Improvement of Regenerative Braking Energy of Fully Battery Electric Vehicle Through Optimal Driving

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Abstract

Though a fully battery electric vehicle serves zero air pollution, people are not getting interest to adopt it. The primary reason is the low driving range of battery electric vehicle. A unique advantage of electric vehicle is to easily implement regenerative braking which converts the lost kinetic energy during braking to electrical energy that can recharge the battery, thereby extending the electric vehicle range. In order to maximize the range extension, maximum braking energy needs to be regenerated. Through past studies, it was noticed that driving harshness lowers the regenerative efficiency in a great extent. Based on this understanding, in the present work, an analysis is carried out to enumerate the improvement nature of regenerative braking energy of fully electrical vehicle through adopting an optimal driving strategy. Regenerative braking energy based on optimal driving strategy is compared with that of using arbitrary driving strategy to examine its effectiveness in different speed changes. The present analysis is carried out using a typical fully battery electric vehicle with serial regenerative braking system. Simulation results suggest that use of multiple deceleration rates during braking is most appropriate. The same concept was found valid after analysing published experimental drive data of an electric bus. A significant regenerative braking energy improvement was noticed particularly when the speed changes is high.

Keywords

battery electric vehicle, optimal driving strategy, regenerative braking energy, trip time, multi-objective optimization

1. INTRODUCTION

Unlike a hybrid electric vehicle (HEV), a battery electric vehicle (BEV) runs entirely using an electric motor and battery, without the support of a conventional internal combustion engine. Consequently, BEV becomes the most efficient vehicle to reduce pollution. In spite of that, IC engine or hybrid vehicles are dominating car market in Asia. Because, people are not confident enough to choose a full battery electric vehicle for performing trip. The primary reason behind that is the low driving range of BEV. Among various possible improvements to extend BEV range, regenerative braking is a unique advantage of electric vehicle compare to fossil fuel based vehicles. RBS converts the lost kinetic energy (KE) during braking to electrical energy that can recharge the battery.

Various efforts were made earlier to increase the regenerative braking energy. A control strategy was proposed in [Jo et al., 2011; Yeo et al., 2006] by adjusting the CVT gear ratio for sustaining motor in high efficiency area. About 8 % improved regeneration efficiency is achieved using this strategy. A new type of regenerative braking system based on anti-lock braking system (EABS control unit) was proposed in [Junzhi et al., 2014] where the proportion of rear braking is increased, and simultaneously hydraulic pressure modulates wheel cylinder pressure to consummate greater regeneration efficiency. It was stated that about 15 % regenerative energy and 3 % fuel consumption are amend by adopting EABS. A fuzzy-logic-based regenerative braking strategy was proposed in [Xu et al., 2011]. Authors suggested that by applying the proposed RBS integrated with series regenerative braking, driving range of LF620 EV was improved by 25.7 %. Based on the distributions of total required braking torque into hydraulic (mechanical) and regenerative braking torque, a combined braking control strategy was proposed in [Peng et al., 2008]. Harada and Fujimoto tried to optimize the vehicle velocity trajectory, and front and rear driving-braking force distribution ratio in order to maximize the regenerative energy [Harada and Fujimoto, 2014]. Based on the charge and discharge characteristics of the battery and motor, a simple regenerative braking strategy was proposed in [Guo et al., 2009].

At the time of deceleration, braking of a vehicle is normally performed by either planned or un-planed manner. A definite stop or desired speed at a particular location is normally known to the driver before apply-

ing the brake at the time of planned braking. Whereas during un-planned braking, driver does not have such information well before applying the brake. Rather, driver has to take the decision suddenly. In planned braking situations, the necessary torque for braking may be fulfilled either by applying regenerative braking or mechanical braking, or both. But, in case of unplanned braking, mechanical braking is the primary choice because of high braking torque demand in order to stop the vehicle within a short distance/ time. In a study [Suntharalingam et al., 2010], it was found that performance of a RBS critically depends on the deceleration rate as well as terrain adhesive coefficient. The maximum and minimum deceleration rates to be applied during braking also depend on the type of vehicle [Maurya and Bokare, 2012]. Driving ruggedness is another important issue which diminishes RBS performance significantly [Walsh et al., 2010; Danny Harvey, 2010]. From these research studies, it is understood that another possible way to improve the regenerative energy is to adopt an optimal driving strategy (ODS) during braking. Driving strategy (DS) is represented by a set of optimal deceleration(s) and its corresponding duration(s). Though there were studies to show that deceleration nature affects the regenerative energy, a very limited studies enumerate the effect of decelerate rate on the RBS performance. Adopting an ODS during braking is not quite easy in case of unplanned braking, where as it can be effectively used in planned braking. In the present work, an effort is made to find the ODS for a speed change, and to quantify how much regenerative energy can be improved compare to an arbitrary DS in planned braking of fully EV with serial regenerative braking system.

2. VARIOUS OBJECTIVES NEED TO BE CONSIDERED DURING BRAKING

Besides maximizing the amount of regenerative braking energy (RBE), another concern of a driver during braking is to minimize the deceleration duration. Though the contribution of deceleration duration to the entire trip time is comparatively low, it cannot be neglected in urban or neighborhood areas since there is a frequent requirement of acceleration/ deceleration. In addition to shorter trip time, another significance of low deceleration duration is to avoid accident.

Thus, the primary objectives during braking are maximization regenerative braking energy and minimization of deceleration duration.

