PERFORMANCE EVALUATION OF AN ELECTRIC VEHICLE INTEGRATED WITH REGENERATIVE BRAKING SYSTEM USING FUZZY CONTROLLER

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Abstract:

Electric vehicles (EVs) receive impressive concerns worldwide due to their efficiency for reducing environmental pollution. Consequently, automotive institutions and academics are facing many challenges to provide various techniques to increase the EVs reliability. One of the crucial parameters is the regenerative braking system (RBS) that helps for optimal usage of the battery stored energy and to extend the driving range. The current research presents a new regenerative braking strategy focusing on various driving cycles to compromise the implementation of the RBS braking control and mechanical braking system using the artificial neural fuzzy system (ANFIS). The tackled different drive cycles are New York City Cycle (NYCC), New European Driving Cycle (NEDC), Federal Test Procedure 72 (FTP-72) and Federal Test Procedure 75 (FTP-75). Furthermore, the basic concepts of the modelling of electric vehicles with different road conditions are considered to demonstrate the vehicle's dynamics performance. The MATLAB/SIMULINK software package is used for developing the model to study the regenerative braking systems' performance under different conditions. The simulation results of this study show that the proposed regeneration braking strategy improves regeneration efficiency by about 40 % and extends the driving travel distance per charge up to 31 %. The obtained simulated results are reviewed with similar simulated and experimental previous works and it is found to be consistent and with minor deviancy.

1. Introduction

Recently, electric vehicles have received impressive concerns regarding the regenerative braking system that is used to save energy [1]-[3]. The kinetic energy of the vehicle can be converted into some valuable amount of electric energy and that can be stored back in the battery. Consequently, this could lead to significant reduction of energy consumption and increasing the travel distance per charge as well [4].

Regenerative braking systems (RBS) can be considered the major technique to save energy for electric vehicles. Regenerative braking systems could make the driving motor of the electric vehicles work as a generator to recover kinetic energy during the deceleration process. Many researchers worldwide have been doing many studies in the regenerative braking systems and energy saving in the field of electric vehicles industry [5]-[8].During electric vehicle deceleration, regenerative braking systems and mechanical friction brake work collaboratively. Initially, the RBS was implemented with DC motors as the DC machines in electric vehicles (EVs) are easy to control for traction applications. However, DC motors have intense maintenance

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needs due to the brushes and commutator wear [9],[10]. Moreover, the rapid advances in AC induction motors and Permanent magnet synchronous motors (PMSM) and their electronic drives yield to the use these motors in electric vehicles intensively because of their high performance and robustness.

Furthermore, with using the Permanent magnet synchronous motor (PMSM) the electric vehicles (EVs) efficiency would be with impressive saving value [11],[12]. Nowadays, the design and manufacturing trends of (EVs) worldwide are focusing on developing a hybrid control strategy between the friction system and the RBS for both electric vehicles (EVs) and hybrid electric vehicles (HEVs) [13]. The hybrid control systems for regenerative braking and friction braking are implemented in many previous studies [14]–[17]. Most of the previous studies found in the literature aimed to enhance efficiency of the energy recovery process of regenerative braking of electric vehicles [18]-[20]. Essentially, these previous studies focused on two different techniques: system design and control strategies. However, these techniques may add a kind of complexity to the system and may add additional costs of the electric vehicles [21].

The amount of energy recovered is basically correlated to the tackled strategy of the braking control system to allow the implemented motor for converting the kinetic energy into electrical energy that can be backed to the battery. Nevertheless, the appropriate control techniques can impressively improve the efficiency of the energy recovery process and can increase the braking system reliability [22]. Consequently, the focus is concerned with the control system approaches to compromise the usage of the RBS in the different models for EVs. Meanwhile, these approaches increase both the complexity of the system and the cost as well, but the recovered amount of energy that can be backed to the system could cause impressive saving [23].

The control strategy of composite braking systems can not only essentially decide the recovered braking energy of regenerative braking, but also, it can effectively affect the braking safety and stability of electric vehicles. Hence, the control strategy of composite braking system has been becoming an important research parameter of electric vehicles. The composite braking systems can be divided into two types: the first one is the parallel braking system while the second one is the series braking system [24],[25]. Modern developed fuzzy control algorithm for the composite braking system can be used impressively to compromise the usage of the RBS systems. The fuzzy controller considers the main parameters as inputs such as the demand braking force, state of charge (SOC) and the vehicle's velocity meanwhile considers the motor regenerative braking force as controller output [26]. The main novelty of the current research is to imply the artificial neural fuzzy controller to compromise the implementation and integration of the RBS and mechanical braking for four wheels electrical vehicle. The simulation is tackling different driving cycles and conditions and is developed by using the MATLAB- SIMULINK software package. Furthermore, this current research has two main contributions. The first is to predict the power regenerated by drivers over different driving cycles through different road conditions, utilizing simulated models. These simulated models can precisely predict how much of the developed power gained by regenerative braking systems to estimate the optimal usage on/off for the RBS systems. The second is to compromise the driver performance of mechanical braking system to show the optimal usage of the regenerative braking strategy design.

