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RESEARCH ARTICLE

Artificial Neural Networks: A Promising Tool for Regenerative Braking Control in Electric Vehicles

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ABSTRACT

Regenerative braking systems (RBS) are a promising technology for recovering wasted kinetic energy during the braking process of electric vehicles. This energy can be stored in the vehicle's battery for later use, reducing fuel consumption, prolonging travel distances, and reducing maintenance costs. RBS is particularly beneficial in heavy traffic, where the brakes are used more frequently. In this research, an artificial neural network (ANN) model was developed to predict the amount of the recovered current and stoppage time needed for different braking scenarios. The ANN model was trained using data from a developed MATLAB Simulink model that was used to investigate the effects of braking force capacity and vehicle running speed on RBS performance. The performance of the RBS was evaluated in terms of the amount of recovered current and the time needed for the vehicle to come to rest. The outputs from the Simulink model were validated statistically using Design Expert ANOVA analysis before being implemented in the ANN model. The results of this study showed that the ANN model was able to accurately predict the amount of the recovered current and the stoppage time needed for different braking scenarios. Hence ANN models can be considered an accurate flexible model that can be used to develop efficient and effective RBS controllers for electric vehicles.

Keywords: Artificial neural networks, Recovered current, Regenerative braking system, Vehicle stoppage time.

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1. Introduction

The evolving energy crisis and growing environmental awareness compelled automotive researchers to consider electric vehicles (EVs) as a potential replacement for conventional fuel vehicles. This is to minimize vehicle's pollutant emissions and the used energy in transportation [1]–[3]. As, it was found that about 1/3 to 1/2 of transportation energy is consumed during the braking process [4]. Regenerative braking system (RBS) has been introduced as a potential replacement for hydraulic and mechanical brakes as they do not produce any pollutant emissions or consume large amounts of energy during braking. Instead, they can be used for charging EV batteries during the barking process [5], [6]. For instance, the kinetic energy wasted in the form of heat during the vehicle braking can be recovered by integrating RBS in EVs or by using hybrid braking systems [1], [7]–[9]. These braking systems are used to recover a portion of the wasted kinetic energy during braking vehicles in motion. The recovered energy can be used for charging an onboard energy storage system such as vehicle batteries. During the braking process, the electric motor acts as generator and reverses the direction of current back to be stored in the battery. It was mentioned that, integrating RBS in buses and trains can reduce fuel consumption by about 30% and increase energy efficiency to 30% [4], [8], [10], [11]. To ensure the efficiency of the energy recovery process some parameters must be considered such as the type of used motor, the applied braking force and EV batteries, different road surfaces coefficients, driver intentions, state of charge of the battery, drive distance, motor braking torque and braking forces distribution on the wheels [2], [9], [12].

Investigations showed that induction and permanent magnet motors generate eddy currents specially when the vehicle is running at high speed (>1500 rpm). These generated currents have a bad impact on the energy recovery process, to enhance the efficiency of the recovery process brushless DC motors (BLDC) are recommended. Moreover, it was also found that the used motor control technique can have an impact on the recovery process. It was proved that integrating fuzzy logic controllers with the regular PID motor controller can improve the efficiency of the recovery process. As this integration can prolong the vehicle travel distance increasing the amount of energy that can be recovered to the battery [5], [13], [14].

The braking force was considered one of the most influencing parameters as it governs the distance traveled by the vehicle. The travel distance decreases upon increasing the applied braking force reducing the efficiency of the recovery process. The applied braking force can be controlled using the vehicle pedals thus its sensitivity must be enhanced to ensure efficient performance of the energy recovery process [15]–[17].

EVs batteries are characterized by their frequent charge and discharge which has a bad impact on their life span. Hence, the development of the battery technology was hindered due to the low battery energy density and the large charging time needed. As a result, researchers are investigating the possibility of introducing energy saving technologies to enhance the expected EVs batteries' life span [1], [18]. It was found that EV battery life span can be enhanced by connecting ultracapacitors or super capacitors with the batteries. These capacitors act as a shield and protect the battery from shocks that can occur due to high charging and discharging currents. In addition, they can store larger amount of energy in shorter intervals of time, providing a means of faster charging for the battery than charging using the regular battery energy recovery process [11], [19], [20]. Up to authors' knowledge, it was observed that most of these investigations have been conducted experimentally which is expensive and time consuming to construct. In this research artificial neural networks (ANN) have been implemented to study the effect of parameters affecting the efficiency of the energy recovery process in passenger EVs RBS without using expensive time-consuming experimental testing. The ANN was used to map a relationship between the RBS recovered current and resultant vehicle stoppage time against variable vehicle speeds and variable amount of braking force applied. To eliminate the need for experimental data needed to construct the ANN, a simulation model using Simulink MATLAB GUI was constructed. At the beginning this model was validated using results obtained from previous experimental work. Then used to study the effect of different vehicle parameters on the performance of the RBS. In terms of vehicle speed and the applied braking force on the recovered current and vehicle stoppage time. The obtained results were validated from statistical point of view using ANOVA test on DESIGN EXPERT software.

2. Simulation Model

This section discusses the MATLAB Simulink model established to study the effect of the applied braking force and vehicle speed using permanent magnet synchronous motor (PMSM) on the vehicle stoppage time and the amount of regenerated current from the vehicle braking process. PMSM was selected over BLDC motor due to its higher efficiency and performance especially at low or high speed. In addition to its ability to produce higher torque and light weight [21]. Fig. 1 presents a layout of the simulated regenerative braking system. The results of this simulation process will be validated then used to build an ANN model that can be used to predict the amount of the regenerated current and time needed to brake the vehicle.