Now for a given speed change, to brake the EV in a shortest duration possible, the deceleration rate must be as high as possible. But in that case, a high braking torque will be required. Such high torque may not be delivered by the electric motor (generator) according to its capacity. Thus there will be a requirement of applying the mechanical brake additionally in order to compensate the extra braking torque, and it results in wasting KE (low regenerative energy). In addition, as the EV speed decreasing during braking, the electric motor (generator) torque (energy recovering) capacity is also reducing since EV KE is diminishing [Larminie and Lowry, 2012]. In contrast, keeping a low deceleration rate though it increases EV range and regenerative energy as the required braking torque solely delivered by the generator, there will be high trip time and chance of accident due to violating the safe braking distance. Such phenomenon suggests that maximization of energy regeneration and minimization of deceleration duration behave conflicting in nature.

During braking, generally, the vehicle deceleration rate varies from a highest value at the beginning to a lowest value at the end of deceleration maneuver to achieve a better comfort. Moreover, in a study [Chakraborty and Nandi, 2016] it was found that multiple deceleration rate during braking increases more regenerative energy. Because in that case the generator is able to function in its most efficient regime. It was also confirmed through an analysis of experimental drive data of an electric bus (presented later). Now applying multiple deceleration rates and other sources lower the journey comfort by creating jerk that leads to passenger's health effects [Wei and Rizzoni, 2004; Grant and Haycock, 2008]. Thus, minimization of jerk is also to be considered as an objective during braking, and it conflicts to the maximization of energy regeneration.

The above three objectives primarily depend on deceleration rate(s), deceleration duration(s) and the gains of controllers that are used to control the motor, and regenerative/Mechanical braking systems.

3. FORMULATION OF MULTI-OBJECTIVE OPTIMIZATION PROBLEM

From the above discussions, a multi-objective optimization problem (MOOP) is formulated as follows:

Minimization of Deceleration duration (T_{dec})
$$= f_D (d_{1, 2, 3 \ldots, K}, t_{1, 2, 3 \ldots, K-1}, k_{1p}, k_{1i}, k_{2p}, k_{2i}) \qquad (1)$$

Maximization of RBE (E_{regen})
$$= f_E (d_{1, 2, 3 \ldots, K}, t_{1, 2, 3 \ldots, K-1}, k_{1p}, k_{1i}, k_{2p}, k_{2i}) \qquad (2)$$

Minimizati of total jerk (J_{Total})
$$= f_J (d_{1, 2, 3 \ldots, K}, t_{1, 2, 3 \ldots, K-1}, k_{1p}, k_{1i}, k_{2p}, k_{2i}) \qquad (3)$$

Subject to
$$0.1 \leq d_{1, 2, 3 \ldots, K} \leq 2.5$$
$$0.01 \leq k_{1p}, k_{2p} \leq 0.3$$

$0.01 \leq k_{1i}, k_{2i} \leq 3.0$

where $d_{1,2,3,...,K}$ (m/s^2) and $t_{1,2,3...,K-1}$(sec) are the K number of deceleration rates and corresponding durations, respectively. k_{1p} and k_{1i} are the gain parameters of vehicle (PI) controller. For mechanical brake (PI) controller, the gain parameters are k_{2p} and k_{2i}. The deceleration rate is allowed to vary 0.1 to 2.5 m/s^2 [Suntharalingam et al., 2010]. Variations of controller gains during simulation are decided through experimentation in order to run the system efficiently.

In order to solve the above MOOP, a multi-objective evolutionary algorithm is adopted here. To find an optimal solution (ODS) through solving the MOOP, first a set of Pareto-optimal solutions are to be find out based on EV component models. Then using some higher level information or multi-criterion decision making technique, a preferred solution is identified for implementation.

4. MULTI-OBJECTIVE OPTIMIZATION METHOD

In the present work, a non-dominated sorting genetic algorithm (GA), namely NSGA-II [Deb et al., 2002] is adopted to solve the optimization problem.
The basic working principle of NSGA-II is illustrated in Figure 1. The simulation run is initiated after initializing a set of population (of fixed size) which is also considered as the parent population, and then follows the different steps.

- Step 1: Assignment of non-domination rank and crowding distance value to each solution based on objective values

- Step 2: Formation of mating pool using crowded tournament selection operator
- Step 3: Creation of offspring solutions using GA-operators (crossover and mutation).
- Step 4: Non-dominated sorting of the combined parent and offspring population.
- Step 5: Construction of new parent (current) population by selecting the ones (from best to worse) based on their ranks. The crowding distance value is used for selection when the number of solutions in a rank is more to maintain a constant population size.
- Step 6: The simulation iteration is continued until a termination criterion is reached.

5. EV COMPONENT MODELS

Electric motor (generator), battery and vehicle are the primary EV components.
There are two types of motors used in EVs: DC and AC motors. Due to the efficiency consideration and speed control, majority of vehicle manufacturers prefer to use AC motors instead of DC motors in EVs. Most of their designs have been used in the prototype electric cars. However some of the manufacturers still see the potential for the DC motor because though AC induction motors offer less expensive nature but more complex controller is needed to control the frequency component. Moreover, the power electronic system (for AC motor) in this vehicle doesn't have a regenerative braking function. Implementation of regenerative braking using AC motor is more complex. To improve and identify the feasibility of using DC motors in electrical vehicles, it is important to design a regenerative braking system for this vehicle and es-
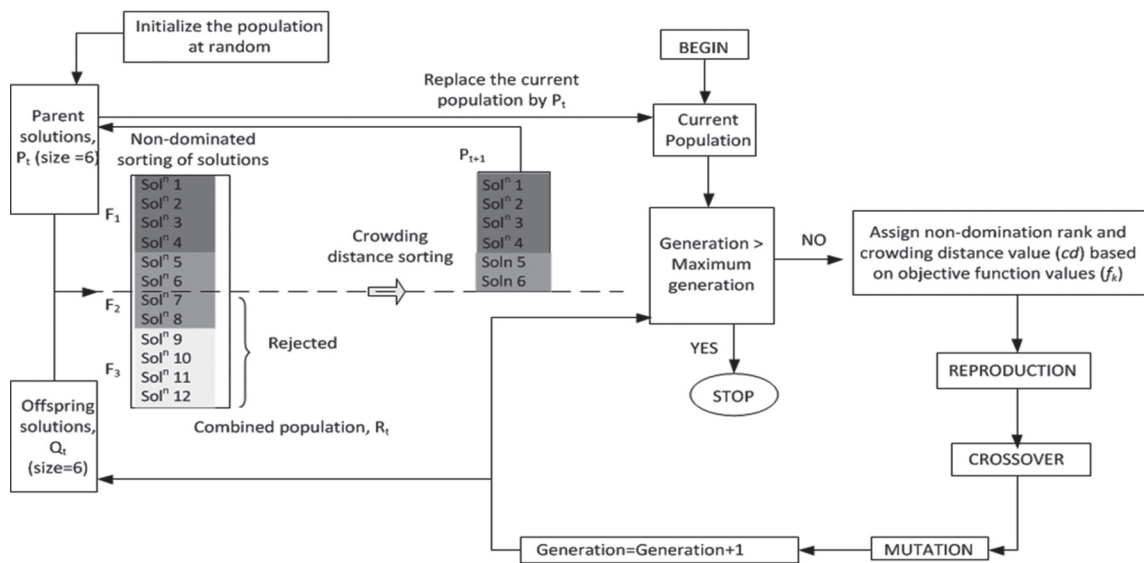

