INTRODUCTION

In recent years, the global automotive sector has witnessed a paradigm shift toward sustainable and environmentally friendly transportation technologies. The continuous rise in fossil fuel consumption, rapid urbanization, and growing concerns about greenhouse gas emissions have motivated researchers and industries to focus on Hybrid Electric Vehicles (HEVs) and Electric

Vehicles (EVs) as a promising alternative to conventional Internal Combustion Engine (ICE)-based automobiles. According to various international climate agreements, such as the Kyoto Protocol and the Paris Agreement, strict regulations are being imposed worldwide to reduce carbon emissions and promote clean energy-based mobility solutions. In this context, HEVs present an optimal compromise between conventional fuel-driven vehicles and pure electric vehicles by integrating the benefits of both technologies [3]. HEVs typically employ multiple energy sources, usually a combination of an ICE and electrical storage devices, to optimize fuel efficiency, reduce emissions, and improve overall driving performance. A key challenge in these systems is the efficient management of power flow between different energy storage elements and the traction motor under various operating conditions such as acceleration, cruising, and regenerative braking. In order to address these challenges, **bidirectional DC-DC converters** have become indispensable in HEV powertrains. These converters ensure controlled energy exchange between high-voltage and low-voltage buses, enabling smooth motoring as well as efficient energy recovery during regenerative braking [1] .Among different power management approaches, the use of a **dual-battery energy storage system** has gained significant attention. Unlike single-battery architectures, dual-battery systems can provide enhanced flexibility in distributing power between a main high-voltage battery (e.g., 96 V) and an auxiliary low-voltage battery (e.g., 48 V). Such configurations allow efficient load sharing, improved system reliability, and extended battery life by reducing stress on a single unit. Furthermore, dual-battery systems enhance vehicle performance by enabling the storage of excess regenerative energy and supplying additional power during high-demand conditions such as hill climbing and rapid acceleration [4].

However, achieving reliable power transfer and stable voltage regulation in a dual-battery bidirectional DC-DC converter requires robust control techniques. Conventional **Proportional-Integral (PI) controllers** have been widely used in such applications due to their simplicity and ease of implementation. Nevertheless, PI controllers exhibit certain limitations such as slower dynamic response, sensitivity to parameter variations, and difficulty in handling nonlinear operating conditions commonly encountered in HEVs. To overcome these challenges, **Fuzzy Logic Controllers (FLCs)** have been introduced as an advanced control alternative. Unlike PI controllers, FLCs are knowledge-based and rule-driven, capable of handling system nonlinearities and uncertainties without requiring an accurate mathematical model. This makes them particularly suitable for complex energy management scenarios in HEVs.

Several studies have highlighted the potential of FLCs in improving the dynamic performance of DC-DC converters in renewable energy and vehicular systems. FLCs offer advantages such as faster response, reduced overshoot, improved voltage stability, and robustness against disturbances compared to conventional PI controllers. In the context of HEVs, integrating FLCs into bidirectional DC-DC converters can result in improved powertrain efficiency, smoother transition between operating modes, and enhanced driving comfort [2].

In this work, a bidirectional DC-DC converter interfaced with dual-battery energy storage for a hybrid electric vehicle is designed and analyzed. The proposed system is modeled and simulated using MATLAB/Simulink, considering two main operating modes: motoring mode (where energy flows from the batteries to the motor) and regenerative braking mode (where kinetic energy is converted back into stored electrical energy). The performance of the converter is investigated under both PI and FLC control schemes. Comparative results are presented in terms of DC-link voltage stability, battery charging/discharging profiles, torque-speed characteristics of the induction motor, and dynamic response of the system.

The primary contributions of this study can be summarized as follows:

1. Development of a dual-battery bidirectional DC-DC converter model suitable for HEV applications.
2. Implementation of PI and Fuzzy Logic Controllers to regulate the converter and manage energy flow under different driving conditions.
3. Simulation-based performance evaluation highlighting the advantages of FLC over conventional PI control.
4. Demonstration of improved system stability, faster settling time, and better voltage regulation with FLC control.

