COMPARATIVE REVIEW OF CONTROL STRATEGIES FOR DUAL-BATTERY BIDIRECTIONAL DC–DC CONVERTERS IN HYBRID ELECTRIC VEHICLE SYSTEMS

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ABSTRACT

The growing demand for sustainable and energy-efficient transportation has accelerated research on advanced power electronic interfaces for Hybrid Electric Vehicles (HEVs). Among these, bidirectional DC–DC converters with dual-battery energy storage systems have emerged as a promising solution for efficient power flow management during both motoring and regenerative braking operations. This review paper presents a comprehensive study of existing bidirectional converter topologies and control strategies, with particular emphasis on the dual-battery configuration proposed and The performance of conventional PI controllers, as widely reported in the literature, is compared with advanced control schemes such as Fuzzy Logic Control (FLC), highlighting their advantages in terms of dynamic response, voltage stability, and robustness against nonlinearities. Simulation results based on MATLAB/Simulink are also considered to provide a comparative perspective between PI and FLC control approaches. The review establishes that while PI controllers ensure basic regulation, FLC offers superior performance with reduced settling time and improved system efficiency. Finally, key research gaps, emerging control methodologies, and future directions for enhancing dual-battery bidirectional converter performance in HEVs are discussed.

Keywords: Hybrid Electric Vehicle, Bidirectional DC–DC Converter, Dual-Battery Energy Storage, PI Controller, Fuzzy Logic Controller.

1. INTRODUCTION

1.1 Introduction

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].There are generally two energy sources provided in any hybrid electric vehicle. Out of these two sources in hybrid electric vehicle, one must be the electrical. In hybrid electric vehicle, there are basically two main sources of energy: one is mechanical ICE and the other one is electrical batteries. Reducing the size and power of the engine is the benefit of adding the battery source to the car. And during usual operating mode at slower speeds and cruising mode, the battery provides the power to the system motor as well as in turn to the vehicle train, while it supports the motor power at the time of accelerating mode when there is higher power demand. Thus the synthesis of these technologies means clubbing the features of ICE driven vehicles with high power density as well as the economic conditions of battery powered vehicles. [1]

1.2 Hybrid Vehicles

For driving a HEV, two different sources of energy are needed in these vehicles. Hybrid Electric Vehicle is the standardized form of HEV. For propelling a vehicle, two different sources of energy are used in this study which are battery powered traction motor and Internal Combustion Engine (ICE). From the above mentioned two energy sources, one is “main energy source” (MES) which has high energy storage capability and the other is “rechargeable energy storage” (RES) which have reversibility and high power capability. The main purpose of MES is to provide an expanded driving range, where steady acceleration as well as regenerative braking is given, as is the case with RES. Owing to the rise in tail pipe pollution, conventional ICE poses a significant environmental threat. This is the key reason why the automotive industry is transitioning to more environmentally sustainable and cost-effective technologies, and one similar technology is HEV that along with improved safety can fulfill the requirements for electric power, vehicle efficiency, and greater passenger comfort. [9]

Drastic increment is observed in luxury loads with the enhancement in consumer comfort demand in recent years. Furthermore, increasing energy demand for advanced vehicles demonstrates the critical role of power electronics in the production of such motor vehicles by further growing the demand for electric power. Distribution systems, DC-DC Convertor and Inverter are using the power electronic based systems. Reduced weight as well as size, better flexibility and better voltage regulation, increased efficiency and isolation are some of the benefits of vehicular application.

Hybrid electric vehicles (HEVs) integrate a traditional vehicle's internal combustion engine with both the electric motor and electric vehicle's battery. The hybrid offers low emissions while offering an equivalent driving range and easy charging without the need to be plug in for traditional (gasoline and diesel) vehicles. They are perfect for private transportation as well as military applications due to the inherent versatility of HEVs. An energy storage device (ultra-capacitor or battery), an energy conversion unit (fuel engine or combustion engine) and an on-board energy source (diesel engine and gasoline) are installed in HEV for power supply. Compressed natural gas, gasoline, hydrogen, methanol or other alternative fuel can be used for energy conversion units to get power. In comparison to conventional vehicles, the fuel efficiency of hybrid electric vehicles is 2 to 3 times more efficient. By combining various components, Hybrid Electric Vehicles are enhanced. Several various types of HEV designs enable the implementation of these power-producing elements with the elements of electricity storage. For regulating the flow of power and for maintaining sufficient energy reserves in the storage systems, a power control strategy is required. [10]

1.3 DC-DC Converter

By using voltage source inverter, both electric vehicle and hybrid electric vehicles get charged from the battery. It's really useful to keep the battery voltage rating pretty low for vehicle performance improvement, as this implies using fewer series-connected cells. Although from the perspective of the engine, since the voltage rating and the power supplied by the engine are completely dependent, it is important to have a high-voltage DC bus. In addition, in the case of permanent magnet synchronous machines, moving the flux-weakening region to the high-speed region is particularly convenient for a high-voltage DC bus. A controlled DC voltage is an additional advantageous feature of the implementation of a DC/DC converter, which results in greater motor drive output. As a result, in order to balance the various voltage ratings of these two components, a DC/DC bidirectional converter is normally inserted between both the battery as well as the inverter. [11]