2.1. Simulink Model Setup

The Simulink model was established to resemble a real RBS of a passenger vehicle. To ensure the simulation results present a real-life RBS, the simulation time is set to infinity to monitor the effect of variations of the vehicle speed and braking force on the regenerated current and time needed to brake the vehicle. The simulation process is set to begin when the SOC (state of charge) of the battery is greater than 20% [5], [10], [18]. This is the least amount of battery SOC sufficient to discharge the current necessary for operating the vehicle's motor. During the braking process, the current is recovered and stored in the battery when its SOC is less than 80% [15]. Fig. 2 shows a flowchart for the RBS simulation process. Fig. 3 shows the details of the built Simulink model. The model consists of four main blocks and two subsystems. The main blocks are responsible for setting the motor speed, converting motor speed (rpm) into voltage (V) and frequency (Hz), producing a balanced three sine waves, and generation of a variable width pluses, respectively. The two subsystems represent the RBS, the motor control unit, and brakes, respectively. Fig. 4 shows details of the recovered current control subsystem. In this subsystem, the lithium-ion battery DC current is converted to AC current necessary to operate the vehicle's motor using a three-phase inverter having six insulated gate bipolar transistors (IGBTs). These transistors are connected to the PMSM

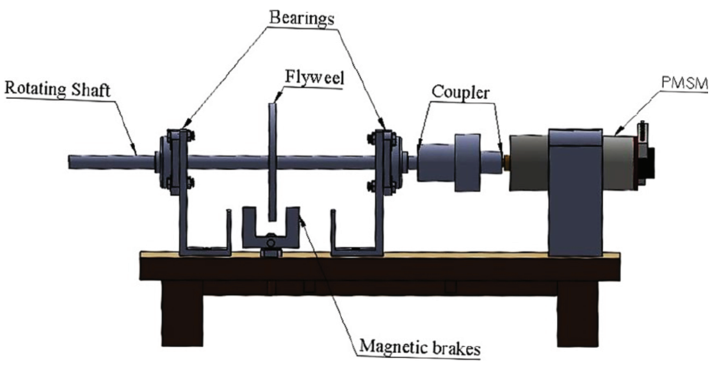

Fig. 1. A schematic layout of the simulated RBS.

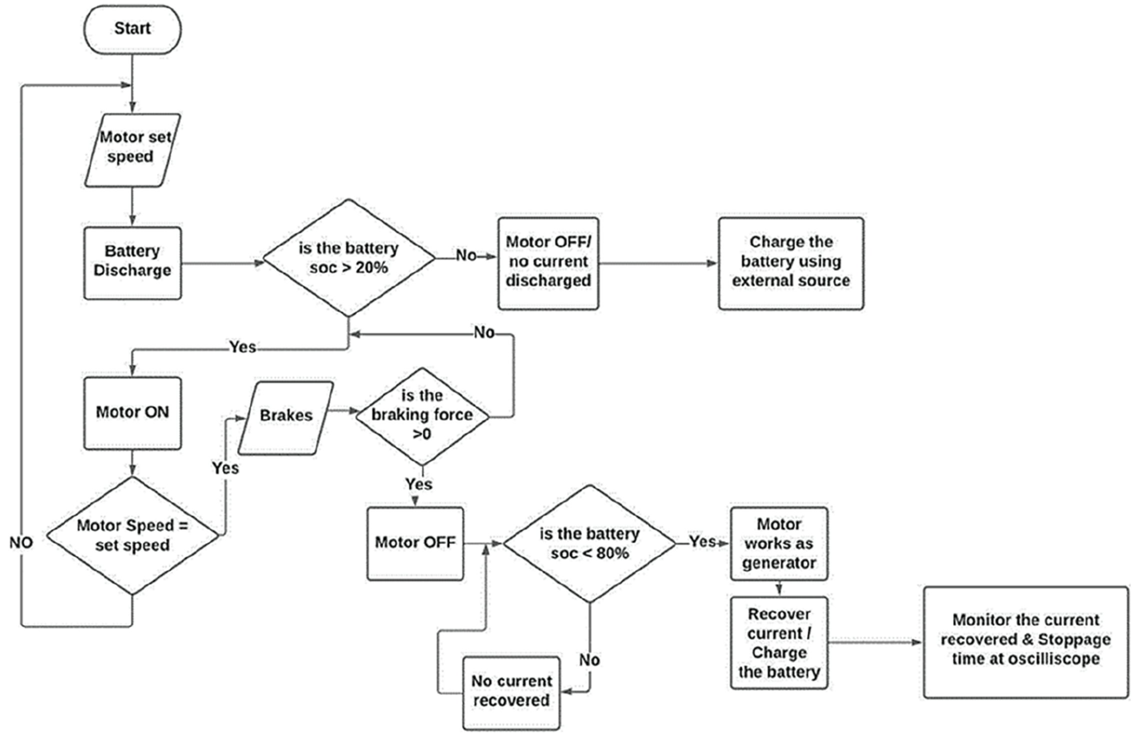

Fig. 2. A flow chart for RBS simulation process.

motor through the three ports A, B, and C. These ports represent the three-phase current used to drive power the PMSM whose magnitudes are displayed on an oscilloscope. The brake and On/OFF Ports indicated in Fig. 4 monitor the brakes' position, the amount of the braking force applied and the motor condition whether it is ON or OFF. Whereas the voltage and current measurement ports monitor the battery current charge state, the battery will be charging when the brakes are applied to the rotating motor.

The brakes subsystem will be activated when the magnitude of the braking force is greater than zero. The magnitude of the applied braking force was controlled using a slider block (brake pedal) shown in Fig. 3 to simulate the effect of the brake pedals. Fig. 5 shows details of the brakes control subsystem responsible for controlling the braking system of the model.

2.2. *Simulation Testing*

The simulation testing process was conducted in three phases to study the effect of the vehicle speed, and the amount of the braking system capacity applied on the recovered current and time needed to stop the vehicle. The first phase studies the effect of varying the applied braking force using the brake pedal indicated in Fig. 3 with an average constant motor speed of 1500 rpm. The test was made by applying variable amount of braking system capacity using the brake pedal indicated in Fig. 3 ranging from 0%:0.95% with step of 0.1%.