This research aims to provide insights into the design and control of advanced bidirectional DC-DC converters for HEVs, ultimately contributing toward the realization of more efficient, reliable, and environmentally sustainable vehicular technologies.A concern has been developed all over the world because of rise in global warming as well as rise in pollution. There is a need to look for alternatives because of various reasons like increasing rates of fuel, increased dependency over conventional fuel and change in driving trends. Normal climate meetings have been held everywhere in the world, along with the most prominent, i.e. The Kyoto Protocol discusses major concerns related to environmental impacts due to global warming and industrial and automobile pollution. There are various regulations to be imposed by governments to reduce the impact of reducing the emission of toxic gases like carbon dioxide and other lead replacements due to the combustion of fuel for automotive applications. In this study, the recent and future possible trends are also discussed about Hybrid Electric Vehicle Industry. [1]Depletion of conventional resources, rise in price of oil and rise in carbon emission are the major concern in the present world. These concerns are especially faced in developing nations like India because of growing cities, rapid economic developments and increasing traffic. Among all these reasons of concern, power grids and ICE vehicles are the major source of carbon emission. All such concerns increase the motivation for using Electric vehicles in transportation. This change will help in making our planet greener and cleaner environment. [2]

2. BIDIRECTIONAL DC TO DC CONVERTER

The Bidirectional DC/DC converter feature consists of interfacing with the DB bus of the driving inverter with dual-battery energy storage.

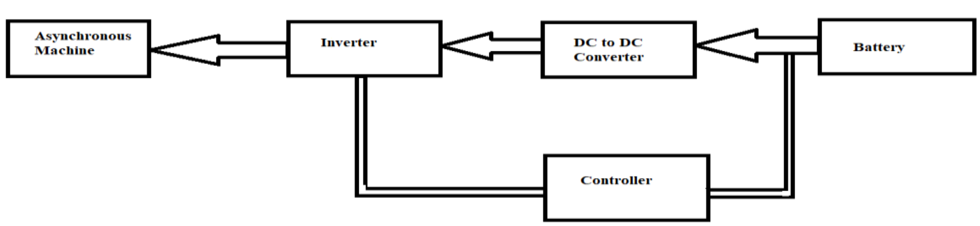

Figure 1 Block Diagram of DC to DC Convertor

2.1 Battery

Energy storage systems, usual batteries, are essential for hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (EVs). The subtype of hybrid vehicles is the plug-in hybrid electric vehicle (PHEV). The hybrid is typically a general electric (parallel or serial) fuel hybrid with additional storage space, usually by a lithium-ion battery that allows the car to travel a distance based on the size of the battery and its mechanical configuration in all-electric mode (series or parallel). At the end of the trip, it could be connected with the power supply to stop charging using the internal combustion engine aboard. Although electric vehicles use less fuel than regular cars, the harm to the atmosphere caused by the hybrid car battery still remains a concern. Today the majority of hybrid automotive batteries are of one kind: 1) nickel-metal hydride; or 2) lithium-ion; all are known to have an environmental effect relative to lead batteries, the bulk of which today form the starting battery or petrol vehicle. Many kinds of batteries are available. There are some that are much toxic. Of the two alluded to above, lithium-ion is the least dangerous.

2.2 Bidirectional DC to DC Converter

For many power-related systems, including hybrid cars, fuel cell vehicles, renewable energies, and so on, the two-way dc-dc converter with energy storage has become a promising choice. It decreases costs and increases productivity, as well as boosts device performance. An auxiliary power storage battery consumes regenerated electricity from the electrical machine during electric vehicle applications. In addition, two-way dc-dc converters are often required to remove power from the auxiliary battery to raise the high-voltage bus during the starting, accelerating, and climbing of the car. The two-directional DC-DC converters are used to perform power transfers from two dc power supplies in either direction by means of their ability to reverse the flow direction and hence power.

3. METHODOLOGY

3.1 Fuzzy Controller

Regulation of logic fuzzy relies largely on the laws of language variables. Unlike other approaches, Fuzzy logic control is free of complex numbers. The model is only tracked using basic mathematical equations. It offers good performance in a control scheme despite relying on simple mathematical analysis. This approach is, therefore, one of the better and much easiest methods for managing a plant.