Fig. 1 Working principle of NSGA-II

pecially, using series configuration. For making it cost effective, the regenerative braking system with maximum energy recovery should be achieved by using only inexpensive power electronic switching devices instead of highly expensive configuration of AC motors [Xiao et al., 2012].

Among different set of batteries, nickel-cadmium had been the only suitable battery for portable equipment. But Lithium is the lightest of all metals, has most electrochemical potential to provide the largest energy density for weight. As researches going on, lithium batteries failed in recharging due to safety problems of lithium metal. Lithium-ion batteries provide safety during recharge though it has slightly lower energy density than lithium metal. Lithium-ion provides low maintenance than standard nickel-cadmium and lead-acid batteries. In addition, the self-discharge is less than half compared to nickel-cadmium, making lithium-ion well suited for modern fuel gauge applications. The energy density of lithium-ion is typically twice that of the standard nickel-cadmium. There is potential for higher energy densities as well.

Present investigation is carried considering an EV in combination with 26 HP DC brushed motor and 394 V Li-ion battery. The vehicle model and parameters were similar to General Motors EV1 model in [Gantt et al., 2011] and [Larminie and Lowry, 2012], which was propelled using a DC motor. This particular model was chosen because it has been well described in the literature. While most modern EVs use AC motors, DC motors are easier to model and simulate. It has been shown that an AC induction motor (prevalent in modern EVs) can be made to behave like a separately excited DC motor [Yamamura, 1986]. Therefore, the authors expect the main objectives of the study to be valid even for AC motors. The EV component models used here to calculate the energy regeneration and deceleration duration follows the EV model topology presented in [Larminie and Lowry, 2012; Gantt, 2011; Chen and Rincon-Mora, 2006].

Various inputs considered for the motor model are battery voltage, k^{th} reference deceleration rate, d_k (m/s^2), vehicle actual deceleration rate, d_{actual} (m/s^2), deceleration duration, t_k reference speed, v_{ref}, vehicle actual speed, v, and rotational speed, w, the controller gains and the outputs are battery current, I_P, and braking torque, τ. The battery model's input is battery current, I_P, and the outputs are battery voltage, V_P, and state-of-charge, SOC. The inputs of vehicle model are electric motor torque, and the outputs are d, v, and w.

6. SERIAL REGENERATIVE BRAKING SYSTEM

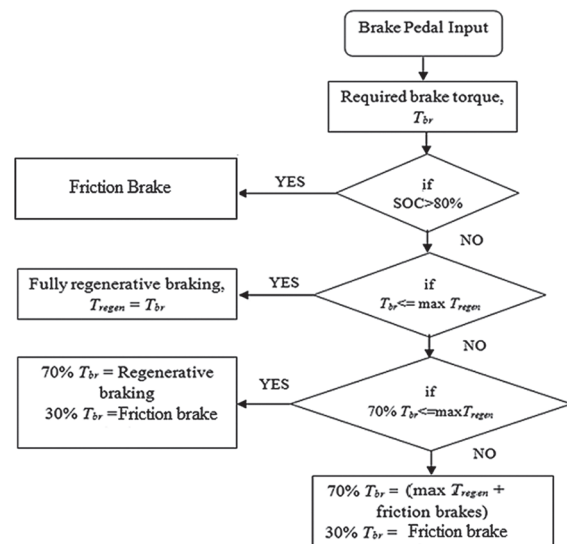In this paper, the study on possible improvement of

Fig. 2 A schamatic layout of Serial regenerative braking system

RBE using ODS is carried out for an EV with a serial RBS. The serial RBS proposed in [Varocky, 2011] is considered here. The schematic layout of the serial RBS is presented in Figure 2(a). In Figure 2(a), τ_{regen} and τ_{br} are the regenerative braking torque applied to the generator and the total brake torque demand, respectively. It was assumed that the maximum τ_{regen} that the generator can withstand is 85 % of motor torque, τ at a speed, ω. That means at any condition 85 % of motor torque can be used to regenerate electricity.

7. CONTROL SYSTEM AND CALCULATION OF OBJECTIVES THROUGH SIMULATION

A control system is designed for the serial RBS as shown in Fig. 2(b). The control system comprises of two PI controllers: vehicle controller and friction brake controller. Vehicle controller is used to control the motor speed. The motor is directly coupled to the EV rear axle through gear transmission. During braking, the motor works like a generator, and converts the EV KE into electricity that is used to charge the battery. Reference deceleration (d_{ref}) and reference velocity (v_{ref}) which are decided by the optimization algorithm are fed as the inputs to vehicle controller. Other inputs such as β_1 fraction of EV actual deceleration, d_{actual} and actual velocity (v_{actual}) are fed back to the vehicle controller in opposite phase to stabilize the system.

