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A Dual Control Regenerative Braking Strategy for Two-Wheeler Application

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Abstract

To reduce the harmful emissions from automobiles and massive surges in fuel prices, automotive electric vehicles are an effective alternate solution. In this paper, a cascaded bi-directional DC/DC buck-boost converter with dual control strategy during regenerative braking is used for a two-wheeler application. The dual control strategy with the cascaded converter is used to increase the average power stored during the braking period and to reduce the vehicle's stopping time. The converter with the proposed control strategy used in this work has made it possible to charge the battery even when the back emf of the machine is less than the battery voltage. A fuzzy logic control strategy is used to consider the non-linear factors like SOC, speed of the vehicle and the required brake force. This is done in order to make the system more reliable and realistic. The complete model is simulated in MATLAB/Simulink. By implementing the dual control strategy, the average power stored by the battery is increased by 2.5 times and the vehicle comes to halt faster in comparison with the existing control strategy. The versatility of the strategy is shown by examining three different scenarios during the regenerative braking process. To support the above claims, simulation results are presented to show the effectiveness of the proposed method

Keywords: regenerative braking; electric vehicle; fuzzy logic; dual control; bi-directional converters; battery charging

1. Introduction

In today's world of dwindling resources and ever increasing prices, spending a lot on fuel has become a major part of the economic budget. Reducing fuel consumption can have a major impact on decreasing the capital spent on fuel. To achieve this, hybrid electric vehicles (HEV) [1]- [3] and plug in – hybrid electric vehicles (PHEV) [4]-[6] are an alternate solution. Installation of high energy battery packs and regenerative braking play an important role in improving the drive range [7] of the electric vehicles as well as improving the battery life.

In order to extract the maximum electrical energy from the rotational mechanical energy, DC/DC converters with appropriate charging and discharging profile are required. Various topologies of DC/DC converters have been discussed in [8]-[10]. However, regenerative braking [11, 12] has to be carried out with the conventional frictional braking. In the braking process, there are two

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issues that are to be addressed. First is accurately applying the brakes which restrains the vehicle speed and maintains the vehicle's travelling course. And the second issue is to recover the braking energy to increase the energy efficiency of the battery[13,14]. In practical scenario, factors like state of charge (SOC) of batteries, speed of the vehicle and driver's brake force requirements limit the effectiveness of electric braking. Thereby mechanical braking has to be incorporated along with regenerative braking. In literature, many works on regenerative braking and various algorithms for the control during the regenerative braking are proposed. The work in [15] proposed a method wherein vehicle's speed is taken into account and not the SOC. Authors in [16] have taken the SOC into account and computed the regenerative force. However, the above works have not stated any methods to utilize the regenerative power to charge the battery. Works carried out in [17] and [18] have used different topologies of bi-directional DC/DC converters to charge the battery. However, the converters used in the works do not address the issue that arises if the terminal voltage of the machine falls below the battery voltage [19] during low speed of the vehicle. In [20] the back emf is neglected when the battery voltage is greater than the terminal voltage of the machine.

In this paper, the focus is on the dual (voltage and current) control strategy which is used to extract the maximum possible energy during the regenerative braking and to ensure that the vehicle stops in an optimum time frame. In addition, fuzzy logic control is used to determine the battery charging current as its determining factors (SOC, vehicle speed and brake force requirement) have an uncertain relation with it. In addition, a cascaded bi-directional DC/DC buck-boost converter with a PMDC machine has been used. This is done to charge the battery even when the back emf of the PMDC machine is less than the battery voltage and at the same time have an effective braking while taking the safety issues and battery conditions into consideration.

2. System Description

The overall configuration of the electric vehicle with the proposed control strategy is shown in Fig. 1. The system consists of a lithium ion battery, permanent magnet DC (PMDC) machine, bidirectional DC/DC buck-boost converter, fuzzy logic reference current generator and control logic block. The bi-directional DC/DC converter can operate in both buck and boost mode. The converter operates in boost mode during motoring operation. During regenerative braking mode, the converter can operate in boost or buck mode and the power flow is from the machine to the battery. The mode of operation during the regenerative braking [21]-[23] depends upon the generated voltage at the terminals of the PMDC machine. If the generated voltage is less the than battery voltage, the DC/DC converter operates in the boost mode and if the generated voltage is greater than the battery voltage the converter works in the buck mode. The control logic block functions during the regenerative braking mode and is responsible for shifting of control strategy from current control (CC) to voltage control (VC) mode during the braking process.

