Regenerative Braking Performance of Different Electric Vehicle Configurations Considering Dynamic Low Speed Cutoff Point

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***Abstract*— This paper addresses the improvements gained by considering a dynamic Low Speed Cutoff Point (LSCP) as an alternative to a constant LSCP for regenerative braking of Electric Vehicles (EVs). The energy harvesting improvement is studied using an EV test bench simulation model in MATLAB/SIMULINK for different vehicle configurations of single axle and all-wheel drives. Different scenarios are studied on a standard drive cycle and the improvements in each case are compared with each other. The simulation results proved that considering dynamic LSCP instead of constant LSCP improves the regenerative braking capability of EVs regardless of the configuration. This improvement is more significant when considering a rear-wheel drive EV.**

Keywords*— *Electric Vehicles, energy harvesting, Low Speed Cutoff Point, regenerative braking.

I. INTRODUCTION

As cleaner alternatives to traditional vehicles, Electric Vehicles (EVs) have received undeniable attention in the past decade. However, the limited driving range is still a challenging obstacle towards large-scale adoption of these vehicles [1]. Hence, extensive research in both industry and academia has been carried out for EVs with the goal of improving the efficiency and driving range. Regenerative braking technology used in EVs is considered to be one of the most effective methods to harvest braking energy and extend the driving range of these vehicles [2], [3]. It is shown that the driving range of EVs can be increased up to 15% by taking advantages of regenerative braking technology [4], and this increase can be even more significant in big cities where the brakes are needed more frequently [5]. The main concept behind the application of regenerative braking is to recapture the kinetic energy of the vehicle while braking through imposing a negative torque on the driven wheels by the Traction Motor (TM) to slow down the vehicle [6]. Generally, due to safety and stability issues, the total demanded brake force should be divided and allocated to the front and rear wheels appropriately. Furthermore, combination of friction-based and regenerative-based brakes is employed in order to accomplish both maximum energy recovery and proper braking performance simultaneously [6]. Thus, the operation of the brake force distribution control strategy is a vital step in designing EV brake controllers [6]-[8].

On the other hand, as the back electromotive force (EMF) induced on the TM is proportional to the motor speed, the EMF falls considerably below the battery voltage level at low speeds and the current flow cannot follow the path from the TM towards the energy source. As a result, regenerative braking is considered inefficient during this time and braking is solely realized by friction brakes [4]. Therefore, it is inefficient to operate the EV TM as a generator at these speeds and a low speed threshold is defined as the cutoff point for regenerative braking in the brake controller. In [9] and [10], due to the small fraction of energy being recovered in speeds below 10 km/h, a constant low speed threshold of 10 km/h is considered while designing the brake controller. In [11], a weight factor is used to reduce the proportion of regenerative braking in comparison to friction-based braking at low speeds. Although a low speed threshold can serve as a boundary to increase the proportion of friction brakes and gradually disable regenerative braking, finding this speed threshold is a challenging and crucial step in maximizing energy savings during the braking instance [12]. This study builds on the authors' previous research to introduce a dynamic Low Speed Cutoff Point (LSCP) for regenerative braking operation of EVs at low speed. Dynamic LSCP represents the instant in which the motor controller DC link current changes direction while the TM is still operating as a generator. At speeds below this point, the TM, which is still operating in regenerative braking mode, extracts energy from the source instead of charging it. Indeed, ignoring this change in current direction at low speeds causes energy loss during the regenerative braking process.

In single-axle drive EVs, energy is only extracted from the driving axle which can vary depending on the connection of the TM to the front or rear axles. In all-wheel drive EVs, energy can be extracted from both axles [13]. Authors in [13] have compared the maximum possible energy recovery during regenerative braking for two different electric drive topologies including a single drive EV with one central TM and an all-wheel drive EV with four individually driven wheels. For the all-wheel drive topology, it is assumed that the four individual TMs convert the kinetic energy of the wheels to electric energy independently through regenerative braking. However, the dynamically changing nature of low speed regenerative braking is overlooked in [13] and a constant low speed threshold is instead employed to deactivate regenerative

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braking at low speeds. The main contribution of this paper is to compare dynamic and constant LSCPs in all-wheel, front-wheel, and rear-wheel drive EVs from the viewpoint of energy saving. The all-wheel drive topology considered in this paper utilizes a single TM to extract energy from all wheels and thus the distribution between friction-based and regenerative-based brakes is not individually controlled for each wheel.