The Friction Brake Controller is directly attached to EV to control the hydraulic/friction braking. This controller is in function if the required braking torque command is higher than the maximum (possible) regenerative braking torque resisted by generator. The reference deceleration value (d_{ref}) is used as input of
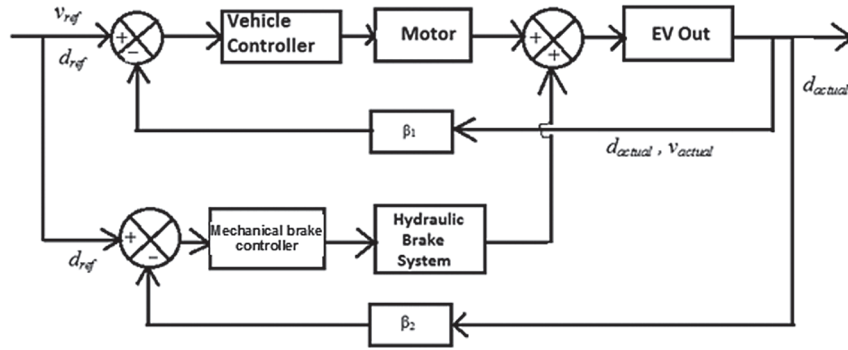
Fig. 3 Layout of control system

Friction brake controller, and β_2 fraction of actual EV deceleration (d_{actual}) is fed back to the controller in opposite phase to stabilize the system.

When $\tau_{br} < \tau_{regen}$, the regenerative braking alone is sufficient, and in this case, $\beta_1 = 1.0$ and $\beta_2 = 0$. In many situations, the regenerative braking alone is not sufficient to the required brake toque demand because it is mostly depended on motor (generator) speed. In unplanned braking (e.g., emergency braking), regenerative systems can neither provide the necessary braking power nor handle the amount of electricity generated from a maximum-deceleration stop. In order to stop the EV in a short distance and time, a large braking torque will be needed. In such situations, the portion of EV KE to be used for energy regeneration is reduced by lowering the β_1 value, and at the same time friction brake torque is increasing by increasing the β_2 value. However in any situation $\beta_1 + \beta_2$ becomes 1.0.

Using the control system presented in Figure 2, the simulation is carried out based on the EV component models for n iterations with a time step, dt. At i^{th} iteration, E_{regen} and J are:

$$E_{regen}(i) = I_P(i) \cdot V_P(i) \cdot dt \qquad (4)$$

$$J_i = \frac{d(i) - d(i-1)}{dt} \qquad (5)$$

$$E_{regen} = \sum_{i=1}^{n} E_{regen}(i) \qquad (6)$$

$$T_{dec} = ndt \qquad (7)$$

$$J_{Total} = \sum_{i=1}^{n} J_i \qquad (8)$$

8. MODEL VALIDATION

EV component models (motor and battery) are validated through analyzing the characteristics of their critical parameters observed during simulation runs. A

typical speed change (80 to 0 km/hr) is considered. Variation of motor current with respect to time is presented in Figure 4(a). The relevant parameter values of electric motor, battery and vehicle considered in the present study are shown in Table 1. As time increases it is seen that motor current increases for some time, after that it starts reducing. Actually, the motor is running here as a generator, and motor speed is controlled by the controller with respect to actual speed of the vehicle. As the vehicle speed (means speed of the motor) reduces, generating current is also reduced, and finally it turns near to zero as the vehicle stops. Armature reaction is also a cause of reducing current. The variation of battery voltage as shown in Figure 4(b) follows the same pattern as battery voltage varies during charging [Ricktech Technology, 2014].

Figure 4(c) shows the details of total braking torque demand during the deceleration process. The torques generated through mechanical and regenerative braking processes are also shown in Figure 4(c). It is noticed that the maximum regenerative torque (126 Nm) is always found lower than the maximum motor torque (148 Nm). Vehicle's actual deceleration with motor speed is shown in Figure 4(d). Motor speed falls down in higher rate when deceleration value is high. It is also seen from Figure 4(f) that maximum regenerative energy is much less than maximum available KE.