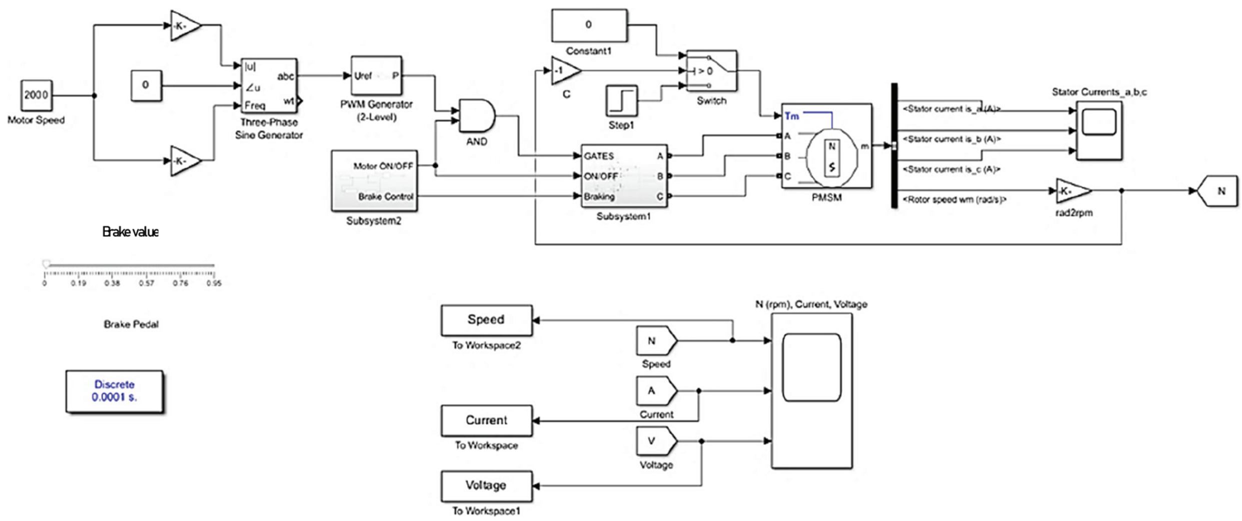

Fig. 3. RBS Simulink simulation model.

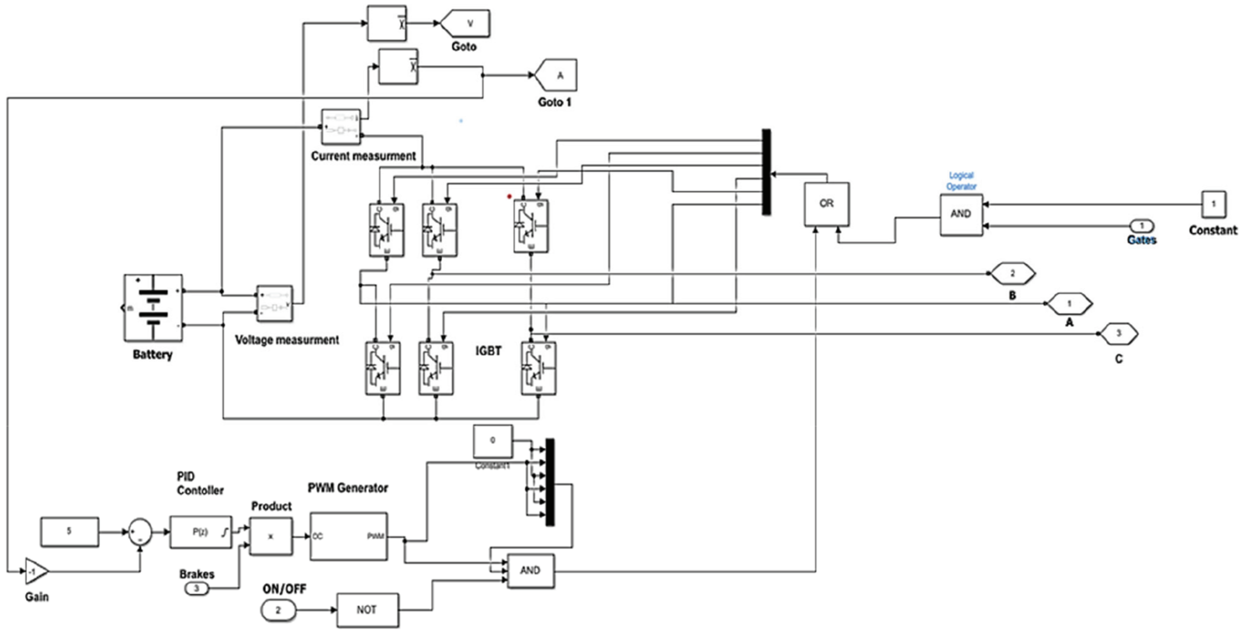

Fig. 4. Recovered current subsystem control (first subsystem).

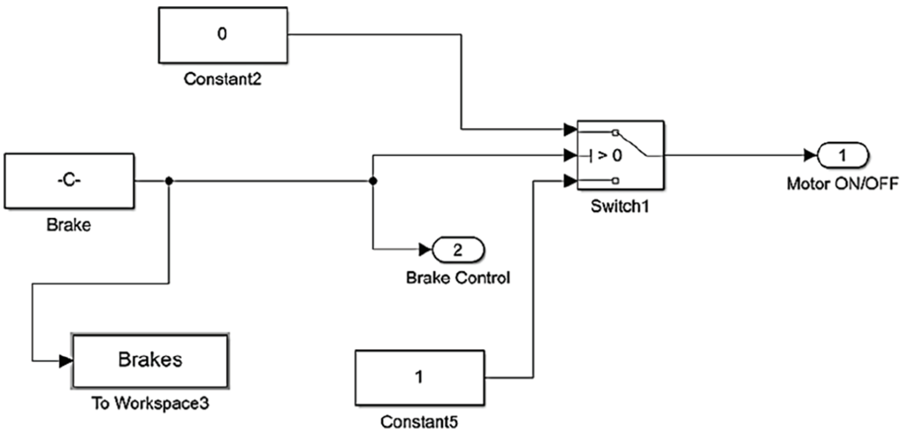

Fig. 5. Brakes control subsystem (second subsystem).