II. EV Brake Force Distribution and Limitation of Regenerative Braking

In order to accomplish maximum energy recovery during braking instance while maintaining vehicle stability, both regenerative and friction braking have to coexist [3], [12]. Taking into consideration that friction-based brakes typically have delays which can be problematic in vehicle slip control, employing regenerative braking simultaneously can significantly improve braking performance due to its quick response. On the other hand, during heavy braking situations, the resistive force produced by the TM may not be sufficient to overcome the required force to stop the vehicle [12]. Thus, designing a brake controller that is responsible for allocation of the braking force between rear and front axles and distributing it between regenerative and friction-based brakes is of extreme importance. Generally, in a single-axle drive EV, the braking force of the drive axle consists of regenerative braking of the motor and friction braking, while the other axle's braking force only consists of friction-based brakes [12]. In an all-wheel drive EV, both axles have the capability to provide regenerative and friction braking to slow down the vehicle [13].

In practice, the distribution of brake force between rear and front axle should guarantee good braking performance as well as vehicle stability. Hence, brake force distribution follows a normalized nonlinear hyperbolic curve known as the ideal braking force distribution or I curve as depicted in Fig. 1 [6]. This curve is set by the load transfer from the rear axle to the front axle while the vehicle is decelerating. If the brake force distribution between front and rear axles follows this curve, the front and rear wheels will lock simultaneously which in turn leads to maximum brake performance and stability of the vehicle [6].

One of the most important limitations to consider regarding regenerative braking is the inability of the TM to operate as a generator and recharge the battery below a certain speed threshold. In most of the studies in the literature, LSCP is considered a constant value; however, LSCP varies dynamically as the operating conditions of the vehicle changes [12]. Thus, a dynamic LSCP should be considered. In this paper, a dynamic LSCP is used to dynamically identify LSCP. It corresponds to the instant when the motor controller DC link current changes direction while the TM is still operating as a generator.

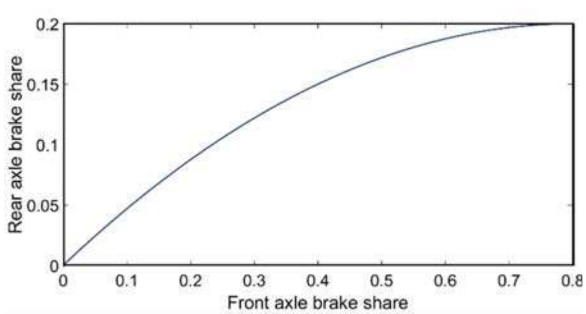


Fig. 1. Ideal brake force distribution curve on the axles of a typical vehicle

III. Brake Controller with Dynamic LSCP

The total braking force of an EV consists of two different terms: regenerative braking force imposed by the TM and friction braking force of the wheels. The concept behind an EV brake controller design that takes full advantage of dynamic LSCP is based on the fact that during regenerative braking at low speeds, the direction change in motor controller DC link current can indicate that regenerative braking process is no longer efficient. While the TM can produce a negative torque during this instance, current is drawn from the energy source resulting in energy loss. Although this energy loss during regenerative braking is small compared to the energy extracted prior to LSCP, when longer driving times with frequent braking at lower speeds are considered, it would have a significant effect on energy consumption and the driving range of the vehicle. Thus, in this approach, monitoring the motor controller DC link current and feeding it back to the controller is a crucial step in determining dynamic LSCP in order to prevent energy loss during regenerative braking process. A flowchart representation of brake force calculation with different brake allocations for an all-wheel drive, rear-axle drive, and front-axle drive EV is shown in Fig. 2 for both control strategies of constant LSCP and dynamic LSCP. Based on Fig. 2, first the brake force distribution between front and rear axle is calculated using the brake distribution characteristic curve in Fig. 1. Then, for the front-axle drive EV, the front axle braking share is made available for energy extraction through regenerative braking, whereas for the rear-axle drive EV, only the calculated rear axle share is accessible for energy extraction. On the other hand, in an all-wheel drive EV with one TM, although regenerative braking can be used to extract energy from both axles, it is limited to twice the calculated rear axle brake share to prevent the rear wheels from locking. This is due to the fact that in this configuration, the TM distributes the brake torque equally between the front and rear axles [14]. According to Fig. 1, the share of rear axle is always less than the share of the front axle and that is why in an all-wheel drive EV the rear axle is the limiting factor when applying regenerative braking. Finally, depending on the control approach, either vehicle speed (n) is considered as a determining factor when applying constant LSCP, or the motor controller DC link current (I) is used as an indicator for determining the low speed threshold point when considering dynamic LSCP. The difference between constant LSCP and dynamic LSCP approach is that one uses a fixed vehicle speed to determine the LSCP while the other uses a change in motor controller DC link current direction, from negative to positive, to identify LSCP during regenerative braking process.