9. ANALYSIS OF EXPERIMENTAL DRIVE DATA TOWARDS EFFECTIVENESS OF MULTIPLE DECELERATION RATES ON RBE

Drive data of an Electric Bus (E-Bus) referred in [Vaz et. al. 2015] are analyzed here in order to demonstrate how EV battery energy varies with constant and multiple decelerations approaches. Sample drive data of E-bus includes the readings of battery voltage, speed, motor current, and road gradient. From drive data, two different deceleration zones (SZ_1 and SZ_2) are identi-
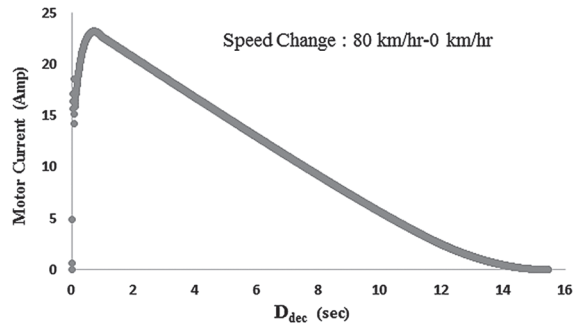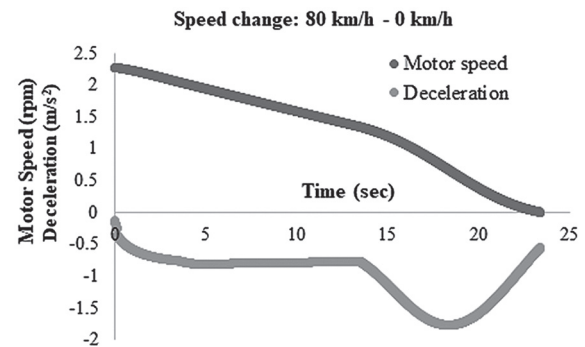
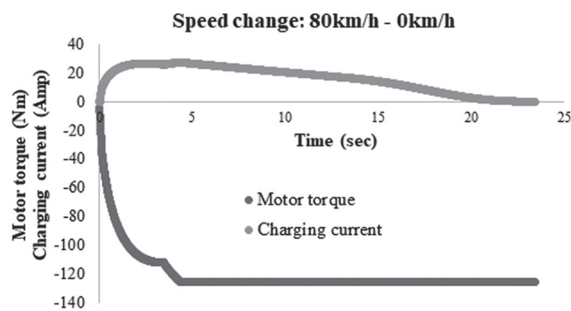(a) Motor current variation with time
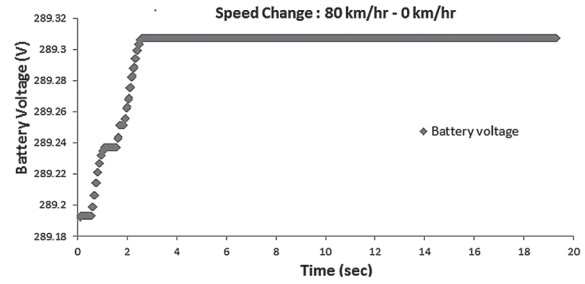
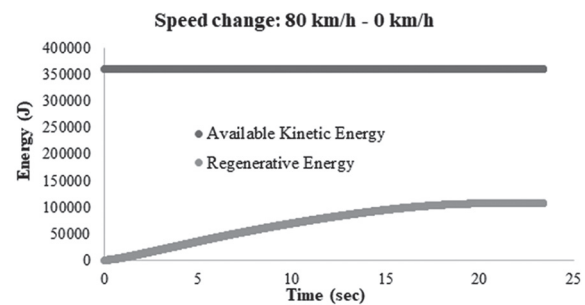(b) Effect of multiple deceleration in battery voltage with respect to time
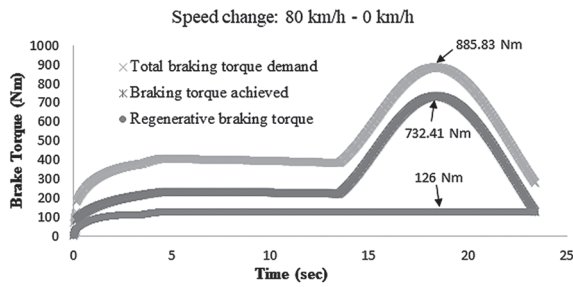
(c) Variation of different types of brake torque with respect to time

(d) Variation of motor speed with deceleration

(e) Variation of motor torque and battery charging current with respect to time

(f) Available kinetic energy and regenerative energy

Fig. 4 Variation of (a) Motor current and (b) Battery voltage (c) different types of braking torque (d) motor speed with deceleration(e) motor torque and battery charging current (f) Available kinetic energy and regenerative energy in simulation run

fied.

Figure 6(a) and Figure 7(a) present the deceleration values of EV applied during a certain speed change in SZ_1 and SZ_2, respectively and the corresponding energy (which is calculated based on measured battery voltage, current, and time duration) and speed are presented in Figure 6(b) and Figure 7(b), respectively. In Figure 6(a), it is noticed that after 10 sec the difference between two consecutive decelerations is very high, and such kind of significant difference is not found before 10 sec. From these circumstances, it may be considered as the single deceleration approach is applied during the period of 1-10 sec, whereas the multiple decelerations approach is treated in the period 10-18 sec. After analyzing the Figure 6(b), it was

observed that energy recovered per second using ODS is almost twice better than that using arbitrary DS.

In SZ_2 (as shown in Figure 7(a)), the entire deceleration duration can be treated as multiple deceleration approach except the durations 2-6sec and 8-14 sec are followed as constant deceleration approach. Contrary to SZ_1, energy recovered per second in these two constant deceleration sections is found 80 % better than energy recovered in multiple deceleration section. Such phenomenon suggests that in multiple deceleration section, driver does not follow the optimal condition for deceleration. It concludes that multiple deceleration approach does not always provide better results unless an optimal driving strategy is followed. Such kind real scenario was also noticed in the opti-

Table 1 EV model parameters

| Electric Motor	
Type	DC brushed
Motor moment of inertia coefficient, I	0.05
Copper losses	0.3
Iron losses	0.01
Windage losses, kw	0.000005
constant electronics losses	600
Proportional controller gain for speed, KP	2.0
Critical motor speed,(rpm)	733
Maximum motor speed,(rpm)	1326
Maximum torque (nm)	148
Battery	
Capacity, (A•h)	53
Initial state-of-charge, SOC_{init}	1.0
Number of cells in parallel	1
Number of cells in series	76
Type	Lithium-Ion
Voltage, V_P (V)	394
Battery efficiency	0.99
Battery long transient capacitance (MF)	0.22375
Battery long transient resistance (mΩ)	0.9968
Battery short transient capacitance (MF)	0.03518
Battery short transient resistance (mΩ)	0.9338
Battery series resistance (mΩ)	1.4932
Vehicle	
Air density (kgm^3)	1.143
Frontal Drag coefficient	0.19
Back Drag coefficient	0.3
Frontal area (m^2)	1.8
Back area(m^2)	1.4
Gravitational acceleration (m/s^2)	9.81
Mass including passengers and drivers (kg)	1460
Overall gear ratio/tire radius(1/m)	37
Rolling friction coefficient	0.014
Transmission	Single-speed
transmission efficiency	0.95

mization simulation results.