Logic control Fuzzy is based on the principle of the Fuzzy series. In the theory of fuzzy, each element is associated with a certain extent of association. We may say that fuzzy sets, without finer borders, are like classic sets. When accuracy is mild, and the plant is devoid of sophisticated mathematical analysis, the Fuzzy Logic Controller (FLC) is used most.

The three main components of a Fuzzy Logic controller are

- Fuzzification
- Fuzzy Rule base and interfacing engine
- Defuzzification.

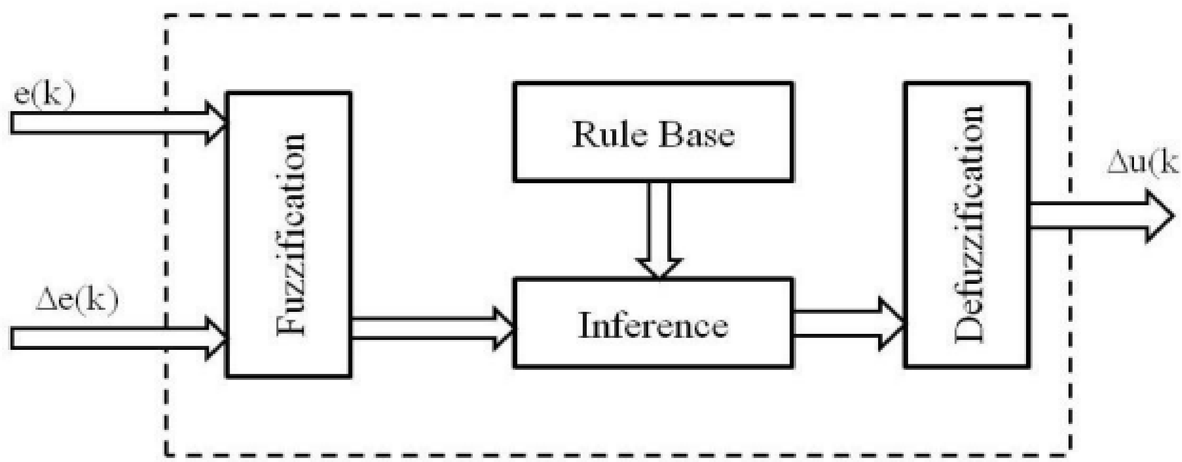

Figure 2 Internal Block Diagram of Fuzzy Control

3.2 Mandani Method

The most widely used approach is Mamdani's Fuzzy interface techniques. The control method was one of the first to use fuzzy set theory. This technique is supposed to conclude the pressure of the output component. Instead of the number of tedious sets, it is easier to use a single membership feature for a linguistic variable. This technique is called the single-lingual performance mechanism for using one single linguistic element. It improves the deflation mechanism because it makes the measurement necessary for the more general Mamdani procedure, which finds the core of the two-dimensional functions much easier. But any inference method with a linear or constant function of the output component can be used in the Sugeno form of inference.

The bidirectional dc-dc converter can be used in clean energy applications to integrate various energy sources with multi-inputs—a domestic system based on fuel cells. The bidirectional multi-input dc-dc converter is the origin of power supplies, storage components, and power control. This two-way dc-dc converter provides galvanic separation between the charge and the fuel cell, two-way flow of power, the ability to suit varying voltage levels, and fast response to the transient load requirement.

For step-up and step-down of voltage, the bidirectional DC-DC converter is used. Charging and unloading into one circuit topology can then be integrated. Isolated converters are used for the program where the output must be completely isolated from the input. Full bridge topology is used for high power applications. The most common bidirectional dc-dc converter is isolated [21-28]. Recently, however, several topologies have not been separated. Owing to their basic form and a limited number of elements, these architectures gain the interest of many researchers. The remainder was discussed and evaluated for soft-switching on topologies derived for bidirectional DC-DC converters. [9]

3.3 Advantages of Fuzzy Control

It has some benefits that make the other controllers superior. The following are:

- Very easy to explain since the regulation principle is very clear.
- It possesses a human intuition that empowers it to respond to control problems.
- Even with vivid inputs, it can work well.
- Multiple inputs can be used, and multiple outputs are given, as they are operating on the basis of rules only. It is better to build a rule foundation for fuzzy control than to refine the PID control parameters.
- If a sensor ceases functioning, it can be configured for secure shut-down rather than continuing to work, which can be unsafe for the facility.
- Complex math analysis is not, however, built very quickly.