These two contributions aim to maximize regenerative energy that can be saved to electrify back the powertrain. In addition, the results of the current work have been found to be consistent with other studies found in literature [27],[28]. The obtained simulated results are validated by comparing with similar simulated and experimental works found in literature [29],[30]. The next parts of this current research are organized as following: Section II describes the main parameters of the electric vehicle used to simulate the developed model for studying the optimal usage of the RBS. In addition, this section presents the proposed braking control strategy ANFIS algorithm and describes the developed model as well. The simulated results are reported and discussed in section III. Finally, the main conclusion is given in section IV.

2. Electric Vehicle's Simulated Model

2.1 EV main parameters

In the current research, a Four Wheels Drive (FWD) Electric Vehicle (EV) with dual motors platform is simulated using MATLAB/SIMULINK software package. The first motor is positioned over the rear axle meanwhile the second one is positioned over the front axle. The simulated platform with Regenerative Braking Systems (RBS) configuration is schematically presented as shown in Figure 1. In order to obtain simulated results for investigating the RBS systems, a MATLAB /Simulink model of the EV is developed considering different driving cycles. Nevertheless, the model faces nonlinearities and uncertainties such as in mass, the center of gravity of the vehicle and road conditions. Table 1 presents the EV and the motor main simulated parameters.

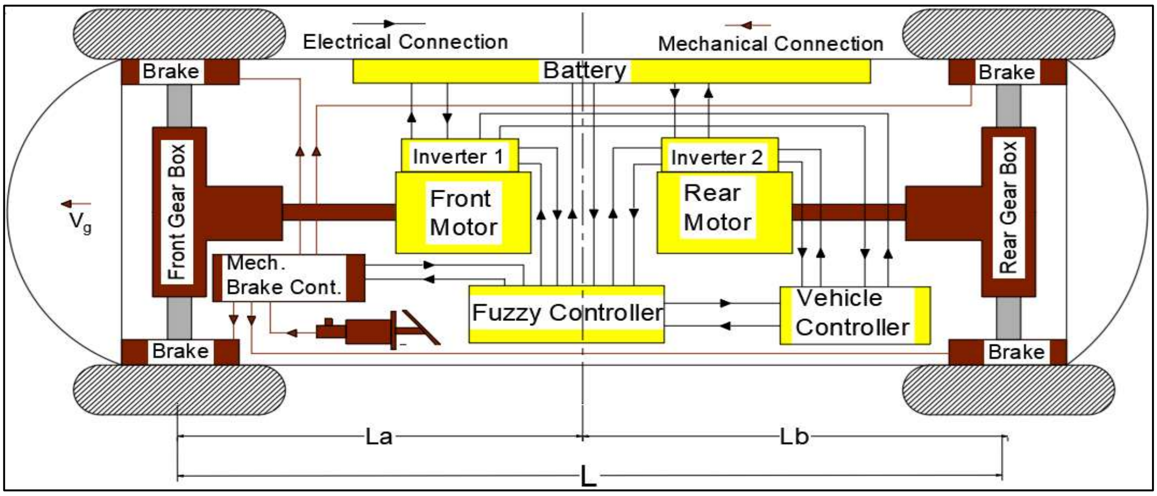

Figure 1. Simple presentation for the schematic diagram of the proposed simulated EV platform.

Table 1. The simulated model main parameters.