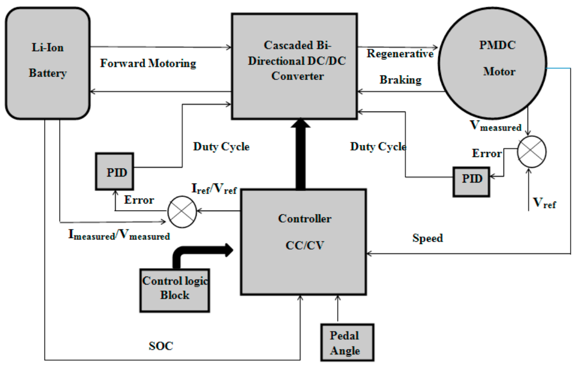


Fig.1. Block diagram of the system

3. Cascaded Bi-directional Converter

The cascaded bi-directional buck-boost DC-DC converter [8] used in this work is shown in Fig. 2. The advantage of this converter is that it can extract the energy when the generated voltage is less than the battery voltage. This is possible because it can operate in both buck and boost modes in both directions whereas a conventional bidirectional converter [17] can operate only in one mode and in one direction. Totally there are four operational modes. However, only three operational modes are used in this work. During the motoring mode, the voltage of the battery is stepped up to the appropriate level as required by the motor. And during the braking mode, regenerative power extraction is achieved by either stepping up or stepping down the voltage generated by the PMDC machine, which in this case is acting like a generator. The switching sequence of the switches for different modes of operation is illustrated in Table 1.

Table 1. Switching sequence for various operating modes

MODE	S1	S2	S3	S4
1	ON	SW	OFF	OFF
2	ON	OFF	SW	OFF
3	OFF	OFF	ON	SW

3.1 Operation Modes of the Converter

3.1.1 Mode 1: Boost Operation – Battery to DC Bus during motoring operation (Primary Boost Mode)

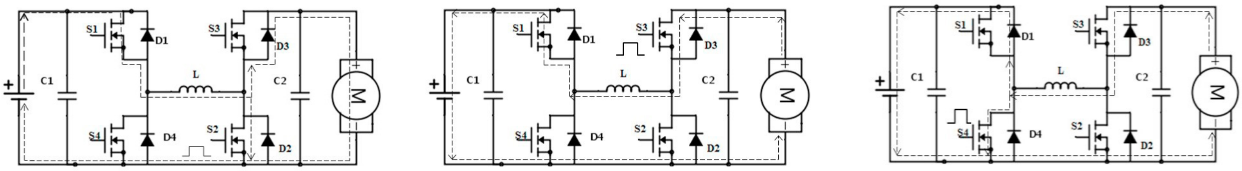
Fig. 2(a) shows the bidirectional converter operating in boost mode.Switches S3, S4 are off, S1 is on and S2 is in PWM switching mode. The battery voltage is stepped up to the level of the terminal voltage of PMDC machine. The converter operates in this mode when the PMDC machine is running as a motor.

3.1.2 Mode 2: Buck operation - DC bus to battery during the regenerative braking.

Fig. 2(b) shows the bidirectional converter operating in the buck mode. Switch S1 is on, S2 and S4 are off and S3 is in PWM switching mode. The PMDC's terminal voltage is stepped down to the level of battery voltage during the braking operation. The converter operates in this mode when PMDC machine is operating as a generator and the generated voltage is greater than the battery voltage.

3.1.3 Mode3: Boost operation - DC bus to battery during the regenerative braking (Secondary Boost mode)

Fig. 2(c) shows the converter operating in boost mode. The terminal voltage of the PMDC is stepped up to the level of battery voltage.



(a) (b) (c)

Fig.2. Operating Modes of Converter

This situation occurs when the generated battery voltage is less than the battery voltage. During this mode S1 and S2 are off S3 is on S4 is in PWM switching mode.