The second phase of simulation tests studies the effect of varying the vehicle speed while applying the same amount of braking force. The test was conducted at a variable vehicle speed ranging from 1000 rpm to 2000 rpm with a step of 100 rpm. As for the applied braking force it was assumed that the driver will use approximately 0.5% of the braking system capacity in most driving situations to stop the vehicle.

The third phase of simulation tests studies the effect of varying both the vehicle speed and the applied amount of the braking system capacity. In this test, the amount of braking capacity used is the same as that tested in the first phase of simulation tests. Also, the range of the vehicle speed used is the same as that tested in the second phase of simulation tests. For each simulation run, the amount of the regenerated current and time taken to stop the vehicle is recorded.

2.3. *Simulation Results*

For the first phase of testing, it was found that the amount of the regenerated current, and the time taken to stop the vehicle decreases with increasing the amount of the applied braking force using the brake pedal. This is due to the fact that increasing the amount of the applied barking force decreases the amount of time available for regenerating current to the battery before the vehicle comes to rest. Figs. 6 and 7 show the effect of the applied amount of the braking force on the recovered battery current, and the time needed to recover current to the battery, and time needed to stop the vehicle, respectively. Upon applying the braking force, the amount of the current supplied to the motor from the battery drops to zero then reverses its direction towards the battery indicating the initiation of the current regeneration process. This process continues during the free rotation of the motor after initiating the braking process till the vehicle comes to rest. The negative magnitudes of current shown in Fig. 6 indicate the peak value of the regenerated current before dropping to zero when the motor stops during each simulation run. The time needed to stop the vehicle can be estimated by studying the curve joining the speed steady state position and zero position for each simulation run indicated in Fig. 7. Also, it can be shown that, at the beginning of each simulation run, the motor applies twice or thrice

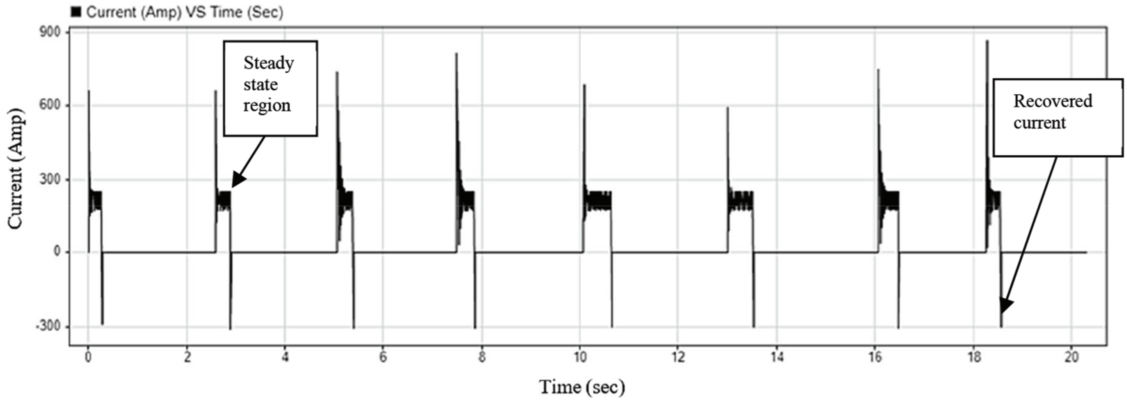

Fig. 6. Recovered current and recovery time at variable amount of braking force applied and constant vehicle speed of 1500 rpm.

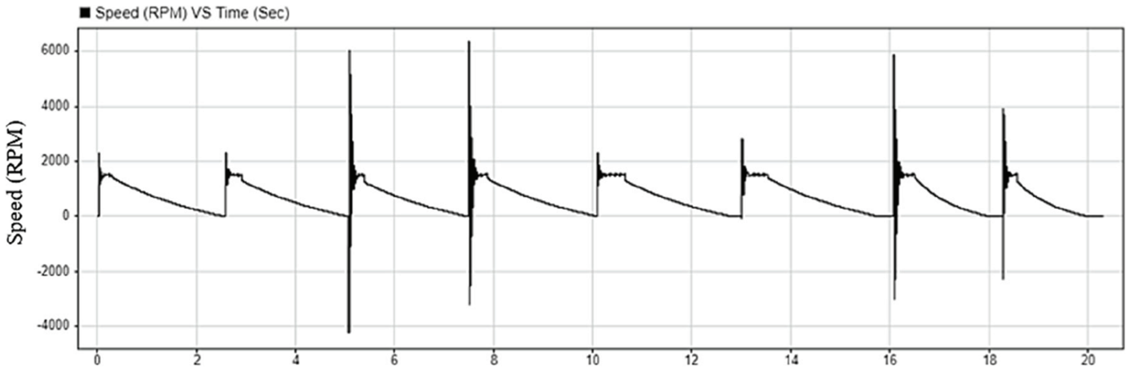

Fig. 7. Vehicle stoppage time at variable amount of braking force applied and constant vehicle speed of 1500 rpm.

its average running current, for approximately 3 msecs before dropping to its steady state. These fluctuations in motor current cause fluctuations in the applied speed till it reaches its steady state. The overshot Phenomenon that occurred is due to the system trials to reach its steady state in a short interval of time. Further developments can be made to overcome this phenomenon by changing the magnitudes of the used proportional and integral gains.