Parameter	Value
Parameters used for vehicle dynamics	
Vehicle mass (kg)	1450
Tire type numbers	175/70/R14
Road roughness coefficient (μ)	0.3 to 1
Wheel base distance – L (m)	3.1
Height of gravity center- hg (m)	0.6
Aerodynamic drag coefficient - Cd (m)	0.35
Air mass density- ρ (kg/m3)	1.17
Angle of inclination – β (rad)	0 to 0.45
Wheel rational inertia - Jw (kg. m2)	0.65
Gear ratio	1 : 2.7
Front wheel base – La (m)	1.5
Rear wheel base – Lb (m)	1.6
The frontal area -Af (m2)	3
The wind speed - Vw (m/s)	0 to 2
Motor parameters	
Parameter	Value
Rated power (kW)	37
No. of motors	2
Rated torque of each motor (N.m)	300
Stator resistance (ohm)	0.03
Rotor resistance (ohm)	0.25
Stator Inductance (mH)	0.23
Rotor Inductance (mH)	0.9
Mutual Inductance (mH)	4.1
Moment of inertia (kg. m2)	0.5
No. of poles	6
Frequency (Hz)	60

Battery rated voltages (V)	360

The vehicle braking force (F_v) depends on the vehicle mass (M_v) and acceleration/deceleration of the vehicle (α_v) as given in Equation 1. The braking force is the sum of two braking forces on the front wheel (F_{fr}) and rear wheel (Fre) [31],[32].

$$F_v = M_v \,.\, \alpha_v = F_{fr} + F_{re} \tag{1}$$

The braking forces F_{fr} and F_{re} which can be represented in Equations 2 and 3 are mainly dependent on the normal forces on the front and rear wheels W_{fr} ,W_{re} and the road roughness coefficient (μ).

$$F_{fr} = \mu . W_{fr} = \mu . \frac{M_v . g(L_b + z.h_g)}{L} \tag{2}$$

$$F_{re} = \mu . W_{re} = \mu . \frac{M_v . g(L_a - z.h_g)}{L} \tag{3}$$

Where L_a and L_b are the Front/Rear wheel bases, g is the gravity constant and z is the brake strength (α_v/g). The moderated braking strength spans a range as 0.15<z<0.7. During braking conditions, the resultant speed of the wheel is less than the vehicle speed because of tire deformation and the traction/braking forces exerted on the tire. Consequently, the vehicle will slip on the road. The slip of the tire (λ(t)) can be calculated using the wheel angular velocity (ω), the wheel rolling radius (r_d), and the vehicle forward velocity (V_x). Particularly, the values of (λ(t)) span a range from 0 (pure rolling) to 1 (locked wheel).

$$\lambda(t) = \frac{V_x\,(t) - \omega(t)}{V_x} \tag{4}$$

The main concern of the developed control systems is to maximize the restored energy from the regenerative braking compared to the total braking energy. The maximum regenerative braking torque (T_{emax}) of the applied motor is constrained by its electrical features and the battery's electrical characteristics as well [33].

$$T_{emax} = \begin{cases} min\left[\frac{A.P_{m\,max}}{n} \quad \frac{A.\,P_{B\,max}}{\eta_b.n}\right] \; for\; n > n_e \\ min\left[T_{m\,max} \quad \frac{A.\,P_{B\,max}}{\eta_b.n_e}\right] \; for\; n_{min} \le n \le n_e \\ 0 \qquad\qquad for\; n \le n_{min} \end{cases} \tag{5}$$

Where the $P_{m\,max}$ is the motor maximum power, the $P_{B\,max}$ is the battery's maximum charging capacity, the η_b is the battery charging efficiency, the $T_{m\,max}$ is the motor's Maximum torque, the n_{min} is the motor's minimum rotational speed for applying RB (350 r_min-1) and A is the motor design factor (10000) .

Moreover, it is essential to increase the battery's life by its state of charge (SOC%) within the safe limits. Consequently, the regenerative braking of the motor is prohibited when the SOC% of the battery pack exceeds 95%, and only hydraulic braking systems should be employed instead.

The % Energy recovery efficiency (ϵ_r) can be calculated using Equation (6). Where the ΔSOC_n is the change of SOC values for the electric vehicles at the end and the initial without regenerative braking system. The ΔSOC_y contains the energy recovered and stored in the battery Er for the electric vehicle with regenerative braking.

$$\epsilon_r = \frac{\Delta SOC_n - \Delta SOC_y}{\Delta SOC_n} \tag{6}$$

2.2 Main parameters of the Fuzzy Controller

The artificial neural fuzzy interface system (ANFIS) is implemented for developing the fuzzy logic controller system. This work could be the first phase of designing the prototype of AFIS control systems used in Electric Vehicles to study the RGBs with integration with mechanical braking systems.The ANFIS fuzzy rules is proposed for studying the regenerative braking systems in EVs to integrate regenerative braking with conventional friction braking. The different simulating techniques [34]-[36] have several limitations compared to ANFIS fuzzy rule-based control. These limitations are such as that they need extensive datasets for training and are computationally intensive. Moreover, the other techniques' performance heavily depends on data quality, making real-time adaptation difficult. Therefore, the ANFIS strategy is proposed for the current research.