10. IMPROVEMENT OF REGENERATIVE BRAKING ENERGY

In order to investigate the regenerative braking energy improvement, an optimization simulation was carried out considering the MOOP presented in Section 3. The ODS is determined considering multiple deceleration rates during braking. Figure 9 demonstrates the Pa-
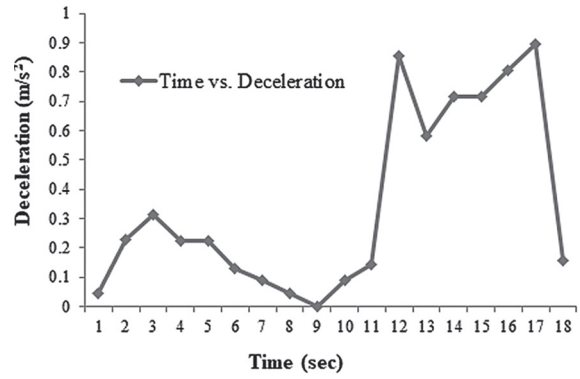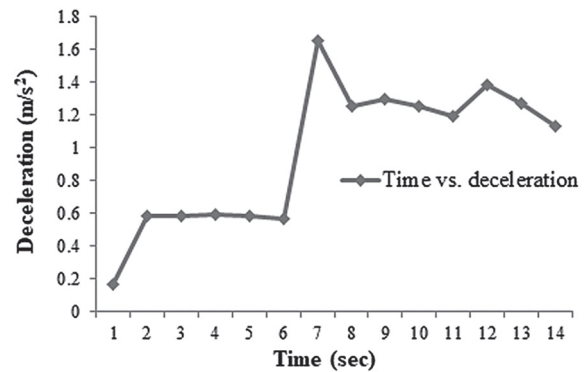

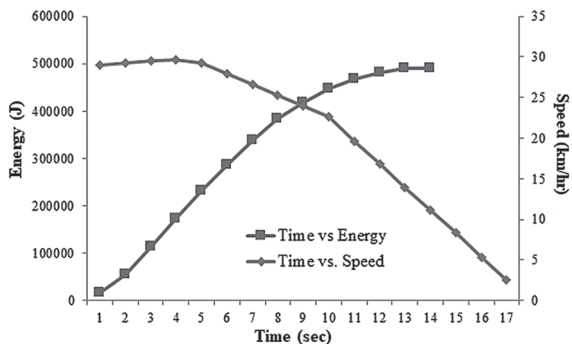(a) Energy variation and speed change with respect to time
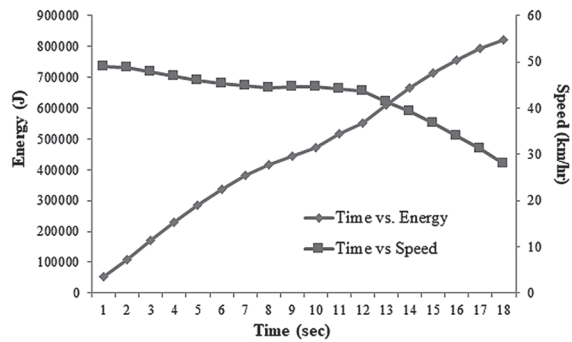
(b) Variation of deceleration with respect to time

Fig. 5 Experimental E-bus data of SZ$_1$

(a) Energy variation and speed change with respect to time

(b) Variation of deceleration with respect to time

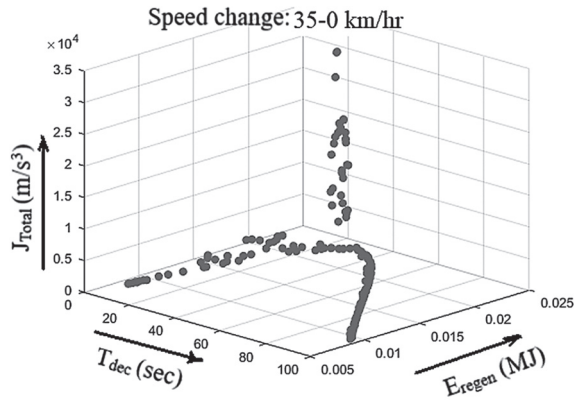**Fig. 6** Experimental E-bus data of SZ$_2$

Fig. 7 Optimization results considering multiple deceleration rates

Fig. 8 Comparisons of RBEs obtained using ODS and arbitrary DS

reto-front obtained after simulation run for the speed change 35-0 km/hr. Now, RBE of ODS is compared with that of arbitrary DS. Since it does not mean any sense of choosing an arbitrary DS, RBE is calculated for best DS considering constant deceleration rate during braking, and it is compared with that presented in Figure 9. The best DS is decided by performing simulation study of the same optimization problem presented in Section 3 considering constant deceleration during braking.

Figure 10 presents the E_{regen} vs T_{dec} plots of a set of ODS and arbitrary DS. From Figure 10, it was noticed that E_{regen} increases with increasing T_{dec}. The comparative analysis was made between an arbitrary DS and the ODS obtained after solving the optimization problem for a same deceleration duration. Up to $T_{dec} = 8.7$, no such significant improvemen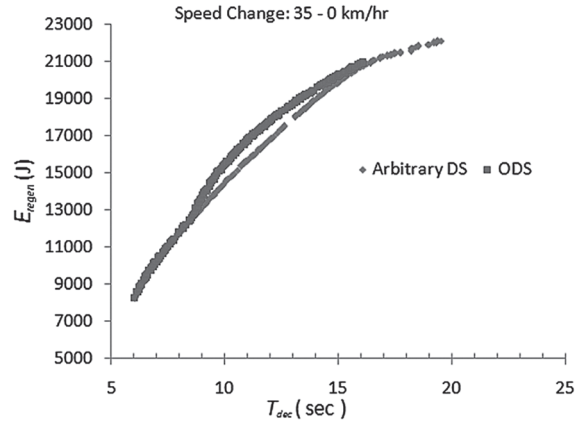t of ODS is found compare to arbitrary DS. The maximum RBE improvement is observed at $T_{dec} = 11.05$ by 6.8 %. Similar analysis was also carried out for other speed changes. In four different speed changes, E_{regen} found by SRBS adopting arbitrary DS and ODS for a certain T_{dec}, are presented in Table 2. Table 2 also enlists the corresponding values of arbitrary DS and ODS. The percentage improvement of E_{regen} is also noticed high in higher speed changes.