For the second phase of testing, it was found that the amount of the regenerated current, and the time taken to stop the vehicle increases with increasing the vehicle speed. This is because increasing the vehicle speed increases the time needed for the vehicle to come to rest. Hence, the amount of the regenerated current to the battery increases. Figs. 8 and 9 show the effect of different vehicle speed on the recovered battery current, the time needed to recharge the battery, and the time needed to stop the vehicle, respectively. In addition, it can be observed that the time taken to reach the peak amount of recovered current of −300 Amp in case of variable applied vehicle speed is more than that taken during the first phase of testing. Moreover, from Figs. 6 and 8, it can be observed that the effect of variation of the vehicle speed is more significant on the amount of the recovered current. Whereas the effect of variation of the applied braking force is more significant on the time needed for the vehicle to come to rest as shown in Figs. 7 and 9.

For the third of phase of testing, to mimic the actual vehicle driving scenario, A simulation test was run to study the effect of interaction of both variable applied braking force and vehicle speed. Figs. 10 and 11 show the effect of variation of applied braking force and time taken to recharge the battery and time needed to stop the vehicle, respectively. It can be observed that the interaction between both variations had a significant effect on both the amount of the recovered current to the battery, and time needed for recharging, and vehicle stoppage time. Hence, to enhance the efficiency of the current regeneration process, the vehicle is recommended to be running at speeds higher than its average speed while applying a small amount of braking force for a long period of time.

To verify the obtained results, the behavior of the proposed system was compared with the one presented in [13]. It was found that despite the two different control techniques used in both systems, at the same applied speed of 1500 rpm both systems showed the same behavior and stopped the motor in the same interval of time. For further validation of the proposed model, ANOVA analysis is conducted in the next section before using its output results to build the ANN model.

3. ANOVA Test

ANOVA analysis was conducted using DESIGN EXPERT software to validate the simulation results obtained from section 2.3. The analysis studies the effect of variation of applied braking force and the effect of variation of vehicle speed separately on recovered current and stoppage time. Then studies the effect of interaction between them on the amount of recovered current, time needed to charge the battery with the recovered current,

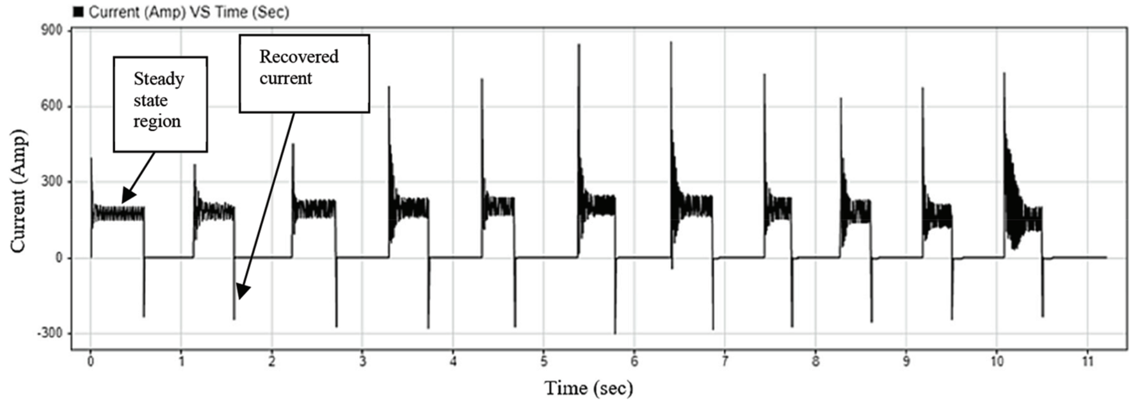

Fig. 8. Recovered current and recovery time at variable vehicle speed (1000:100:2000 rpm) and constant amount of braking force applied of 0.5%.

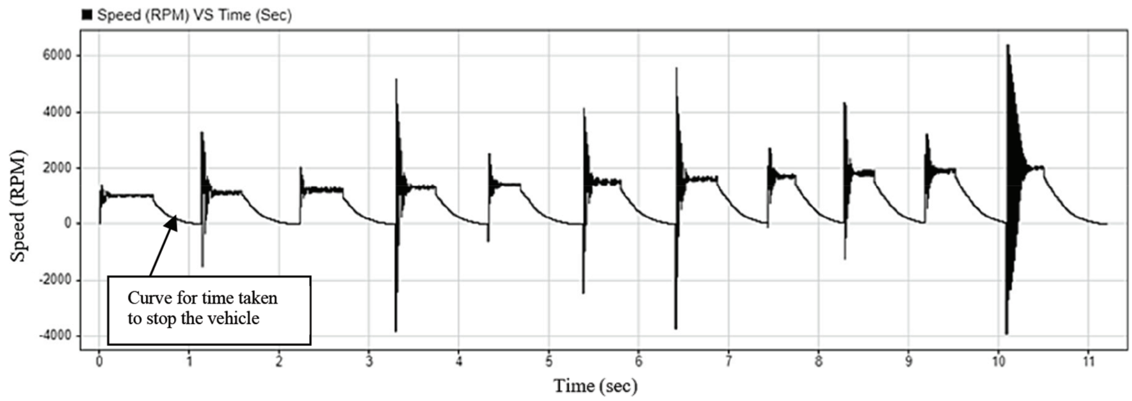

Fig. 9. Vehicle stoppage time at variable vehicle speed (1000:100:2000 rpm) and constant amount of braking force applied of 0.5%.

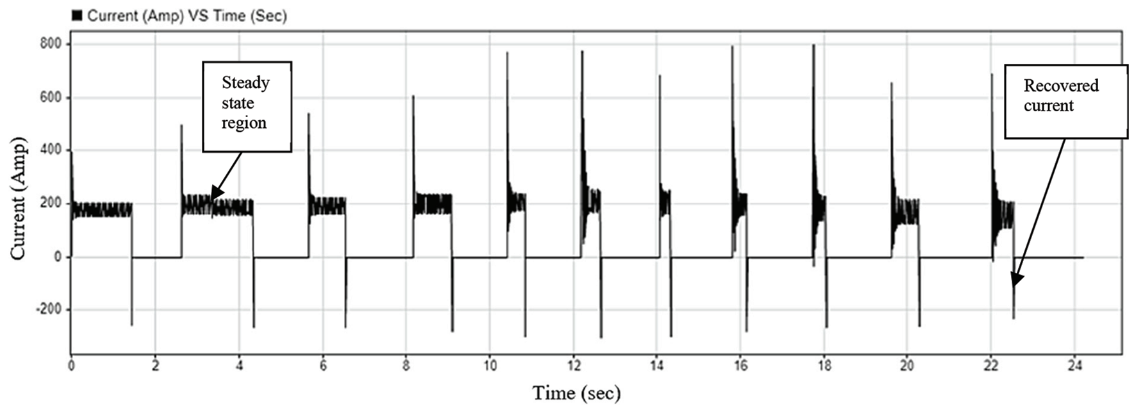

Fig. 10. Recovered current and recovery time at both variable vehicle speed and braking force.