The ANFIS aims to control and to distribute the motor and hydraulic braking forces in terms of the front/rear axles regenerative braking. The ANFIS controller uses three inputs as, battery state of charge SOC%, vehicle speed u and the braking strength z with considering the regenerative braking torque as the output variable as summarized in Table 2. The main objective of fuzzy control system is to maximize the involvement of the regenerative braking force in the braking process. Accordingly, the degree of membership and fuzzy rules of the fuzzy controller are determined.

Figure 2 presents the relation between the two main inputs of the ANFIS (SOC% and Vehicle speed) with the FIS output torque of each motor. This is done to correlate and estimate the relation and variation the different input parameters with ANFIS output. The state of charge of the battery can be expressed as SOC% = 1–100%. If the SOC% is too large or too small, braking energy recovery is not recommended to keep long life of the battery and the driving motors as well. The regenerative braking force is to be applied when the total braking force is larger than the hydraulic braking force that is applied to the front and rear wheels.

Table 2. Fuzzy input ranges and output demand torque.

ANFIS Inputs			ANFIS Output
SOC%	Speed(m/s)	Braking(z)	Demand Torque
95	0	0.7	0
60	20	0.5	150
40	25	0.15	300

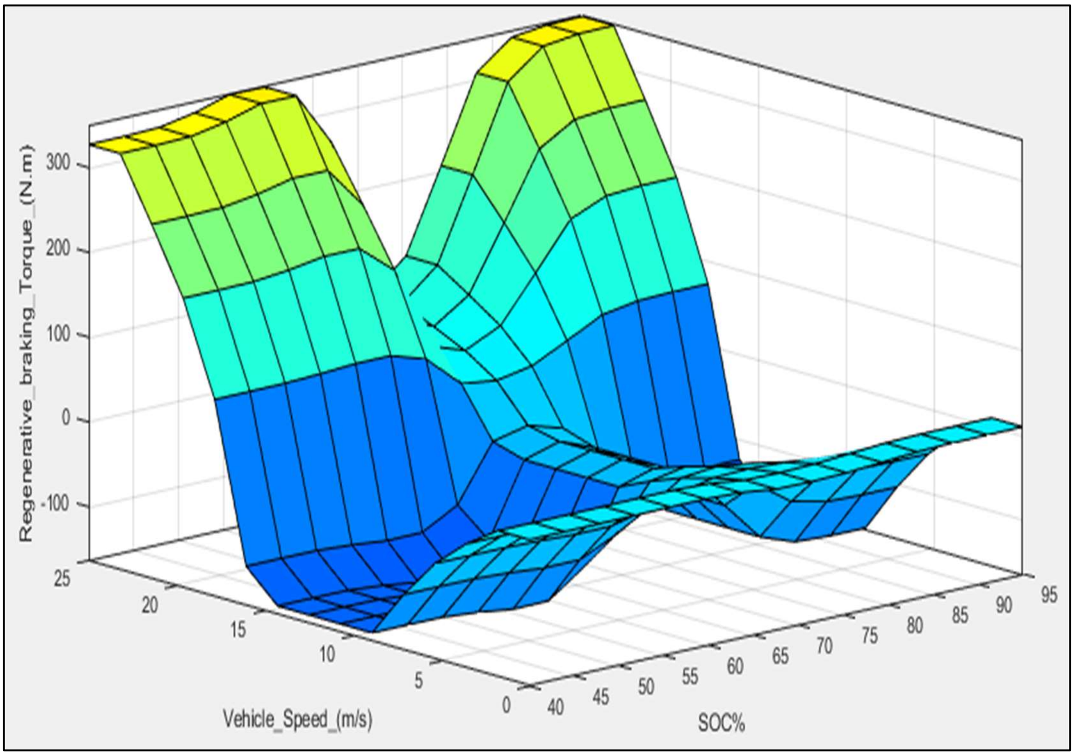

Figure 2. ANFIS output torque of each motor with two inputs (SOC% and Vehicle speed).

