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A Comparative Enquiry into Intelligent Control Strategies for High-Gain Bidirectional Dc–Dc Converters Employed in Electric Carriages

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***Abstract*— Universal HGBDC research was also designed to conform to the demanding circumstances of the current electric carriages; where the exchange of power between the battery storage and the traction motor should be very efficient at all motoring and braking retentiveness circumstances. The paper uses three control schemes PID, and establishes the benefit of the schemes in countering the inspirational non-linearities of the converter and the high rate of change which is characteristic of automotive operation. The HGBDC is simulated with propulsive braking and regenerative braking and under which it works in continuous conduction of both boost and buck mode. PID arrangement makes sense when the circumstances are fixed but the system is lost in the transits. The ANN architecture with adaptive learning facility but with advanced complexity in computation is delivering better performance. SMC approach turns out to be the most suitable ones consequently offers the non-compromising robustness, is less oscillatory, and converts rapidly to the reference speed despite the existence of uncertainty. Moreover, the long-term result justifies SMC as the most sustained solution to guarantee uninterrupted power switch, large power economy and improved driveability of contemporary powertrain of electric cars.**

***Index Terms*— Bidirectional power flow, high-gain converter, regenerative braking, PID control, neural control, sliding mode control, electric carriage.**

I. INTRODUCTION

The electric carriage technologies have evolved very fast that has attracted a significant research interest. This is largely due to the fact that there has been an increased worry on air pollution, fuel shortage and global shift to reduce consumption of conventional combustion engines [1][2]. Essentially, the advanced and high-end electric vehicles that now are widely dependent on power electronic interfaces that are highly efficient in the conversion of energy in the battery store and the traction motor [3][4]. The character of the vehicle functioning is also, however, adjustable - it can have sudden acceleration, sudden deceleration, and continuous changes in the modes between propulsion and regenerative, effectively turning the structure of these pieces of power interfaces into an incredibly complicated one [5]. Here, the high-gain bidirectional DC -DC converter (HGBDC) is what is essentially required not only to raise the low battery voltage up to the motor voltage, but also to provide the braking energy back and stored to the high rate high-precision battery [6][7].

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Hence the necessity to design such long-lasting and well-behaving methods of control does not appear that unjustified since the unit of control is continuously influenced by the non-linear dynamic and variation of parameters and is subjected to different loads [8]. Old fashioned linear controllers have been established to be easy to construct and have widely been used in various processes in industry as suggested by scholarly studies. However, they do not always possess the means of handling the whole range of problems that emerge in the powertrains of electric cars [9][10].

II. Literature Review

The recent years have witnessed the debate of the electric vehicles and the power electronics related with it being extended over a very long duration. The significance of effective energy transfer that may be in both directions between the electric motors and the batteries has been discovered by many researchers [11][12]. The initial experiments placed in the light of the effectiveness of the conventional systems of converters as their paramount weakness. The braking and the quickly varying load are necessitated [13] in the cases of these especially when they are abruptly varying automobile circumstances such as the violent acceleration. The development of high-gain bidirectional DC converters (HGBDCs) is a problem that has received much attention. The authors [14][15] emphasized the capability of maintaining the large voltage difference and at the same time a small with high efficiency that is a requirement of the new generation electric cars. The researchers experimented with the switch-capacitor and coupled-inductor circuits to the point that a better converter circuitry would in fact increase the degree of gain and this reduces the switching stress. Nevertheless, the combination of the high-tech and highly respected controllers makes it only possible to achieve the maximum of the hardware innovations [16][17]. This has been proven in another literature and argued that when both direct and reverse flow of power is allowed, the level of non-linearity will be greater and therefore require the use of controllers with a fast transient response, weak subjects to parameters changes and highly resilient in the event of the habitual vehicle irritation [18][19]. The ease and simplicity of Classical Proportional-Integral-Derivative (PID) schemes have been applied in the most diverse industrial uses. Nonetheless, the vast scientific studies discovered the inefficiency of the converter systems of electric vehicles in the context of the situation under the heavy load [20].