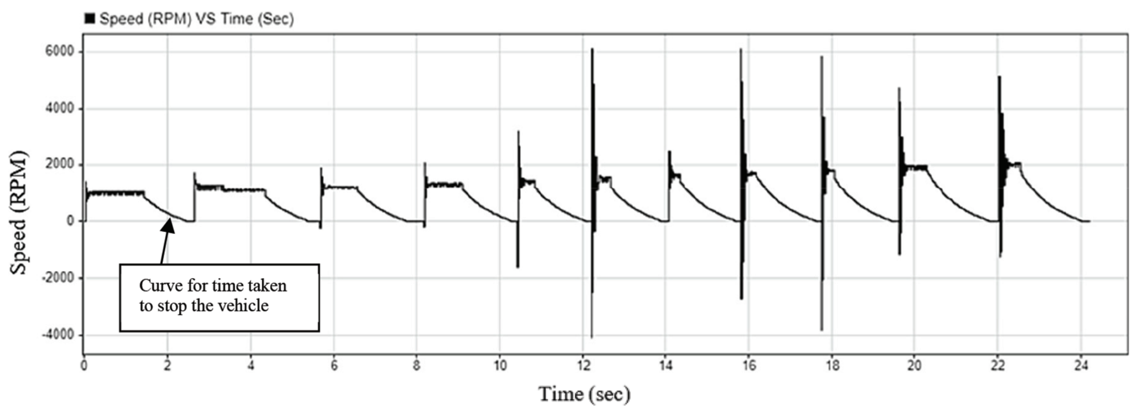

Fig. 11. Vehicle stoppage time at both variable vehicle speed and braking force.

and vehicle stoppage time. Where A is the vehicle speed in rpm and B is the applied amount of braking force capacity %.

From ANOVA analysis for the current recovery process, it was found that the model is significant with P-value < 0.05. The model indicates that the vehicle speed is the most significant parameter on the amount of the recovered current to the battery. Fig. 12 shows a 3D surface plot for the effect of vehicle speed and the amount of braking force applied on the recovered current to the battery and vehicle stoppage time. It can be observed that the peak value of the recovered current can be obtained when the vehicle is running at average speed slightly higher than its average speed with least the amount of braking force capacity applied. The least amount of the recovered current can be recovered when the vehicle is running at its minimum speed with the largest amount of braking force applied. These results are consistent with results obtained using MATLAB Simulink model. The effect of interaction between the two parameters has a significant effect only at higher levels of A and linear values of B such as A^2B, A^3B, A^4B and A^5B in addition to square orders of both A and B (A^2B^2) as shown in Fig. 13.

From ANOVA analysis for the vehicle stoppage time, it was found that the model is significant with P-value < 0.05. The model indicates that the vehicle speed is the most significant parameter on the amount of the recovered current to the battery at higher levels i.e., starting from

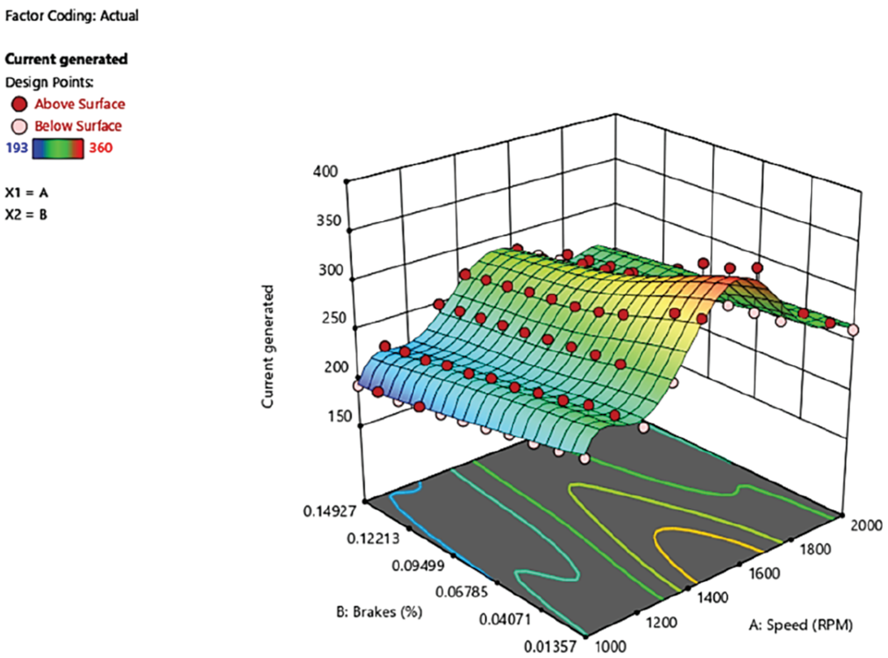

Fig. 12. 3D surface of the battery recovered current.