IV. Simulation Model and Case Studies

In order to compare and analyze dynamic LSCP and constant LSCP modes of operation on different EV configurations, a test bench simulation model is used to emulate the EV operation for various cases. The simulation platform is depicted in Fig. 3 and consists of a 400V Li-ion battery model as the main energy source, two Permanent Magnet Synchronous Motor (PMSM) drives coupled together through a mechanical shaft which emulate both the TM and the Dynamometer (Dyno), and a controller block. The TM emulates the EV drive motor while the Dyno emulates the different road load conditions by mimicking the equivalent resistive forces acting on the EV at each instance.

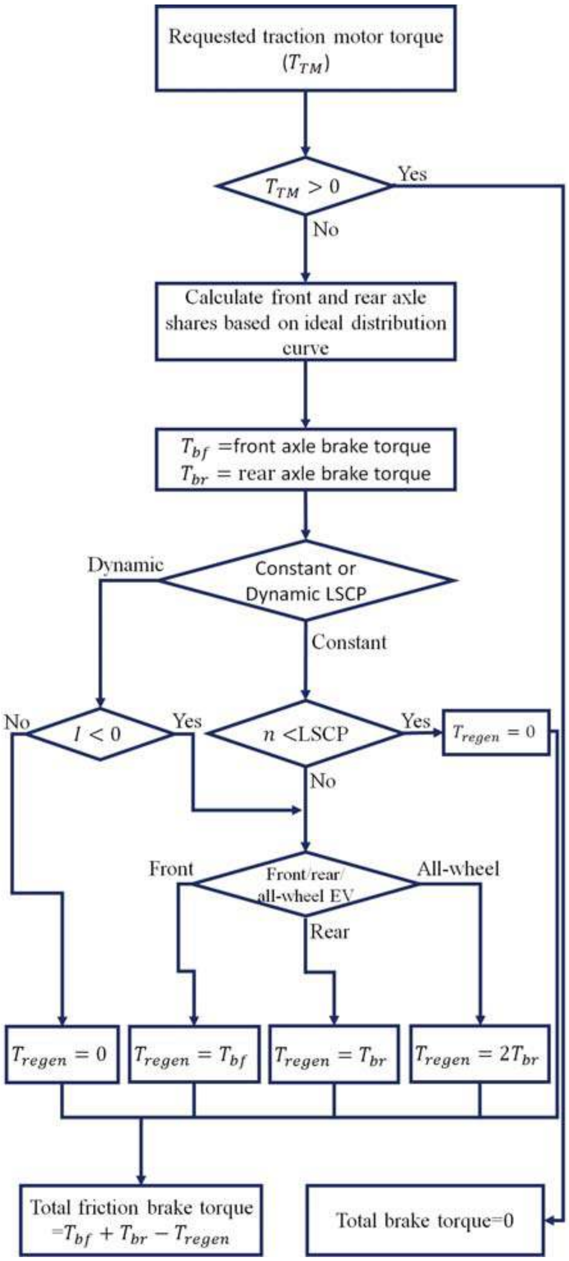


Fig. 2. Flowchart representation of brake controller for different EV configurations

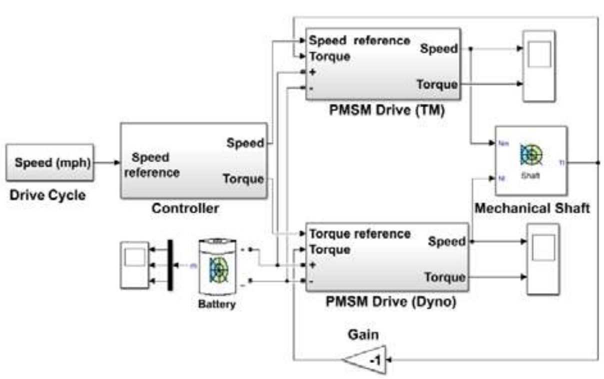


Fig. 3. Test bench simulation model

The controller block is responsible for calculating the speed and resistive torque commands at every instance while considering the brake controller algorithm, EV parameters, and operating conditions; thus, providing an accurate model of the actual vehicle under study. In other words, the controller block calculates the speed and torque commands for each operating point for the TM and Dyno, respectively. In this configuration, the reference speed is obtained from a predetermined driving cycle and is translated to a required rotational speed, which is then given to the TM drive that is operating in speed control mode and ensures precise speed tracking. Furthermore, torque commands representing resistive forces acting on the vehicle are calculated within the controller and commanded to the Dyno drive, which is operating in torque control mode, to emulate road load conditions [6]. It should be noted that in order to provide a fair comparison, all case studies are conducted on a predetermined Urban Dynamometer Driving Schedule (UDDS) as shown in Fig. 4, where the speed at each instance is known and given. The vehicle parameters used for these simulations are presented in Table I.