- It needs no high-precision sensors, so it makes it very cost-efficient by using intuitive power, which makes this method very economical.
- Even in extremely non-linear environments, it performs very well to conform to the scenario. However, it is very difficult to develop such traditional controllers to conform to non-linear functionality.
- Very concise user interface. Easier understanding by end-users as the end-user is not an authority.
- Easy to compute. Extensive toolboxes and advanced dedicated programs.
- Ambiguousness. The logic of fugitive is a "natural system in which unknown knowledge is conveyed. The instruments are available for the fluid logic help to infer various acts based on the probable or required condition of those plants.

4. SIMULATION RESULT & DISCUSSION

DC voltage sources and electric loads were substituted for the main energy storage and the auxiliary energy storage. The system developed in this study included two loads for the high-voltage dc-bus energy-regenerating mode and two sources for the low-voltage dual-source-powering mode.

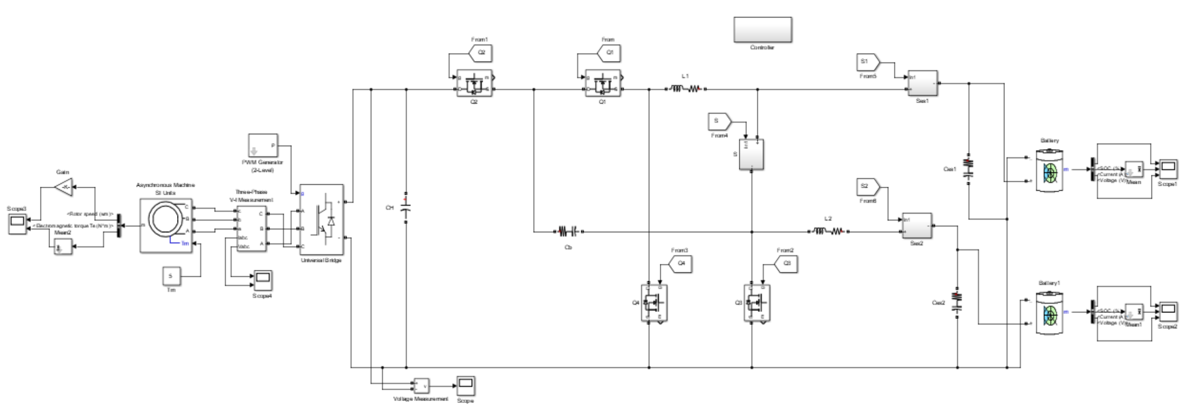

Figure 4: Proposed bidirectional converter

In the above proposed converter there are three bidirectional switches and four MOSFETs for changing the mode of operation of the circuit. The modes are changed with respect to the state of the charge of the battery and the induction machine operation (motoring mode or generator mode).