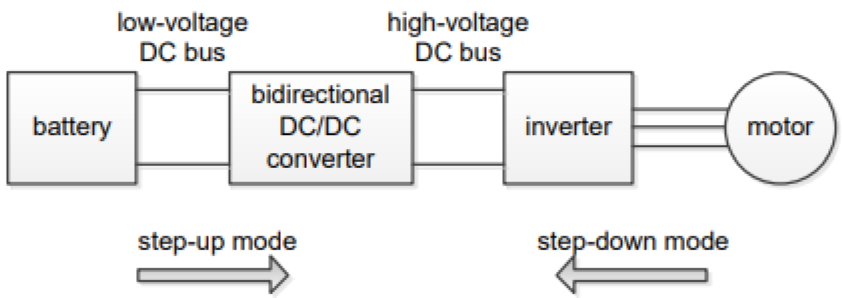

Figure 0 DC-DC converter in an electric vehicle

2. LITERATURE REVIEW

(Sonar, 2020) [1] Recently, Hybrid Electric Vehicles (HEV) has seen enormous development around the world. HEV's growth in this field has been huge. Because of rising emissions from traditional cars, rising fuel costs, and global warming environmental issues, the automotive sector is turning its attention towards developing HEVs. The HEV's are divided into different configurations based upon the degree of hybridization to involve the performance of the IC engine and electric battery simultaneously for the traction function. There are a physical description and simulation of hybrid fuel vehicles. In this article, the bidirectional complete bridge dc-dc converter, and the implementation of this converter in Series-Parallel HEV is discussed. The topology of the transforming converter accounts for motoring as well as regenerating breaking operations. The value of the dc-dc converter is suggested.

(Sowmya et al., 2017) [2] It was proposed to promote recovery of energy before and during braking downhill travel by using a bi-face DC-DC converter between the power source and traction engine. This integration will also increase traction driving performance and improve the range by 25 percent. Now the right bidirectional DC-DC converter heading can be used to maximize architecture efficiency in order to decrease weight, size, and system expense. This paper reviews and explores the fundamental bidirectional topology of the DC-DC converter and describes the comparative benefits for making the right electric car design decision.

(Chakraborty et al., 2019) [3] This paper discusses the scientific implications, the state of the world of research and development. In the sense of increasing alarm over increased emissions and the resulting global warming, Hybrid Electric Vehicles (HEV) has earned considerable interest. HEV is driven by a battery or mixed with electricity. HEV is primarily driven by a bacterium. HEV and other vehicle configurations such as Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV) is also gaining importance with growing concern towards the environment.

(Sai Teja et al., 2019) [7] Explained that a bidirectional chopper (BDC) is the one which can interface main source (HVS), auxiliary source (LVS), and a DC Bus voltage at different levels which is implemented in Hybrid Electric Vehicle (HEV). This converter operation consists of two modes: dual power and regeneration mode with power flow control in both directions. And two outlets control independent power flow (i.e., the dual-source buck-boost mode). Simulation results include the operation as well as closed neural artificial network (ANN) loop control and comparison between PI and ANN control.

(de Melo et al., 2020) [15] Presented that Hybrid electric vehicles (HEVs) and pure electric vehicles (EVs) rely on energy storage devices (ESDs) and power electronic converters, where efficient energy management is essential. This work discusses a potential EV design based on super condensers (SCs) and batteries for a stable and quick transfer of electricity. Power flow between the above energy sources and the EV takes place via dc connection associated with a two-way dc-dc converter. This topology demonstrates the limited number of components and high efficiency over a large range of loads, which are ideal for high-performance, high-current values. There is a comprehensive modeling process consisting of the qualitative and quantitative study of the converter and the application of the control scheme using a basic approach, i.e., the average current mode control.

(Devi Vidhya & Balaji, 2020) [16] The electronic power interface, with its powerful control system, has an important role in the use of energy sources to use electric cars. For this reason, a multiple-input converter (MIC) topology hybrid fuzzy pi-based control scheme is suggested. Include a traditional solid PI controller and fluid transfer PI in the proposed hybrid fuzzy PI controller. The proposed control design also supports the monitoring of a pre-defined speed profile to complete electric vehicle development. Detailed simulation and efficiency analyses are carried out with traditional controllers. The results show that the device is resilient and offers two-way power control, fast monitoring capability with less stable state error, increased dynamic response by improving flexibility and proper use of energy sources. A simulation of the output of the multi-input converter in the MATLAB/SIMULINK environment with the built control system is performed.

(Antony & Rajitha, 2020) [7] Announced that a range of applications such as electric vegetables, renewable sources, and UPS have been transformed by DC-DC converters. These converters are useful to transform the direct current to various voltage levels. A two-way DC-DC converter (BDC) is a DC-DC converter which, with its high power transmission and reduced dimensions, is used to flow power in both directions and dominates unidirectional converters.