The simulation is conducted for different configurations of EV (front-wheel, rear-wheel, and all-wheel drive) considering the two regenerative braking methods of control, constant LSCP and dynamic LSCP. The amount of energy extracted through regenerative braking and the required net energy to complete the drive cycle is calculated and compared for each configuration for the two cases of considering dynamic LSCP and constant LSCP. The results are shown in Table II for the duration of one drive cycle. Furthermore, the harvested energy

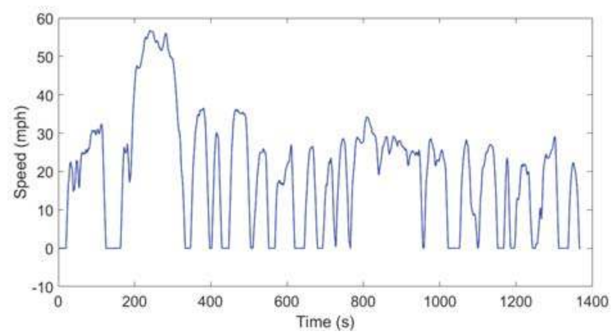


Fig. 4. UDDS drive cycle used for the simulation studies

TABLE I
VEHICLE SPECIFICATIONS UNDER STUDY

Parameter	Value
Vehicle mass (m)	1000 kg
Air density (ρ_α)	1.22 kg/m^3
Aerodynamic drag coefficient (C_D)	0.3
Frontal area (A_f)	1.6 m^2
Constant LSCP	10 mph
Rolling resistance coefficient (f_r)	0.01
Wheel radius (r_d)	0.28 m
Wind speed (v_W)	0 m/s
Road slope (α)	0°
Overall gear ratio (G)	2.3

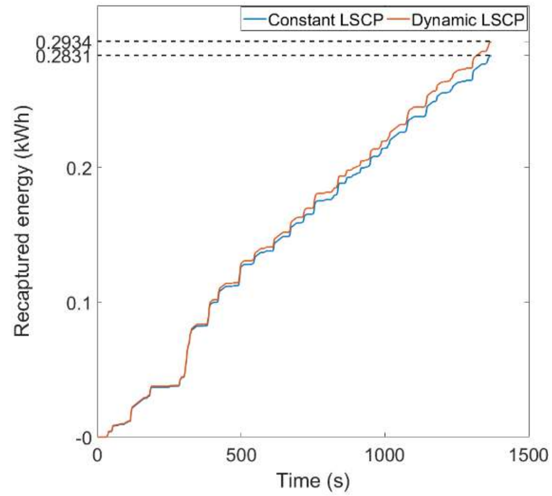
TABLE II
ENERGY EXTRACTION AND CONSUMPTION FOR DIFFERENT EV CONFIGURATIONS

EV configuration	Constant LSCP	
	Energy extracted through regenerative braking (kWh)	Net energy consumption (kWh)
All-wheel drive	0.2564	1.0224
Front-wheel drive	0.2831	0.9956
Rear-wheel drive	0.2449	1.0338
EV configuration	Dynamic LSCP	
	Energy extracted through regenerative braking (kWh)	Net energy consumption (kWh)
All-wheel drive	0.2709	1.0078
Front-wheel drive	0.2934	0.9852
Rear-wheel drive	0.2604	1.0183
EV configuration	Percentage of energy saving improvement when considering dynamic LSCP instead of constant LSCP (%)	
All-wheel drive	5.66	
Front-wheel drive	3.68	
Rear-wheel drive	6.37	