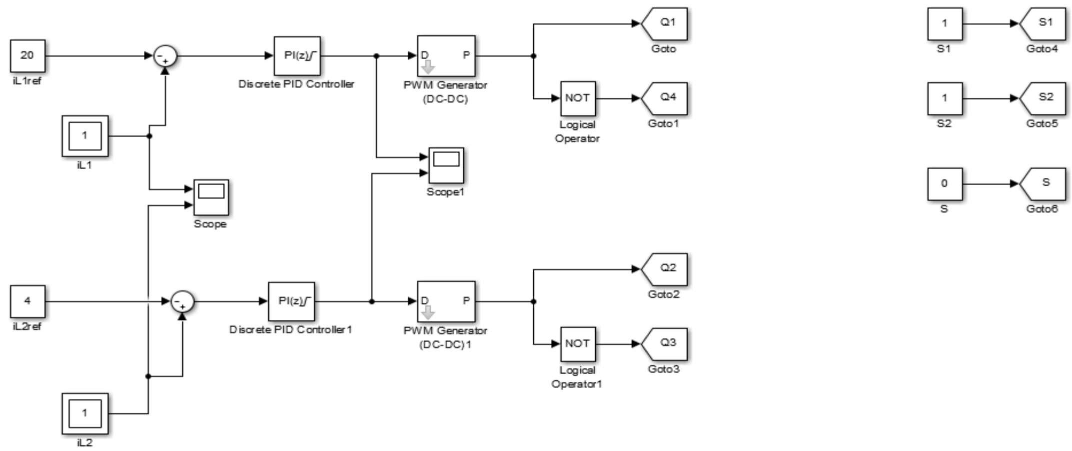

Figure 5: Proposed control srtucture

The above is the controller in mode A for operating swithces Q1 Q2 Q3 and Q4. In mode A the swithces S1 and S2 are ON and S is in OFF states. The swithces Q1 Q4 and Q2 Q3 are complimetary switches which operate alternatively. The duty ratio is generated by PI controller with comprison of reference value with measured value. The below are the operating characteritics graphs of the devices during all modes.

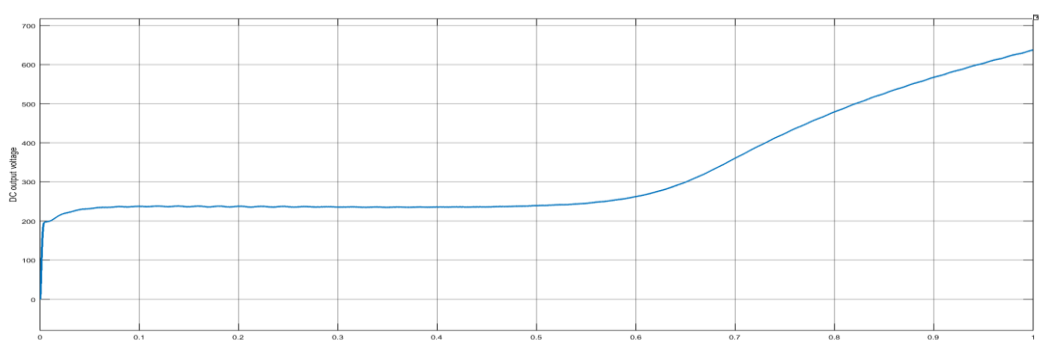

Figure 6 DC terminal voltage of the converter in mode A

The DC terminal voltage is variable with respect to change in induction motor torque and speed charateristics which needs to be fixed which will be updated in further update of the controller.

The below are the phase voltages and currents of the induction machine in motoring mode A.