The deceleration rates fo arbitrary DS and ODS corresponding to E_{regen}-T_{dec} plot of Figure 8 are presented in Figure 9 and Figure 10, respectively. From Figure 10, it was noticed that the values of 1st deceleration are found high for low E_{regen}, but is was found low for high E_{regen}. On the other hand, almost a constant high value of 2nd deceleration is noticed for any E_{regen}. Similar observations were also noticed in case of other speed changes.

Table 2 Energy regeneration in Approach I and Approach II in different speed changes

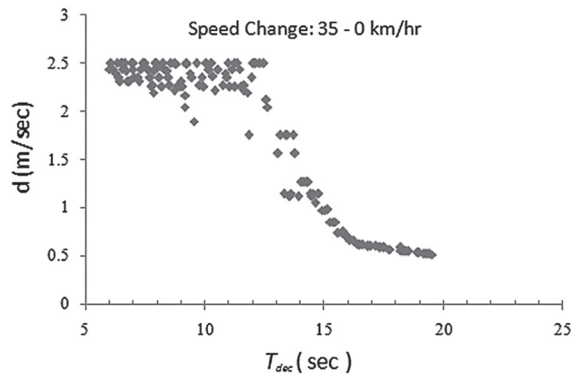| Speed change (km/hr) | T_{dec} (sec) | Arbitrary DS | | ODS | | (%) Improvement of $E_{rege}n$ |
		d (m/sec^2)	E_{regen} (J)	d (m/sec^2), t (sec)	E_{regen} (J)	
35-0	10.93	2.348	15583.2	$d_1 = 0.723$, $t_1 = 4.693$, $d_2 = 2.490$, $t_2 = 6.238$	16622.9	6.67
55-0	13.0502	2.335	36343.2	$d_1 = 0.831$, $t_1 = 6.209$, $d_2 = 2.433$, $t_2 = 6.840$	41178	13.304
80-0	19.24	2.116	87203.5	$d_1 = 0.844$, $t_1 = 9.720$, $d_2 = 2.430$, $t_2 = 9.520$	98137.7	12.54
110-0	27.82	1.416	181655	$d_1 = 0.855$, $t_1 = 12.850$, $d_2 = 2.484$, $t_2 = 14.970$	205327	13.03

Fig. 9 Deceleration rate of arbitrary DS corresponding to Figure 8

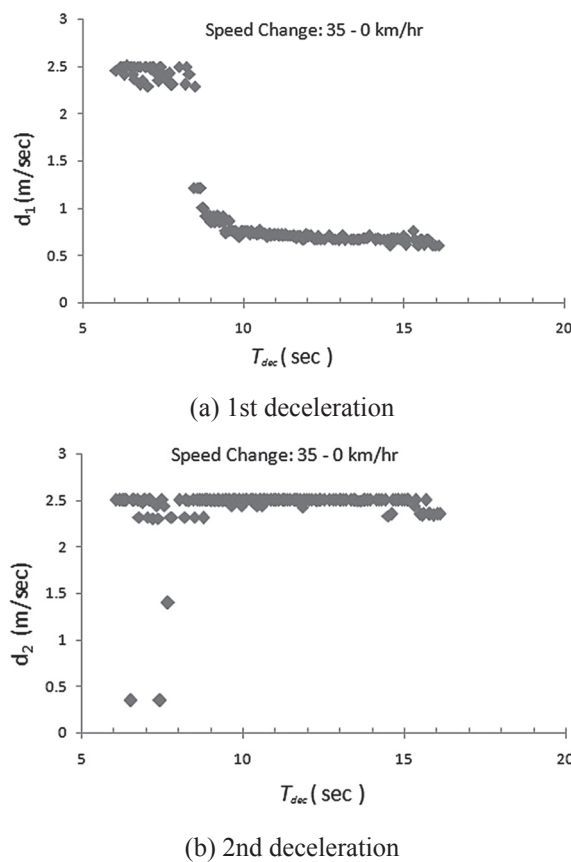(a) 1st deceleration

(b) 2nd deceleration

Fig. 10 Deceleration rates of ODS corresponding to Figure 8

The strategy of RBE improvement using an ODS may be implemented to an electric vehicle without any additional cost. This strategy can immediately benefit the driver since adopting it does not require any changes to existing EVs. Moreover, such RBE improvement is not limited only to a fully battery electric vehicle. It can also be adapted to HEV or PHEV, particularly where (electric) regenerative braking system is used.

The present strategy not only guides the driver to regenerate more KE but also takes care to effectively operate the EV components with maximum efficiency to obtain the best performance. As a result, it substantially reduces the operating cost of the EV by maximizing RBE, increasing the operating life of the components, increasing the safety.

However, the present concept of RBE improvement is difficult to implement during unplanned braking where a high braking torque is required for a short time.

The method of designing ODS to change a speed may be useful to derive a driver assisting system for optimal trip planning. This strategy can be used in existing automated driving systems such as described in [Ardelt et. al., 2012].