[34] Solar power is used for the production of solar power. We plan to develop solar-powered cars in our city through this technology. The solar panel is the key feature in the construction of a solar vehicle. Solar cells absorb and store in a solar battery a portion of the solar energy. In order to allow the battery and motor to be used, power trackers have before translated the energy obtained from the sun into proper device voltage. When power is saved in the batteries, the motor & power controller is available to drive the engine. Two sets of batteries were used: one provides electricity in the form of an auxiliary power supply from an engine driving panel to the rest of the electrically driven equipment in the vehicle.

3. METHODOLOGY

3.1 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.

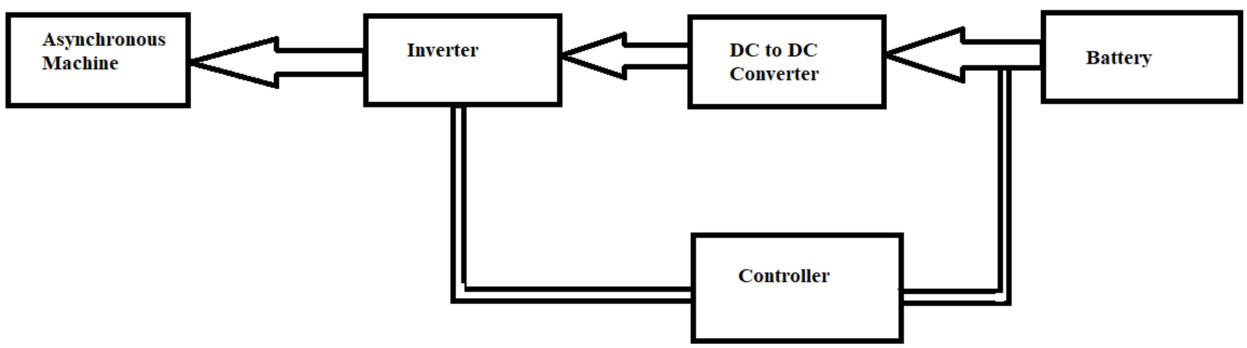

Figure 2 Block Diagram of DC-to-DC Convertor

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.

3.2 Basic Components of Fuzzy Controller

Regulation of fuzzy logic 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.

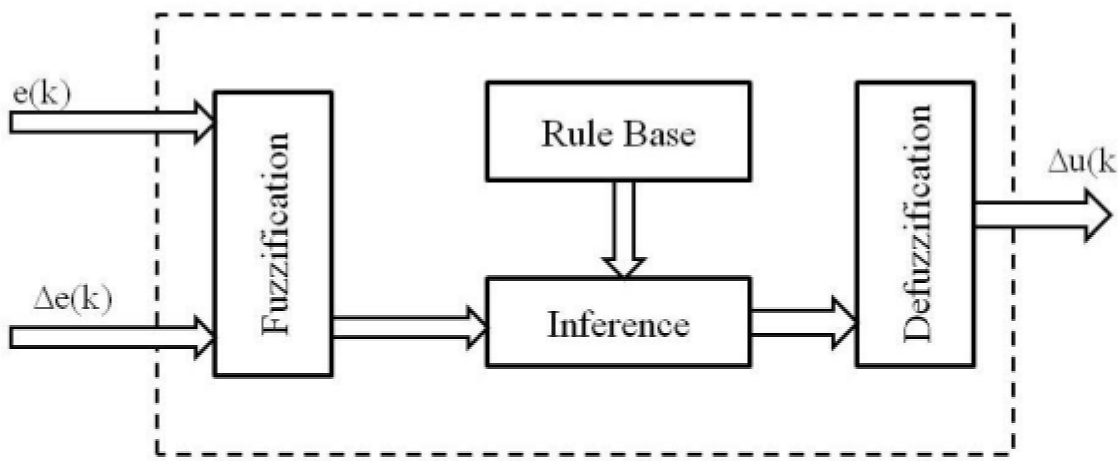

Figure 3 Internal Block Diagram of Fuzzy Control

3.3 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 [2-8]. 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]

4. CONCLUSION

This review highlights the critical role of bidirectional DC–DC converters in hybrid electric vehicle (HEV) applications, particularly when integrated with dual-battery energy storage systems. A detailed survey of existing literature shows that while numerous topologies and control approaches have been proposed, most practical implementations rely on PI controllers due to their simplicity. However, several studies, including the dual-battery topology by Lai et al. (2018), reveal that PI control suffers from limited dynamic performance and sensitivity to parameter variations. Comparative analyses across various works demonstrate that advanced control strategies, especially Fuzzy Logic Control (FLC), provide significant improvements in terms of settling time, voltage stability, and robustness under nonlinear and rapidly changing load conditions. Our review further reinforces that dual-battery architectures enhance flexibility and reliability in HEVs by balancing power between high- and low-voltage buses, thereby improving energy utilization and extending battery life.

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