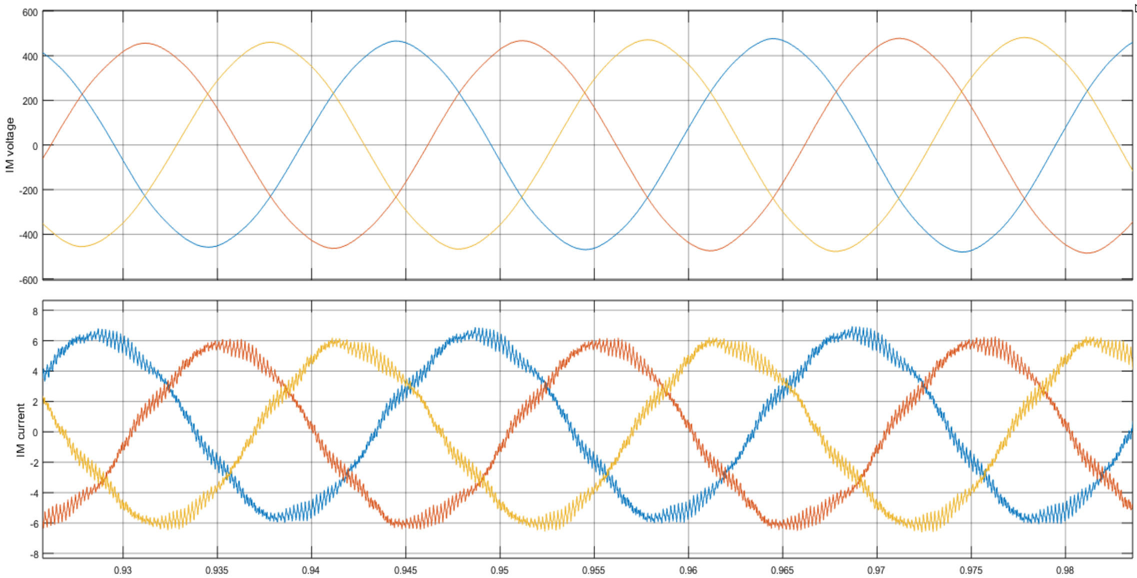

Figure 7 Voltage and current of IM in motoring mode

The below are the Speed and Torque of the induction machine in motoring mode A.

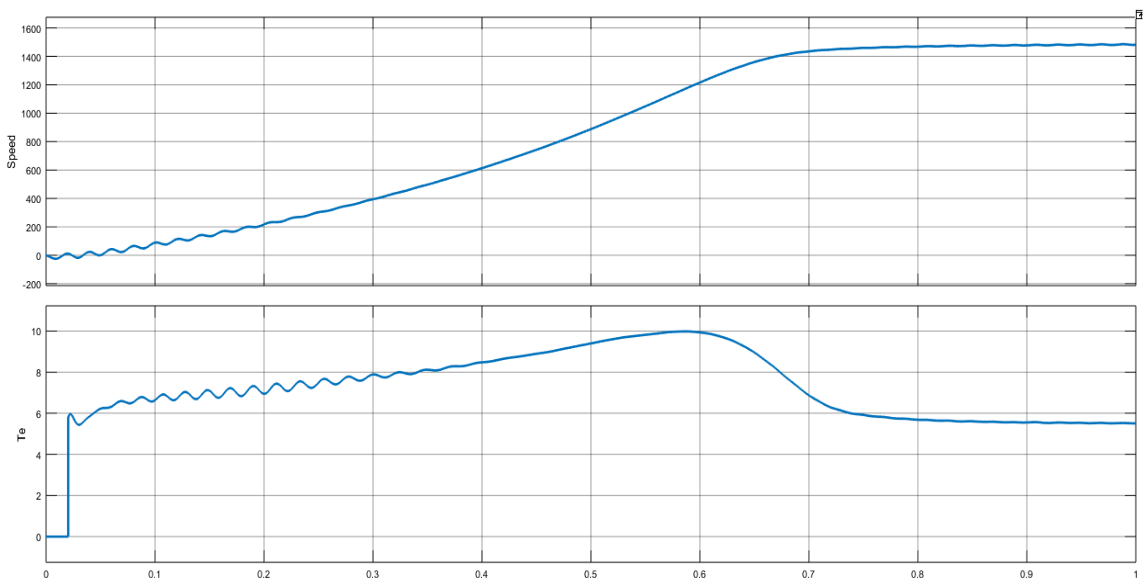

Figure 8 Speed and Te of IM in motoring mode

The above are the speed and torque charateristics of the induction mahcine operating in mode A. The speed in Mode A is continously increasing. And at first, the value of torque increases rapidly and after reaching the value 0.6, it starts decreasing.

4.1 Speed and Torque characteristic of IM in regenerative braking mode in Mode B

The graph shown below indicates the value of speed and torque characterstic in Mode B. In this regenerative braking mode, both speed and torque characteristics are decreasing. The above are the charatericstics of the induction machine in regenerative breaking mode.

