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Regenerative braking of electric vehicle using a modified direct torque control and adaptive control theory☆

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ABSTRACT

This paper represents a novel regenerative braking approach for electric vehicles. The proposed method solves the short-range problem which is related to the battery discharge. The direct torque control switching algorithm is modified to recover electrical energy from electric vehicle, driven by brushless direct-current motor, without using the additional power converter or the other electrical energy storage devices. During regenerative braking process, a switching pattern is applied to the inverter which is different from the normal operation due to the special arrangement of voltage vectors. The new switching pattern is considered to convert mechanical energy into electrical energy. State of charge of the battery is used as a performance indicator of the proposed method. Simultaneously, a model reference adaptive system is designed to tune the system's parameters. Several simulations are conducted to validate the performance and effectiveness of the proposed methods. The results show the high capability of designed methods.

1. Introduction

Currently, due to the concern of global warming, fossil fuels cost and uncertainty of oil supply, the necessity of using renewable energies become more obvious [1–3]. Therefore, the government's policies have been changed to encourage automobile manufacturers to allocate research budget for electric vehicles (EVs) [1,4]. In comparison with the conventional vehicles, there are still some drawbacks of EVs that can be noted such as, batterypack, charging system and a short driving mileage due to battery charging capacity [4–5]. Therefore, under government's instruction and the people demands, automobile manufacturers have tried to improve the products in terms of standard quality and fuel efficiency [5].

In order to increase the efficiency of the EVs, high-tech equipment such as sensors, extra storage devices, and inverter circuits can be employed. However, these technologies, on one hand, may make EVs complicated, and on the other hand, increase the total cost of producing EVs [6]. Therefore, researchers are trying to tackle this problem by modifying the regenerative braking system. The battery pack, the motor drive system, and the converter controller are three significant components of EVs [4]. Motor drive system technology plays a crucial role in power transfer mechanism [3]. The common electric motors that are used in EVs are switched reluctance machine (SRM), induction motor (IM) and brushless direct-current (BLDC) motor [3]. Among them, the BLDC motors are the

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preferred one.The most applications of the Brushless DC motors can be categorized into the servo drives, appliances, medical equipment and a broad spectrum of power systems [7]. Its popularity goes back to the great efficiency, suitable torque-speed characteristic, dependability, stableness, lower noise and simple structure to control [7–8]. However, the significant defect of BLDC motors is related to the torque ripple which is resulted in cogging torque [9].

Also, awareness of the exact position of the rotor is one of the key issues in this kind of motor to sustain the windings in the right direction of rotation [10]. These positions are sensed by the Hall sensors owing to their cost-effectiveness, especially where the phase currents should be commutated on and off. The proximity sensors detect the pole's sign of the rotor when the rotor magnetic poles are passing in front of the sensors [11]. Assessing the received signals determines the precise sequence of commutation. The signals can be decoded by understanding the combinational logic. The outputs are six voltage vectors. Therefore, the firing commands are applied to the phases to conduct them to 120 electrical degrees.

Various methods have been proposed to control BLDC motor such as dc link current control, direct torque control, hysteresis current control and pulse width modulator control [12], that among them direct torque control (DTC) is more reliable. A three-phase switching circuit is used to control the motors based on the received command from the controller [3]. Switching pattern in DTC can be altered in diverse ways which differ in purpose. Heretofore, a multitude of articles has published to improve the regenerative braking approaches of EVs in various procedures in distinct motors [13–16]. The energy efficiency is a crucial attribute [15], and reusing the brake energy can make a profound contribution, a distinct difference between conventional vehicles and EVs. By regenerative braking, the energy is reversed into the battery so that the torque is used for reducing the speed of the motor, and the motor generates power consequently [10–11]. In [17] a new switching pattern based on the rotor position at different operating speeds is introduced. Although in the proposed method the braking current maintains the braking torque at the high level, a closed-loop temperature controller is required to solve stator overheating. Recovering the potential and kinetic energy during declaration or stopping can increase the range of the car's path. Adding equipment such as sensors, extra storage devices, and new inverter circuits, in some ofthe proposed methods only make system complicated [14]. In the proposed method, it has been attempted to recover the kinetic energy only by changing the switching pattern without the major revolution in structure. Voltage vectors are sorted based on the roles that they play in reducing or augmenting in torque and flux. The controller is the heart of the system for both driving and regenerative braking of motors. A very typical control system is proportional-integral (PI) controller, which is popular due to a simple structure and high torque and speed responses. Nonetheless, the performance of this controller is not acceptable in the presence of speed changes, parameters fluctuation and load effect [16,18].One of the cases that PI controller is not efficient and need to be replaced with other controllers is under mode transition in DTC. In [19] this problem is addressed by a robust algorithm. In this paper, a model reference adaptive system (MRAS) is applied for tuning the controller parameters automatically and track the reference speed signal. The performance of the proposed method is evaluated in simulation results section, where the new regenerative braking method in parallel with the adaptive controller is employed to enhance the state of charge (SOC) of the battery during 0.9 s simulation for 0.6% in comparison with the conventional switching pattern and PI controller. By this energy saving the driving range of EVs can be improved. Moreover, the proposed controller is superior to the conventional PI controller at response speed and steady-state tracking error.

This paper organized as follows. Section 2 describes the dynamic behavior of EV by calculating the resistance forces on the vehicle. In Section 3, the traditional DTC for BLDC motor is analyzed, it shows how the speed vectors should be selected to fulfill the requirements of increasing or decreasing flux linkage and electromagnetic torque. A novel DTC algorithm is proposed in Section 4, in order to improve the state of charge of battery. This method is done by changing the sequence of switching without using the additional power converter or the other electrical energy storage devices. Section 5 introduces a MRAS with higher efficiency in comparison with the former controller. Section 6 describes the simulations and the results. For this part, a driving cycle alike to the urban driving cycle ECE and real parameters of an EV are selected. Finally, Section 7 presents the paper's conclusion is brought.

2. Dynamicmodel of electric vehicle

The motion and acceleration of the vehicle can be analyzed by the forces applied to it. In the motoringmode, resistance forces acting on EV as shown in Fig. 1, can be equivalent to the following formulas [4]:

$$F_{tot} = F_{rr} + F_{hc} + F_{ad} + F_{la} \tag{1}$$

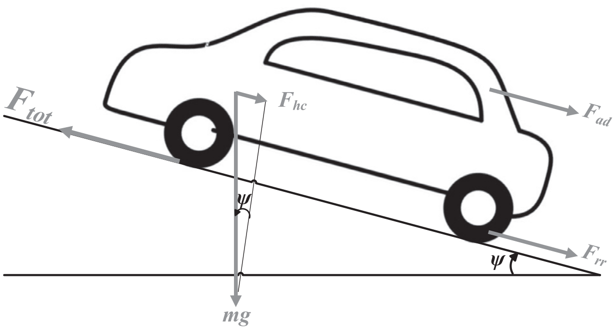

Fig. 1. The forces acting on a vehicle moving along the slope.