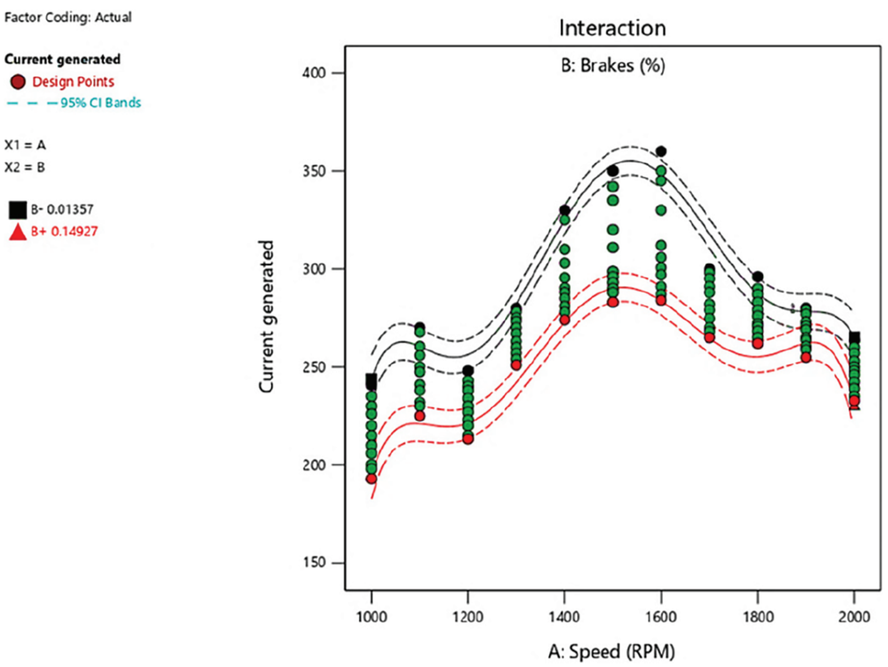

Fig. 13. Interaction plot between vehicle speed and the amount of applied braking force on the battery recovery current.

squared value of the applied vehicle speed. As for the applied braking force it has an effect only when its linear or squared magnitude has an interaction with squared and triple magnitude of the applied speed, respectively. Fig. 14 shows a 3D surface plot for the effect of vehicle speed and the amount of braking force applied on the recovered current to the battery and vehicle stoppage time. It can be observed that the peak value of the vehicle stoppage time can be obtained when the vehicle is running at its maximum speed with the least amount of braking force capacity applied. The least vehicle stoppage time can be reached when the vehicle is running at its minimum speed with the largest amount of braking force applied. These results are consistent with results obtained using MATLAB Simulink model. The effect of interaction between the two parameters has a significant effect only at higher levels of A and linear values of B such as A^2B, A^3B, and A^3B^2 as shown in Fig. 15. Hence, it can be observed that applied vehicle speed can be considered as the most factor governing the vehicle stoppage time.

4. Artificial Neural Networks

Artificial neural network (ANN) is one of the most powerful tools that can be used to map a relationship between different I/P and O/P parameters that cannot be related using conventional mathematical equations. ANN prediction models reduce cost, effort, and time needed for constructing experimental test rigs to study the parameters

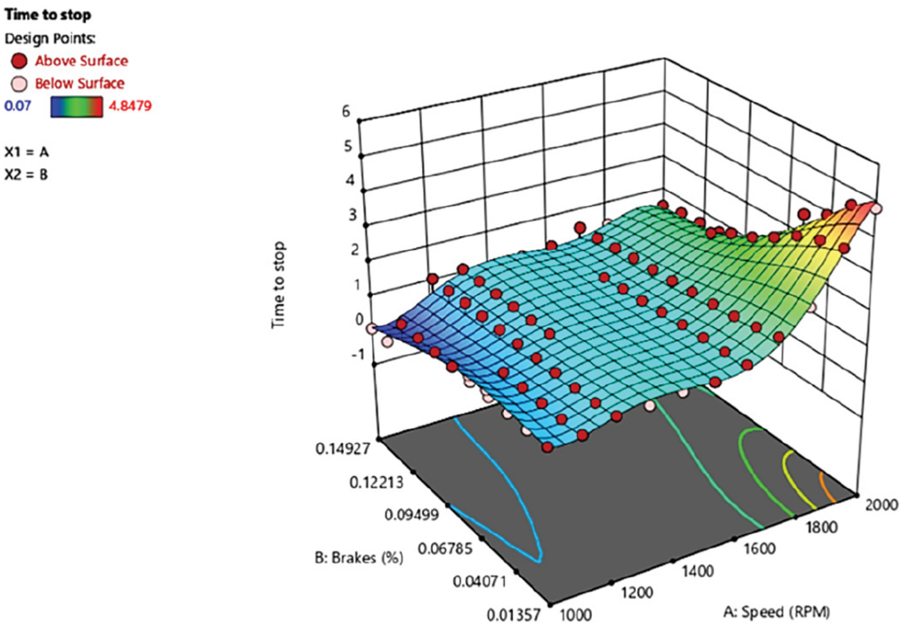

Fig. 14. 3D surface of the vehicle stoppage time.