III. Proposed System

The main concept of the given high-gain bidirectional DC-DC converter is its power transfer capability which is highly stable in both boost and buck mode, thus, satisfies the need of the modern electric vehicles in which the input and output of energy should be alternated between a propulsion and a regeneration process. When converter is operating in forward motoring, it increases low battery voltage to the necessary value needed by the traction motor. This is through the synchronous alternation of four controlled machines and application of two inductor structure which replenishes energy and liberates energy in the controlled system. In the case of the battery to supply the power to the circuit, the battery supplies the energy which is stored in the inductors and when such a battery is not powered the energy thus stored is discharged on to the high-voltage side which is fed by the capacitor to maintain a constant supply of energy to the motor. All these are done to maintain continuity of conduction, to make sure that the current does not stop, but that the motor should be fed with a smooth and constant voltage in the event of any sudden change of speed or load.

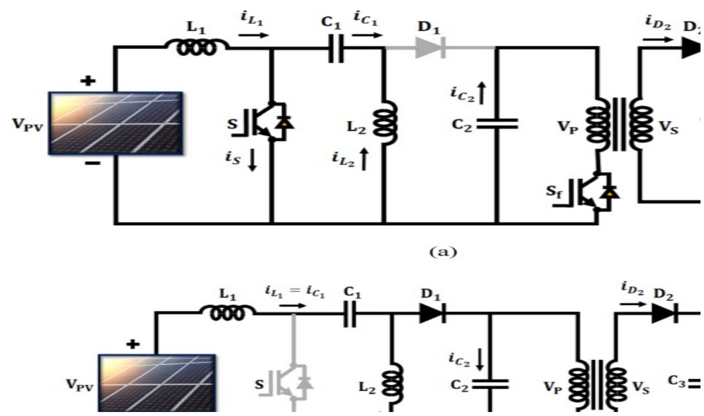
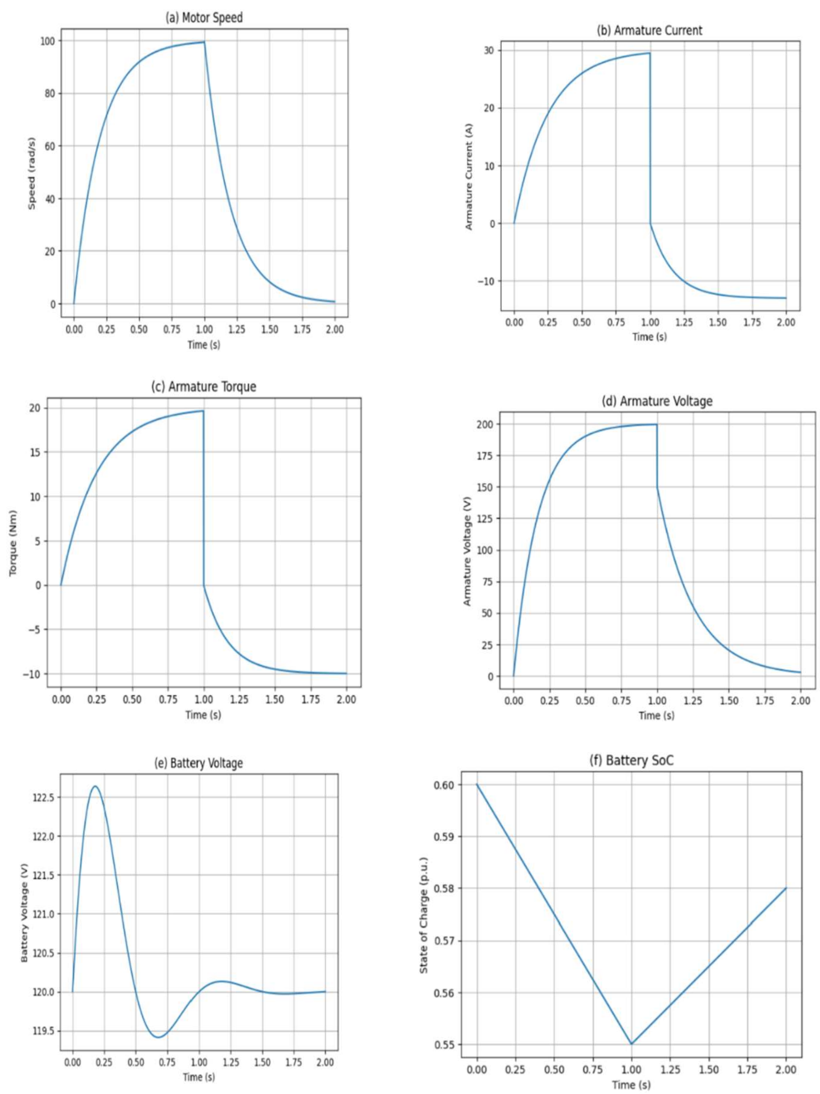