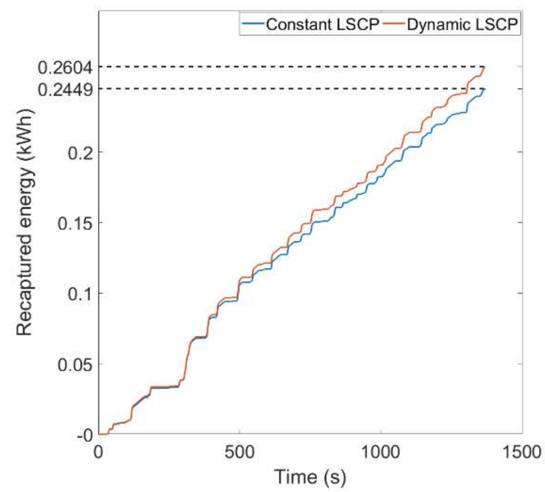
from regenerative braking during a complete drive cycle is depicted for different EV configurations in Fig. 5. As shown in Fig. 5, the recaptured energy through regenerative braking increases when considering dynamic LSCP instead of constant LSCP for all configurations.

Furthermore, the results of Table II show that for all configurations, using the dynamic LSCP method to control regenerative braking cutoff point improves the amount of extracted energy compared to the constant LSCP method. It is also noted that among the three configurations, the front-wheel configuration yields the highest energy extraction during regenerative braking whereas the rear-wheel drive configuration has the lowest energy harvesting capability for both methods. As a result, the required net energy consumption that is calculated from the difference between the required energy to propel the vehicle and the energy recovered through regenerative braking is higher in rear-wheel drive EVs. According to the last section of Table II, the energy saving improvement with dynamic LSCP is greater for rear-wheel configuration compared to the other two configurations which indicates that the energy savings are more significant for this configuration if dynamic LSCP is implemented.

This improvement in energy harvesting is even more noticeable when considering a typical passenger vehicle annual driving range of 12,000 miles [15]. Thus, a considerable portion of energy can be saved through regenerative braking by considering dynamic LSCP for all EV configurations under study. Assuming that a vehicle's traveling path follows a UDDS drive cycle every day and taking into account that a UDDS is almost 7.45 miles, a vehicle in a year completes around 1610 UDDS drive cycles. Thus, as shown in Table III, implementing dynamic LSCP instead of constant LSCP for a single EV can save anywhere from 17 kWh to 25 kWh annually depending on the EV configuration. These energy savings can be even more significant when considering driving patterns with more stop-and-go-traffics in which the brakes are frequently used in lower speeds.



(a)



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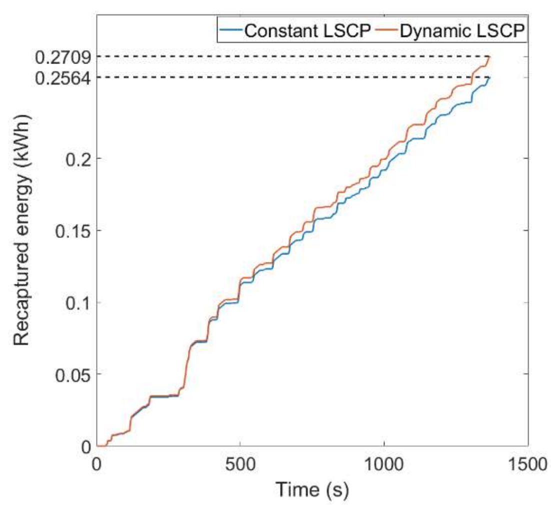

(c)

Fig. 5. Recaptured energy through regenerative braking for different configurations of EVs (a) Front-wheel drive EV (b) Rear-wheel drive EV (c) All-wheel drive EV

TABLE III
ANNUAL ENERGY SAVINGS FOR DIFFERENT EV CONFIGURATIONS (KWH)

	Constant LSCP	Dynamic LSCP	Improvement in energy savings
All-wheel drive	413	436	23
Front-wheel drive	456	473	17
Rear-wheel drive	395	420	25

V. CONCLUSIONS

In this paper, the importance of considering dynamic LSCP during regenerative braking was discussed from the perspective of maximizing energy recapturing during low speed braking. The strategy was examined on single-axle and all-wheel drive EVs. Different cases were studied and simulation results revealed that the energy recapturing capability is improved by considering dynamic LSCP for all EV configurations under study. Moreover, it was concluded that this increase in energy harvesting was more significant for rear-wheel drive EVs compared to all-wheel drive and front-wheel drive EVs. Implementing dynamic LSCP requires no hardware modification to the existing EV platforms that already have regenerative braking capability and can simply be implemented through modifications in the brake controller strategy. This study can be useful for EV automotive companies looking into improving regenerative braking capability of their existing products or planning to invest in different EV configurations from the viewpoint of maximizing regenerative braking performance.

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