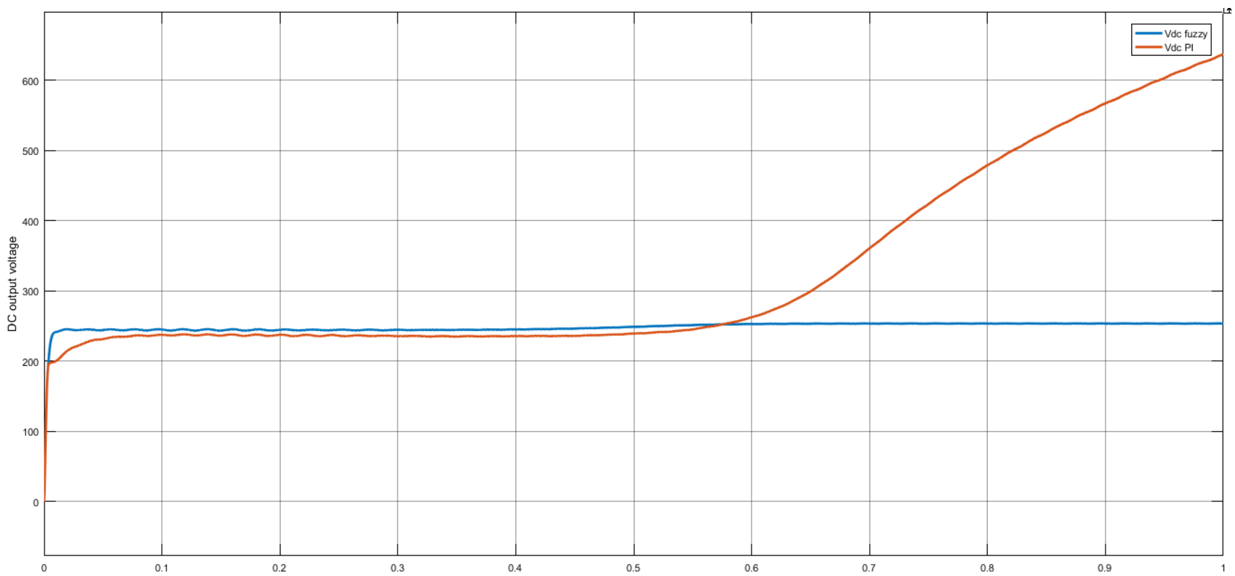

Figure 9 DC link voltage comparison of the converter during mode A

5. CONCLUSION

This study presented the design, modeling, and simulation of a **bidirectional DC-DC converter with dual-battery energy storage** for hybrid electric vehicle applications. The system employed two batteries of different voltage levels (96 V and 48 V) to ensure flexible energy management during motoring and regenerative braking modes. A comparative analysis between a conventional PI controller and a Fuzzy Logic Controller (FLC) was carried out to evaluate their performance in regulating the converter and maintaining system stability.

The simulation results demonstrated that both controllers were capable of regulating the DC-link voltage and managing the charging/discharging operation of the dual-battery system. However, the FLC-based approach provided significant improvements over the PI controller. Specifically, the FLC achieved **faster settling time, reduced voltage fluctuations, and better torque–speed response of the induction motor**. Moreover, the DC-link voltage remained more stable under FLC control, even during sudden load variations, highlighting its robustness in handling nonlinear operating conditions.

The outcomes confirm that the use of a Fuzzy Logic Controller enhances the efficiency, reliability, and dynamic performance of bidirectional converters in HEVs. By enabling smoother transitions between operating modes and optimizing the utilization of stored energy, the proposed system contributes toward higher fuel economy and reduced emissions in hybrid vehicles.

REFERENCES

[1] S. Sonar, "DC-DC Converter used for Series-Parallel Hybrid Electric Vehicle," Int. J. Recent Technol. Eng., vol. 8, no. 5, pp. 1661–1666, 2020, doi: 10.35940/ijrte.e6190.018520.

[2] K. Sowmya, M. T. Student, and K. S. R. Kumar, "A Review on Bidirectional Isolated DC-DC converter In Electric Vehicle," vol. 5, no. 6, pp. 826–833, 2017.