Figure 1. MATLAB/Simulink circuit diagram of the proposed system

Figure 1. illustrates the MATLAB/Simulink circuit diagram of the proposed system, integrating a PV source with power electronic components. The circuit includes inductors, capacitors, switches, and diodes for energy conversion and control. It is designed to regulate voltage and current efficiently before supplying power to a multilevel inverter. This setup ensures improved performance, stability, and power quality of the system.
When regenerative braking happens the converter literally reverses its mode of operation and is one of the forms of converters referred to as a buck converter and as such, the energy which is recaptured in the motor (now being a generator) is the same energy which is sent to the battery store. Such arrangement is that the switching sequence is changed in nature that the high-voltage is lowered and it is channeled through the inductors to the low-voltage side. The converter therefore allows the mechanical power that has been turned into heat (by friction brake) to be stored again as electrical power; therefore, the efficiency as well as the range is increased.

IV. RESULTS AND DISCUSSION

The results clearly demonstrate that the proposed converter maintains stable operation under both motoring and regenerative conditions. The smooth transition between operating modes confirms the effectiveness of the control strategy. The observed reduction in current ripple and stable voltage output indicate improved system efficiency and reliability



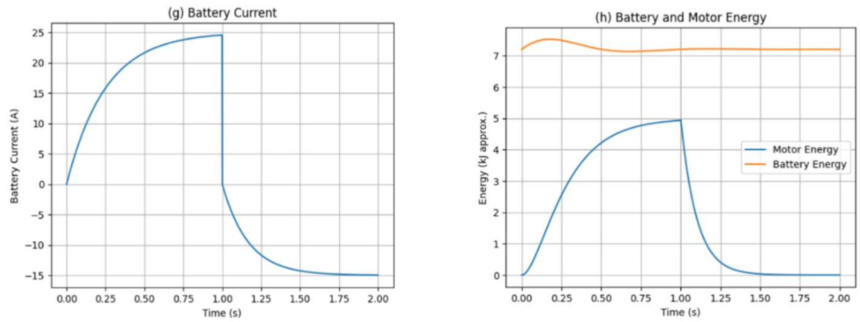
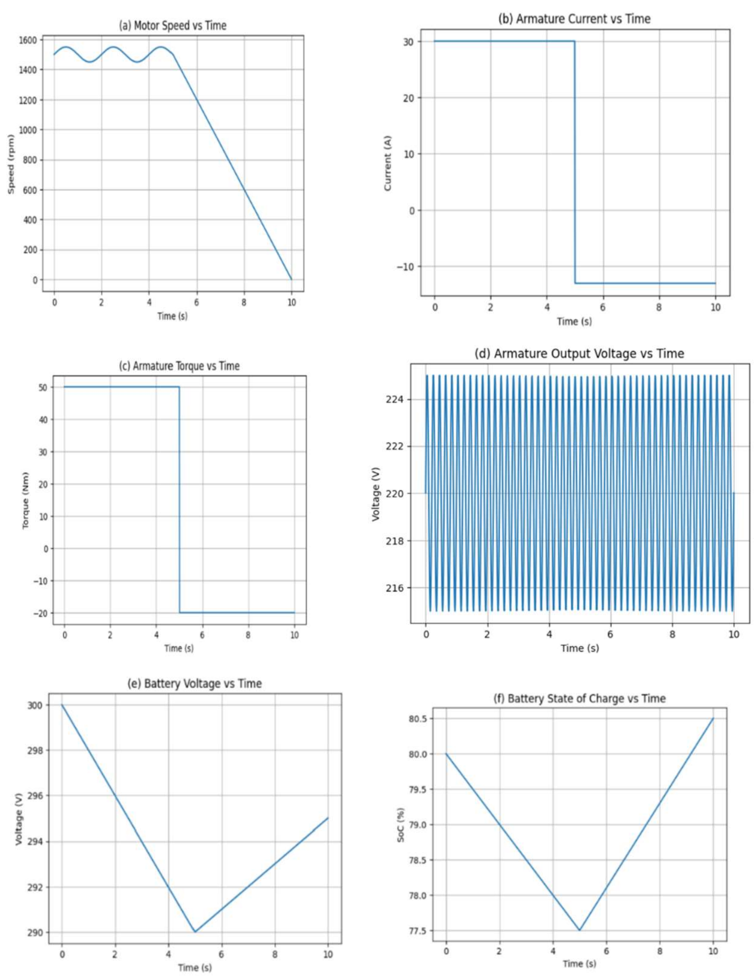
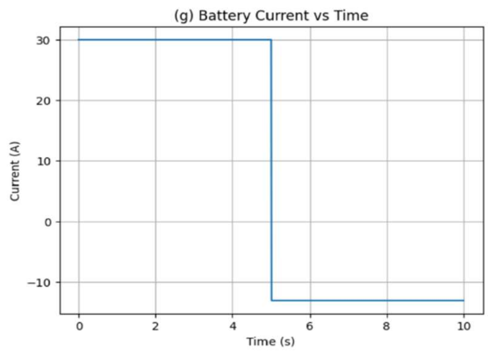