4. Control Strategies

Various control strategies are implemented in order to fulfil the requirement of effective regenerative braking. The strategies are implemented by taking various requirements into consideration like vehicle safety, effective braking of the motor, enhanced battery life, charging capability of the battery and to make the system invulnerable to input or load fluctuations.

4.1 Dual control (Voltage and Current) strategy during regenerative braking mode

During the regenerative braking mode, based on the voltage of the machine, the converter operates in Mode II (buck mode) or Mode III (secondary boost). Voltage Control (VC) and Current Control (CC) [24] strategies are implemented during both the modes of operation. The need for this strategy is to extract the maximum possible energy through regenerative braking and at the same time considering the battery conditions and ensure that the vehicle stops in a limited time frame. The algorithm of this strategy is explained though the flow chart as shown in Fig. 3. For the VC mode, the reference voltage is the rated battery voltage. For the CC mode, the reference current is generated using fuzzy logic controller as discussed below.

4.2 Reference current generation using fuzzy logic control during regenerative braking mode

Regenerative braking process cannot be solely used in the braking process. Mechanical braking becomes essential during emergency situations, when vehicle is to be stopped in a very limited time frame. A fuzzy logic control strategy is used to determine the ratio (Kreg) of the regenerative braking power to the total braking power. The battery charging current is then obtained depending on the regenerative braking power available during the braking process. The rest of the power required to stop the vehicle is provided by mechanical braking. This paper focuses on the implementation of only the electrical braking portion. Regenerative braking power during the braking period is determined by various factors like state of charge (SOC), amount of braking power as required by the driver (Preq), and speed of the vehicle (ω)[12][15][16]. Vehicle speed and driver's brake requirements determine the safety of the vehicle whereas the state of charge is used to prevent the battery from getting overcharged or deep discharged. The permissible current entering the battery 'I' is a function of all of the aforementioned determinants. As these factors are constantly changing with time, therefore regeneration strategy is difficult to be expressed. These factors all together determine the total regenerative braking power which is required during the braking process. Since the regenerative braking power is varying, therefore the charging current of the battery is also varying. Hence fuzzy logic control strategy is applied for this uncertain process. The output power (P) of the running vehicle can be determined using (1).

$$P = T_e\omega \tag{1}$$

$$P_{reg} = PK_{reg} \tag{2}$$

$$K_{reg} = \frac{\text{Regenerative braking power}}{\text{Total braking power}} \tag{3}$$

Also

$$P_{reg} = V_{bat} I_{ref} \tag{4}$$

Where Iref is the permissible current entering the battery and Kreg is the calculated using (4). The relationship between the regenerative braking constant. Hence permissible value of current can be braking power and its determinants are as shown in Table 2.

5. Results and Discussions

5.1. Regenerative braking – dual control strategy

5.1.1. Case I

Fig. 3 shows the waveforms during the regenerative braking period. When the power flow is from the PMDC machine to the battery, the PMDC machine works like a generator. In this case, the machine is working under no load condition i.e. freewheeling. With the decrease in speed, the terminal voltage of the PMDC machine reduces during the braking process. The converter during the regenerative braking period works in Mode II and III. The converter operates in Mode II till 0.04 seconds.

The use of dual control strategy during the regenerative process is explained as follows. When brakes are applied the terminal voltage of the PMDC machine, Vgen, is 40V and the battery voltage, Vbat is 18.96V for 75% SOC.

The converter initially operates as buck converter (Mode II) and in CC mode. As the speed decreases Vgen, also decreases (7) and as the terminal voltage of the PMDC machine reaches below 38V, the output of the converter is less than 18.96V. As a result of which Vbat is greater than Vgen and instead of braking, motoring operation will start. In order to prevent the system to enter the motoring mode, the CC mode is switched to VC mode, as shown in Fig. 3 (a). The speed and the terminal voltage of the PMDC machine further reduces. When Vgen crosses 19V, the system will again try to shift in motoring mode as Vbat > Vgen. Now, the converter shifts its operation from Mode II to Mode III (secondary boost), that is after 0.04 second. Now, the converter is operating as boost converter in CC mode till 0.012 second. Again there is a shift from CC mode to VC mode after 0.012 second and it continues till 0.016 second as shown in Fig. 3 (b). The shift from CC mode to VC mode is made when the armature current reaches zero. The speed and torque waveforms are shown in Fig. 3(c) and (d). It can be observed that the speed is gradually decreasing with time and the motor comes to a halt within 0.16 second. Since the battery current is negative and the SOC is increasing with time as shown in Fig. 3 (e), it can be inferred that the battery is getting charged and regenerative braking is taking place.