11. CONCLUSION

The present work deals with the improvement of regenerative braking energy of electrical vehicle using optimal driving strategy. Three primary objectives (maximization of regenerative energy, minimization of deceleration duration and minimization of jerk) need to be considered during braking. It was found that these objectives are conflicting with each other. ODS is determined by solving a multi-objective optimization problem consisting of these objectives using an evolutionary algorithm. Analysis of regenerative braking improvement is conducted on an electric vehicle with 26HP DC brushed motor, 394 V Li-ion battery and serial regenerative braking system.

To calculate the objective values, EV component models available in the literature are considered. The EV component models and its parameters are validated through analyzing their characteristics exhibited in the simulation run. A comparative analysis is carried out among the regenerative braking energies obtained by serial braking system using ODS and arbitrary DS. It was found that around 13 % more braking energy regeneration may be achieved using ODS. The ODS is found to follow two deceleration rates during the entire braking.

References
Ardelt, M., Coester, C., and Kaempchen, N., Highly automated driving on freeways in real traffic using a probabilistic network, *IEEE Transactions on Intelligent Transportation Systems*, Vol. 13, No. 4, 1576-1585, 2012.
Chakraborty, D. and Nandi, A.K., Finding optimal deceleration with serial regenerative braking of

electric vehicle using a multi-objective genetic algorithm, *IEEE International Conference on power electronics, intelligent control and energy systems* (IEEE ICPEICES 2016), 2016.

Chen, M. and Rincon-Mora, G.A., Accurate electrical battery model capable of predicting runtime and I-V performance, *IEEE Transactions on Energy Conversion*, Vol., 21, No. 2, 504-511, 2006.

Danny Harvey, L. D., Energy Efficiency and the Demand for Energy Services, Earthscam Ltd, Dunstan House, 14a Cross Street, London ECIN 8XA, UK, 2010.

Deb, K., Pratap, A., Agarwal, S., and Meyarivan, T., A fast elitist non-dominated sorting genetic algorithm for multi-objective optimisation: NSGA-II, *IEEE Transactions on Evolutionary Computation*, Vol. 6, No. 2, 182-197, 2002

Gantt, L.R., Alley, R.J., and Nelson, D.J., Battery sizing as a function of powertrain component efficiencies for various drive cycles, *Proceedings of the ASME International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE 2011), Washington*, 2011.

Grant, P. R. and Haycock, B., Effect of jerk and acceleration on the perception of motion strength, *Journal of Aircraft*, Vol. 45, No. 4, 1190-1197, 2008.

Guo, J., Wang, J., and Cao, B., Regenerative Braking Strategy for Electric Vehicles, *IEEE Intelligent Vehicles Symposium*, 2009.

Harada, S. and Fujimoto, H., Range extension control system for electric vehicles based on optimal-deceleration trajectory and front-rear driving-braking force distribution considering maximization of energy regeneration, *IEEE 13th International Workshop on Advanced Motion Control* (AMC2014), 2014.

Jo, C., Ko, J., Yeo, H., Yeo, T., Hwangand, S., and Kim, H., Cooperative regenerative braking control algorithm for an automatic-transmission-based hybrid electric vehicleduring a downshift, *Proceeding of IMechE Part D: J Automob Eng*, Vol. 226, 457-467, 2011.

Junzhi, Z., Yutong, L., Chen, L., and Ye, Y., New regenerative braking control strategy for rear-driven electrified minivans, *Energy Conversion and Management*, 135-145, 2014.

Larminie, J. and Lowry, J., *Electric vehicle technology explained*, Second ed., John Wiley & Sons, 2012.

Maurya, A. K. and Bokare, P. S., Study of deceleration behaviour of different vehicle types, *International Journal for Traffic and Transport Engineering*, Vol. 2, No. 3, 253-270, 2012.

Peng, D., Zhang, Y., Yin, C.-L., and Zhang, J.-W.,

Combined control of a regenerative braking and antilock braking system for hybrid electrical vehicles, *International Journal of Automotive Technology*, Vol. 9, No. 6, 749-757, 2008.

Ricktech Technology, Corporation, Understanding the characteristics of Li-ion batteries and Richtek power management solutions, Application note (AN023), 2014.

Suntharalingam, P., Economou, J. T., and Knowles, K., Effect on regenerative braking efficiency with deceleration demand and terrain condition, *5th IET International Conference on Power Electronics, Machines and Drives* (PEMD 2010), 1-6, 2010.

Varocky, B. J., Benchmarking of regenerative braking for a fully electric car, TNO Automotive, Helmond & Technische Universiteit Eindhoven (TU/e), 2011, Report No. D&C 2011.002.

Vaz, W., Nandi, A. K., and Koylu, U. O., Finding an optimal driving strategy for an electric bus based on driving data, *ASME conference on Power & Energy*, No. PowerEnergy2015-49089, 2015.

Walsh, C., Carroll, S., Eastlake, A., and Blythe, P., Electric vehicle driving style and duty variation performance study, *Cenex*, 1-11, 2010.

Wei, X. and Rizzoni, G., Objective metrics of fuel economy, performance and driveability – a review. SAE Technical Paper Series, 2004.

Xiao, Y., Nemec, M., Borle, L. J., Sreeram, V., and Llu, H. H. C., Regenerative braking of series-wound brushed DC electric motors for electric vehicles, *7th IEEE Conference on Industrial Electronics and Applications* (ICIEA), 2012.

Xu, G., Li, W., Xu, K., and Song, Z., An intelligent regenerative braking strategy for electric vehicles, *Energies*, Vol. 4, No. 9, 1461-1477, 2011.

Yamamura, S., *AC motors for high performance applications: analysis and control*, CRC Press, 1986.

Yeo, H., Hwang, S., and Kim, H., Regenerative braking algorithm for a hybrid electric vehicle with CVT ratio control, *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, Vol. 220, No. 11, 1589-600, 2006.