[3] S. Chakraborty, H. N. Vu, M. M. Hasan, D. D. Tran, M. El Baghdadi, and O. Hegazy, "DC-DC converter topologies for electric vehicles, plug-in hybrid electric vehicles and fast charging stations: State of the art and future trends," Energies, vol. 12, no. 8, 2019, doi: 10.3390/en12081569.

[4] O. Hegazy, J. van Mierlo, and P. Lataire, "Control and analysis of an integrated bidirectional DC/AC AND DC/DC converters for plug-in hybrid electric vehicle applications," J. Power Electron., vol. 11, no. 4, pp. 408–417, 2011, doi: 10.6113/JPE.2011.11.4.408.

[5] Q. Zhang, W. Deng, S. Zhang, and J. Wu, "A Rule Based Energy Management System of Experimental Battery/Supercapacitor Hybrid Energy Storage System for Electric Vehicles," J. Control Sci. Eng., vol. 2016, pp. 18–20, 2016, doi: 10.1155/2016/6828269.

[6] P. Pany, R. Singh, and R. Tripathi, "Bidirectional DC-DC converter fed drive for electric vehicle system," Int. J. Eng. Sci. Technol., vol. 3, no. 3, pp. 101–110, 2011, doi: 10.4314/ijest.v3i3.68426.

[7] T. Sai Teja, M. D. Yaseen, and T. Anilkumar, "Bidirectional Dc to Dc converter with ann controller for hybrid electric vehicle," Int. J. Innov. Technol. Explor. Eng., vol. 8, no. 12, pp. 4446–4453, 2019, doi: 10.35940/ijitee.L3497.1081219.

[8] F. Maloberti and A. C. Davies, A short history of circuits and systems. 2016.

[9] S. Gargies, "Isolated Bidirectional DC-DC Converter for Hybrid Electric Vehicle Applications," Security, pp. 1–8, 2006.

[10] J. Everts, Modeling and Optimization of Bidirectional Dual Active Bridge AC–DC Converter Topologies, no. April. 2014.

[11] R. Navaneethan, R. Illango, and V. Prabaharan, "Design and control for Bidirectional AC-DC Converters for Plug-in Hybrid Electric Vehicle," Int. J. Eng. Appl. Sci., vol. 2, no. 5, p. 257935, 2015.

[12] A. Kumar and P. Gaur, "Operation of DC/DC Converter for Hybrid Electric Vehicle," Int. J. Electron. Electr. Eng., vol. 7, no. 4, pp. 335–340, 2014.

[13] B. Zhao, Q. Song, W. Liu, and Y. Sun, "Overview of dual-active-bridge isolated bidirectional DC-DC converter for high-frequency-link power-conversion system," IEEE Trans. Power Electron., vol. 29, no. 8, pp. 4091–4106, 2014, doi: 10.1109/TPEL.2013.2289913.

[14] F. Z. Peng, H. Li, G. J. Su, and J. S. Lawler, "A new ZVS bidirectional DC-DC converter for fuel cell and battery application," IEEE Trans. Power Electron., vol. 19, no. 1, pp. 54–65, 2004, doi: 10.1109/TPEL.2003.820550.

[15] R. R. de Melo, F. L. Tofoli, S. Daher, and F. L. M. Antunes, "Interleaved bidirectional DC–DC converter for electric vehicle applications based on multiple energy storage devices," Electr. Eng., 2020, doi: 10.1007/s00202-020-01009-3.

[16] S. Devi Vidhya and M. Balaji, "Hybrid fuzzy PI controlled multi-input DC/DC converter for electric vehicle application," Automatika, vol. 61, no. 1, pp. 79–91, 2020, doi: 10.1080/00051144.2019.1684038.

[17] S. Antony and A. R. Rajitha, "A NOVEL NON-ISOLATED BIDIRECTIONAL DC-DC CONVERTER WITH V2G CAPABILITY," no. 07, pp. 1509–1523, 2020.

[18] I. Jagadeesh and V. Indragandhi, “Review and comparative analysis on dc-dc converters used in electric vehicle applications,” IOP Conf. Ser. Mater. Sci. Eng., vol. 623, no. 1, 2019, doi: 10.1088/1757-899X/623/1/012005.