Table 2. Rules for fuzzy logic controller

SOC	SPEED	PEDAL ANGLE				
		VL	L	M	H	VH
VL	L	mf0	mf2	mf2	mf1	mf0
	M	mf0	mf2	mf1	mf1	mf0
	H	mf0	mf1	mf1	mf0	mf0
L	L	mf1	mf1	mf2	mf1	mf0
	M	mf10	mf9	mf7	mf5	mf1
	H	mf10	mf10	mf8	mf6	mf2
M	L	mf4	mf2	mf2	mf1	mf0
	M	mf10	mf9	mf7	mf5	mf2
	H	mf10	mf10	mf8	mf6	mf2
H	L	mf2	mf2	mf2	mf1	mf0
	M	mf2	mf2	mf2	mf3	mf2
	H	mf2	mf2	mf2	mf2	mf1
VH	L	mf1	mf1	mf1	mf1	mf0
	M	mf1	mf2	mf1	mf0	mf0
	H	mf1	mf11	mf1	mf0	mf0

5.1.2. Case II

Another case has been examined in which an external load torque 1 N.m has been applied to the machine externally. The current and voltage waveforms of the machine and the battery are shown in Fig. 4(a). It is evident form the waveforms that the basic wave shape is same for both in the Case I and II. Moreover, the battery is getting charged and the speed is reducing to zero within 0.1 second. This shows that the control strategy is versatile and is applicable to both in the case of load and no load condition.

5.1.3. Case III

Another scenario is examined in which the SOC of the battery is 60% and the pedal angle is 0.8. The voltage and current waveforms of the PMDC machine and the battery are shown in Fig. 4(b). The waveforms for this case are similar to the cases discussed before. The whole process is completed within 0.08 seconds. This again shows the wide range of operation of the control strategy.