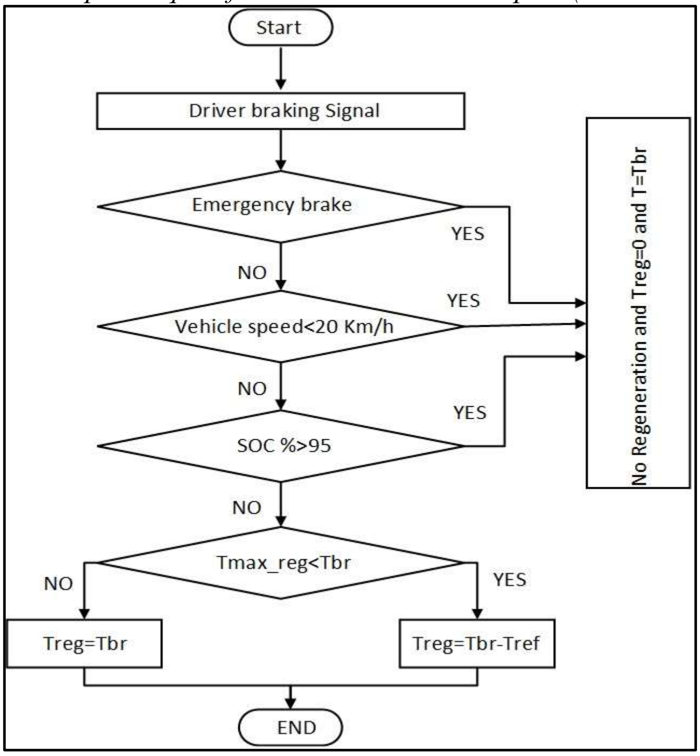

Figure 3. Simplified flowchart of the regenerative energy control algorithm.

2.3 Simulated Model

The regenerative braking control model is developed using MATLAB/Simulink. This model includes two motors with their controllers distributed over the front and rear axle. The two controllers control the performance of the two motors while acceleration and deceleration based on the demanded driving torque. This driving torque is generated by the ANFIS based on the driver signals and the driving cycles integrated with the EV feedback signals of the EV actual speed and its battery state of charge SOC%.

The driving conditions such as the wind and road conditions are implemented to simulate the real environment of the vehicle air dynamics working conditions. The braking forces distributed over the front and rear axles are used to generate the maximum regenerative torque with considering the SOC% which should be less than 95 %. The distributed braking forces over the two axles are analyzed by tackling four different driving cycle conditions (NYCC), (NEDC), (FTP-72) and (FTP-75). The regenerative braking control strategy developed in this research should be watched and constrained by the following three main conditions.

The four considered driving cycles can be summarized as mentioned in [37]: NYCC (New York City Cycle) is developed specifically for low-speed urban road conditions with frequent parking. The driving time of the vehicle is 598 s, with a driving distance of 1.89 km. Its average speed is 11.4 km/h, and the maximum speed is 44.6 km/s. NEDC (New European Driving Cycle) includes two driving cycles: an urban driving cycle of 0–780 s and suburban operating conditions after 780 s. The characteristics of the NEDC conditions are short testing time, low mileage, low speed, and few gear changes. It does not consider the impact of environmental temperature or the continuous starting and stopping of vehicles during urban traffic congestion on energy consumption.

The FTP-72 (Federal Test Procedure 72) cycle simulated 12.07 km of urban road conditions, including frequent parking. The maximum and average speeds are 91.2 and 31.5 km/h, respectively. The FTP-75 (Federal Test Procedure 75) is divided into three parts. The first part is the cold-start stage, which takes 505 s. The second part is the transient phase, which takes 864 s. Subsequently, the engine is shut down for 9–11 min, and the third part is a hot-start phase test, which takes 505 s. The total duration is about 2474 s.

The first main condition is that the driver braking signal is related to the braking distance and time required by the driver. If the braking signal is high, it indicates that the regenerative braking force should be reduced at this time. Meanwhile, the braking signal is moderate, the regenerative braking force should be increased. Moreover, if the braking signal is low, a maximum regenerative braking force should be generated back to the battery.

The second main condition is that when the state of charge of the battery is within the range between 40% and 95%, the regenerative energy can be sent back to the battery elsewhere, the regenerative braking strategy is discarded. The third condition is that, when the EV speed is within the range between 10 m/s to 25 m/s the regenerative control strategy should be implemented.

The emergency braking conditions are given the maximum priorities in the proposed model. In Figure 3, the emergency braking condition is allocated at the first option. The emergency braking condition depends on the driver braking pedal force and accuracy and the speed. Moreover, the proposed algorithm compromises the application of regenerative brake and friction brake as per many parameters to provide the maximum safety condition for the electric vehicles.