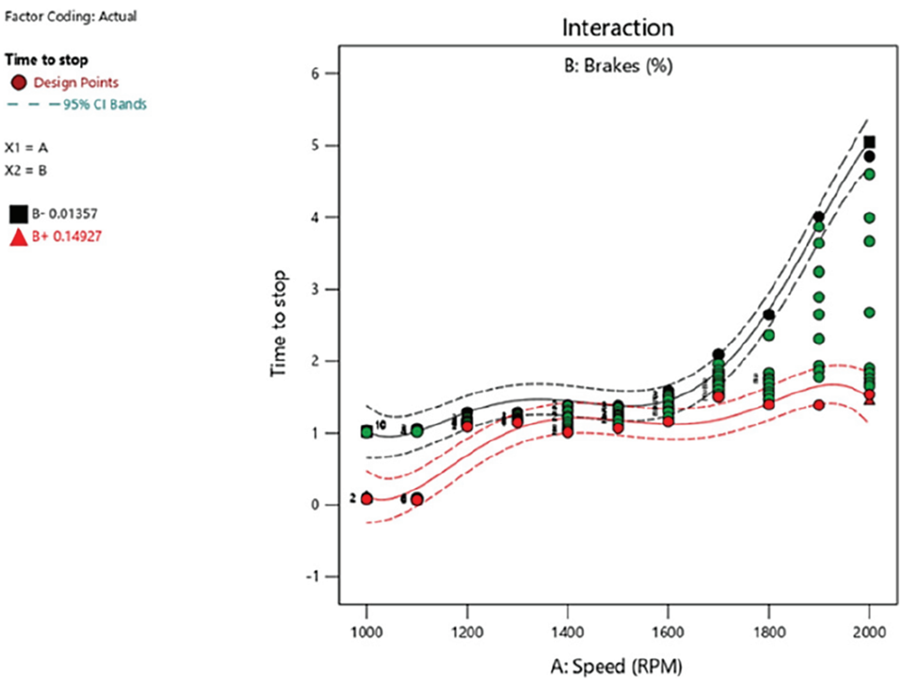

Fig. 15. Interaction plot between vehicle speed and the amount of applied braking force on vehicle stoppage time.

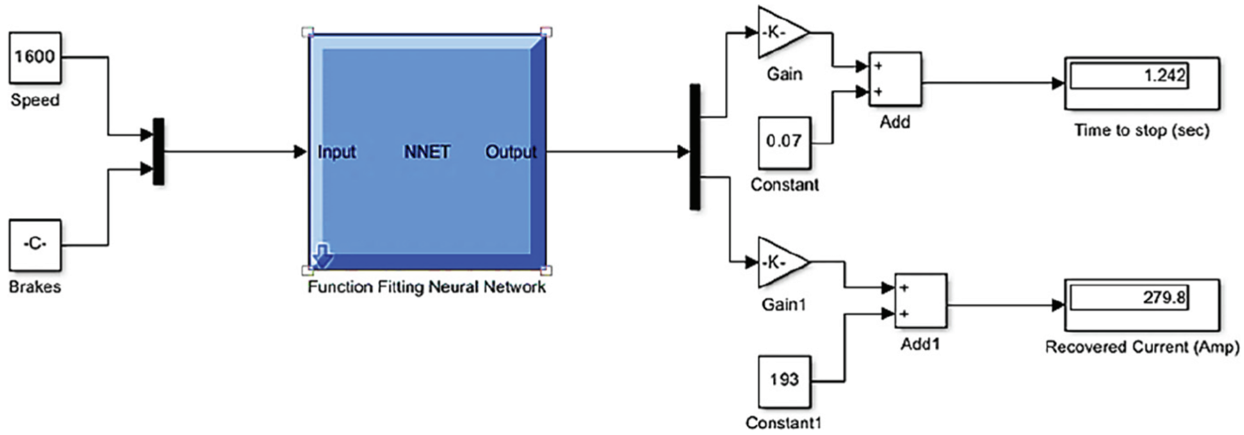

Fig. 16. ANN Simulink model.

TABLE I: Comparison between Predicted Recovered Current and Vehicle Stoppage Time Using Simulink and ANN Models

Speed (RPM) & braking force (%)	Simulink recovered current (Amp)	Simulink stoppage time (Sec)	ANN recovered current (Amp)	ANN stoppage time (Sec)	Recovered current error %	Stoppage time error %
1400 RPM 0.068%	295.5	1.24	300.4	1.24	1.66	0.16
1500 RPM 0.081%	298.7	1.25	310.2	1.22	3.09	2.01
1600 RPM 0.095%	300.6	1.36	293.6	1.33	2.32	2.28
1800 RPM 0.122%	268.3	1.53	265.1	1.62	1.19	5.81
1900 RPM 0.136%	258.8	1.78	259	1.70	0.08	4.22

affecting the performance of RBS. In this research, ANN was used to predict the effect of variable vehicles' speed and applied braking force capacity for a passenger vehicle RBS. In terms of the current that can be recovered to the vehicles' battery and the time needed for the vehicle to come to rest.

MATLAB Simulink output data sets obtained from section 2 were used to build the proposed ANN model. The training process was made on 70% of the available Simulink output data. The remaining 30% of the available data were used for validating and testing the proposed ANN. The network architecture consists of a feedforward network having 3 layers: input, hidden and output layers, respectively. The hidden layer consists of 10 hidden neurons while the number of neurons in the I/P and O/P layers depends on number of I/P and O/P parameters under investigation. The training process was conducted using Levenberg-Marquardt algorithm and was completed in 71 epochs. The resultant mean square error was <1 for all the training, validation, and testing phases. Further, the regression correlation coefficient for the three phases was <1 of magnitude of 0.9946 indicating the efficiency and strength of the proposed ANN model.

To ensure the efficiency and validity of the proposed ANN model, it was imported to Simulink workspace as shown in Fig. 16. Where the effect of random data sets of I/P parameters was predicated using the built ANN model. The ANN O/P parameters readings were compared against the O/P obtained using the Simulink model presented in section 2 as indicated in Table I. It can be observed that the average error % was estimated to be 2% and 3% for recovered current and stoppage time respectively proving the efficiency of the built ANN.

5. Conclusions

This paper showed that ANN models can be considered as a potential accurate flexible models for predicting the performance of RBS in EVs. The proposed ANN model can be used as a promising tool for developing efficient and effective RBS controllers. As, the average error between Simulink model and ANN model was 2% and 3% for the recovered amount of current to the battery and vehicle stoppage time, respectively. The proposed ANN model can be further improved by increasing its size to include the effect of other parameters such as road surface coefficient, distribution of braking forces on the wheels, and SOC of the battery on the performance of RBS. In addition, further developments can be made to the proposed Simulink model to enhance its response by integrating anti-winding to prevent the accumulation of errors in the integral controller to overcome the overshot phenomena. Moreover, further research can be conducted to improve the accuracy and robustness of the ANN model, as well as developing more sophisticated Simulink models to capture the dynamic behavior of RBS in real-world conditions.

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Conflict of Interest

Authors declare that they do not have any conflict of interest.

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