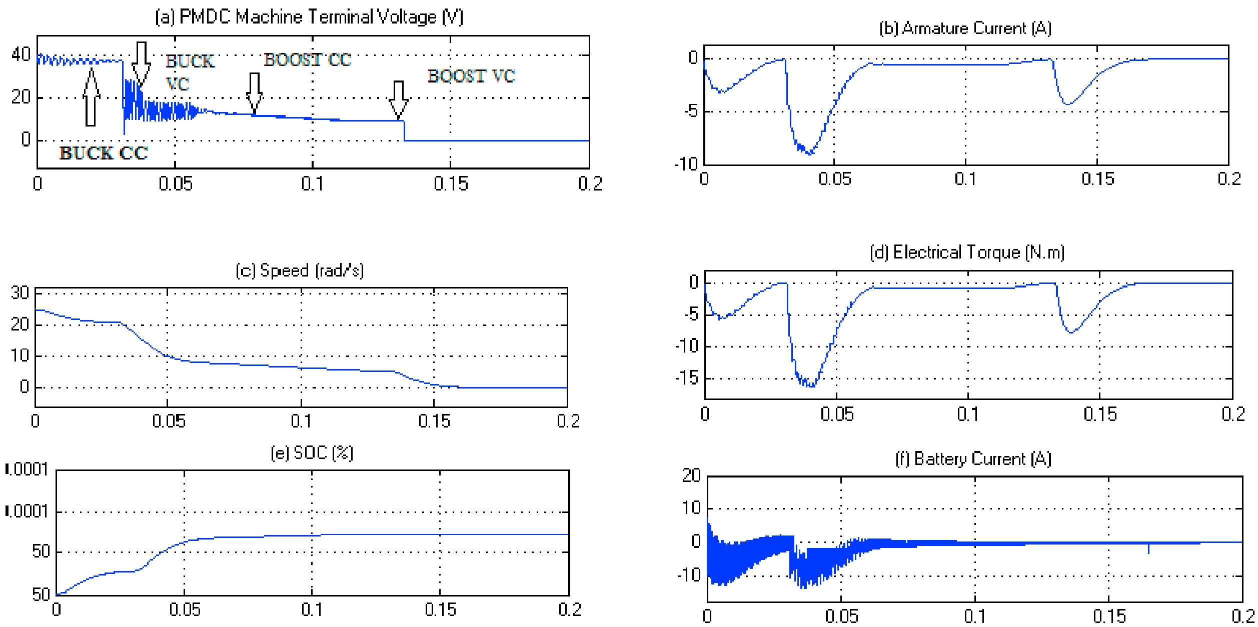


Fig. 3. Simulation waveforms for regenerative braking mode.

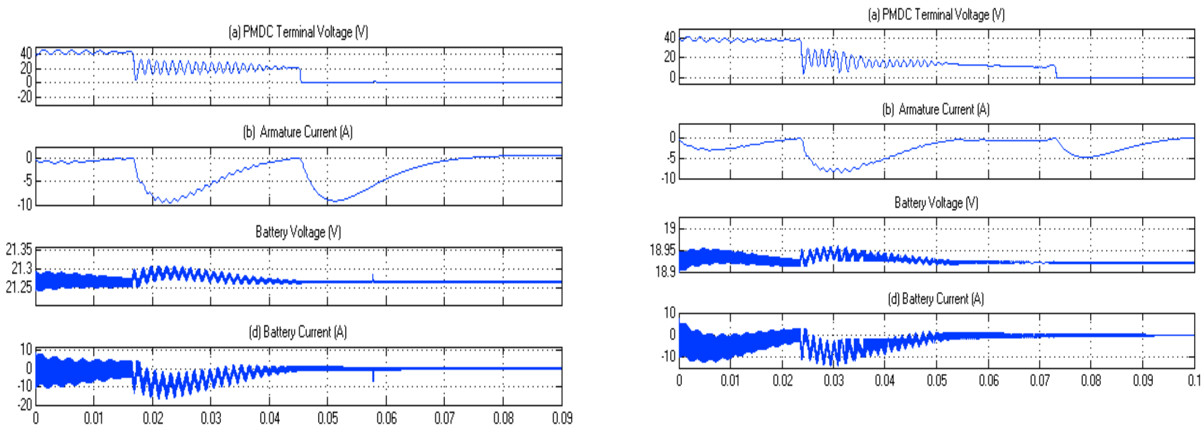


Fig. 4. Regenerative bralking with (a) 60 % SOC (b) external load

5.2 Comparison with existing Control Strategy

The simulation waveforms during the braking process with conventional bi-directional DC/DC converter and the control strategy adopted [20] is shown in Fig. 5 for comparison. The terminal voltage of the PMDC machine is shown in Fig. 5 (a). It can be seen from Fig. 5 (b) that the current drawn by the battery is till 0.03 seconds only. After that the current is almost negligible. Because of which the power stored by the battery is for duration of 0.03 seconds only whereas the battery draws power for duration of 0.16 seconds in the case of cascaded converter, as shown in Fig. 3(f). The speed of the vehicle in Fig. 5 (c) reduces to 20 rad/s in 0.16 seconds whereas in the case of cascaded converter the vehicle comes to complete halt, as shown in Fig. 3 (c). The power stored by the battery during regenerative braking process with the conventional converter and the cascaded converter is shown in Fig. 5 (d) and (e). The average power stored by the battery with conventional converter is 9.13 W, whereas it is 23.22 W for the cascaded converter. The waveforms of the SOC of the battery are shown in Fig. 6 for both the proposed and the control strategy implemented in [20]. Increase in the SOC is much more for the proposed method as compared to the one used in [20] as shown in Fig. 6. This is indicative of increase in the energy stored by the battery during regenerative braking process by using the proposed control strategy.