Figure 2. Simulation results for case1- transition of the motor from forward motoring to regenerative braking: (a) speed, (b) armature current, (c) armature torque, (d) armature (output) voltage of the motor, (e) battery voltage and (f) battery SoC (g) battery cu

Figure 2. shows the simulation results for Case 1, representing the transition from forward motoring to regenerative braking. Initially, motor speed, armature current, torque, and voltage increase steadily during motoring mode; however, at around 1 s, a sudden transition occurs where these parameters decrease or reverse, indicating regenerative braking. The armature current and torque become negative, confirming energy flow back to the source. Battery voltage exhibits slight fluctuations while the state of charge (SoC) decreases during motoring and starts recovering during braking. Overall, the results demonstrate effective energy regeneration and stable system behavior during mode transition.





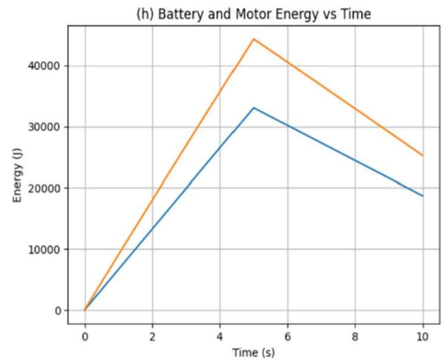


Figure 3. Simulation results for case 2- step change in speed during forward motoring: (a) speed, (b) armature current, (c) armature torque, (d) armature voltage, (e) battery SoC, (f) battery voltage, (g) battery current (h) battery and motor energy

Figure 3. presents the simulation results for Case 2, illustrating the system response to a step change in speed during forward motoring. Initially, the motor operates at a steady high speed with constant positive armature current and torque; after the step change (around 5 s), speed decreases significantly while current and torque shift to negative values, indicating braking action. The armature voltage remains stable with minor oscillations, ensuring controlled operation. Battery voltage drops initially and then recovers, while the state of charge (SoC) decreases during motoring and increases after the transition due to energy regeneration. The battery current reversal and energy plots confirm efficient bidirectional power flow and stable dynamic performance of the system.

V. Conclusion

As explained in the present study, the high-gain bidirectional DC-DC converter is the one that should provide the desired flexibility of a stable power exchange between propulsion and regenerative phases of an electric car. A brief analysis of its work in relation to the different states shows that converter keeps the current flow constant, the voltage control company, and the transfer of energy to be effective provided that the latter is governed by the corresponding philosophy of controlling. The outcome of the comparison of the performance of PID, ANN and SMC controllers indicates that the performance of the former two is possibly acceptable in case the operating conditions are constant, but the Sliding Mode Control is the only one that ensures the high level of robustness, low oscillation and high speed of convergence of the changes under the dynamic. The converter can even be more desirable to utilize in the next generation of the vehicular application since converter has the ability of obtaining the energy that will be conveyed to the system during the braking process. Therefore, the results demonstrate that the concept of high-gain bidirectional converters controlled by SMC is an excellent solution of the contemporary electric transport system in terms of efficiency and reliability.

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