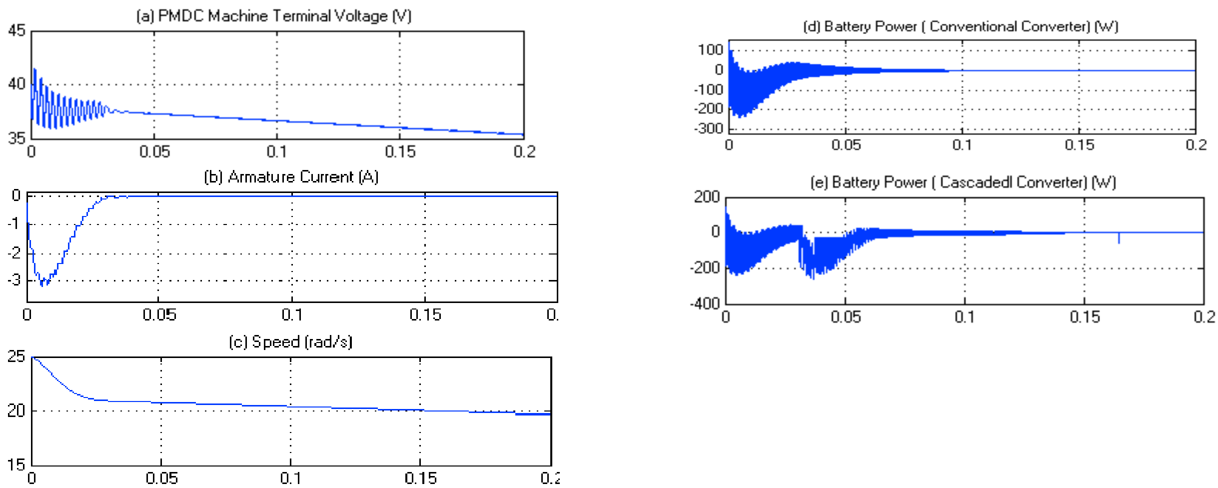


Fig. 5. Simulation waveforms with conventional bi-directional DC/DC converter.

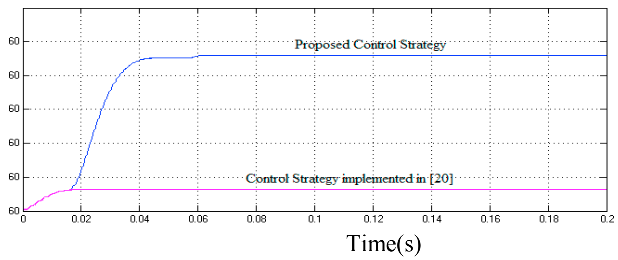


Fig.6. Comparison of SOC.

6. Conclusion

This paper has focused on increasing the energy stored by the battery during the regenerative braking process in order to make the system more reliable and reduce the vehicle stopping time. More energy is stored in the battery during the regenerative braking process, by charging the battery even at low back emf, which is achieved by using the cascaded bi-directional converter with the proposed strategy. By implementing the dual control strategy, the average power stored by the battery is increased by 2.5 times and the vehicle comes to halt faster in comparison with the existing control strategy implemented in [20]. The versatility of the strategy is shown by examining three different scenarios during the regenerative braking process. The system is made more realistic by using a fuzzy logic controller that determines the ratio of regenerative braking to the total braking and the permissible battery charging current. Simulation results validate that during the regenerative braking process energy is stored in the battery even for low back emf using the dual control strategy.

Appendix A. System Parameters

Table A.1. System parameters

BATTERY PARAMETERS	VALUE	PMDC MACHINE PARAMETERS	VALUE
Nominal voltage	21 V	Power rating	350W
Rated capacity	50Ah	Voltage rating	48 V
Fully charged voltage	24.4437 V	Armature resistance	1.55Ω
Discharge current	21.7 A	Armature inductance	0.005 H
Internal resistance	0.0042 Ω	Inertia	0.02215 kg m^2
Fully charged voltage	24 V	Viscous friction coefficient	0.002913 N.m.s
Nominal discharge current	10 A	Torque and voltage constant	1.8 Nm/A and 1.8 V/rpm

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