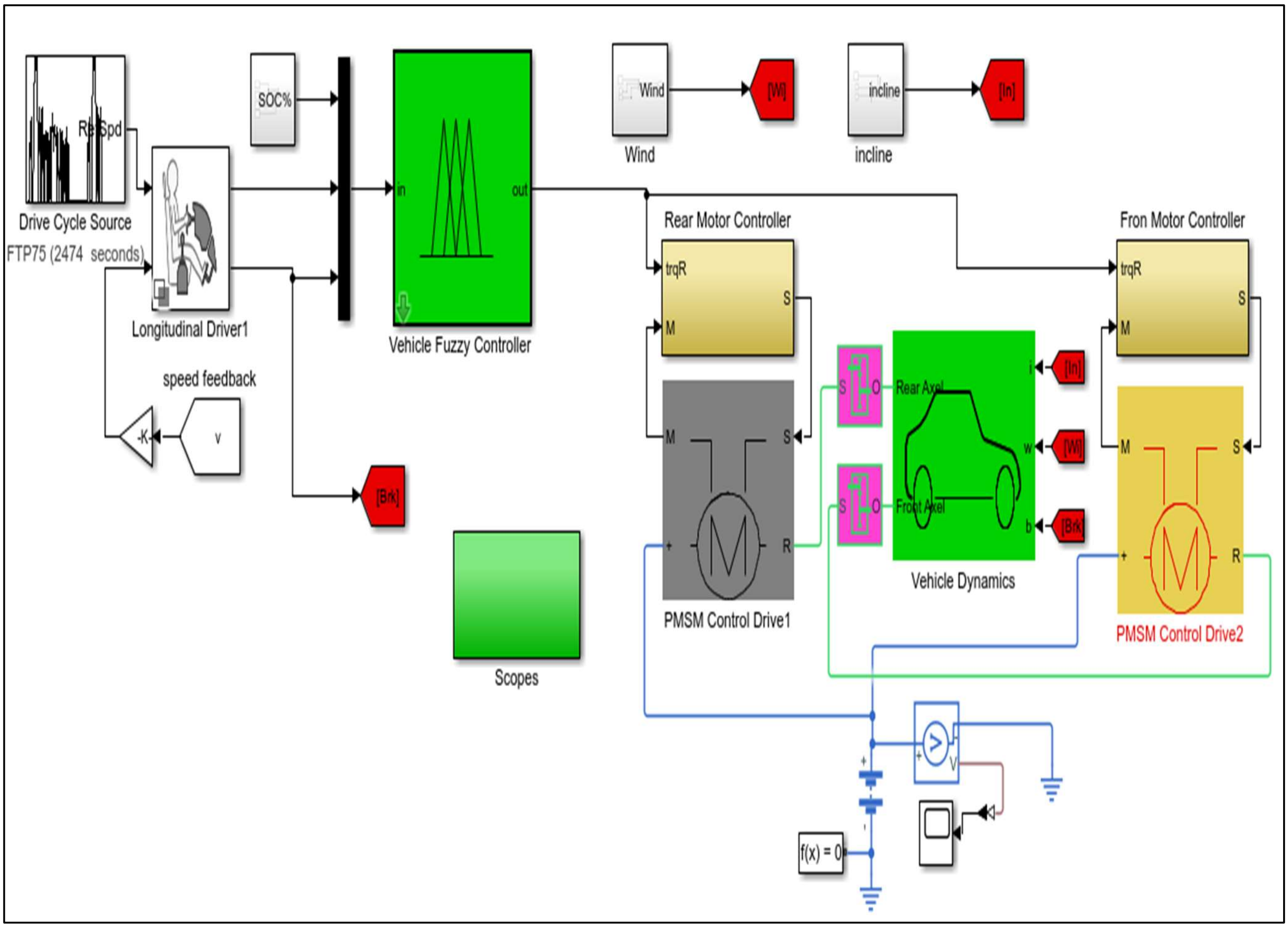

Figure 4. Screenshot for the simulated electric vehicle model for regenerative control strategy with two driving motors using the ANFIS.

3. Simulated Results Analysis

The developed control strategy of the ANFIS allows the mechanical braking to be employed when the braking strength of the vehicle is very high and forbids or minimizes the regenerative braking systems. The regenerative braking system is mainly employed when the SOC% is less than 95 % and the electric vehicle's speed spans the range between 10m/s to 25 m/s. The four different driving cycles are used to demonstrate the effects of the different road conditions on the variation of the battery state of charge SOC%. Figure 5 presents the SOC% variation for the different considered driving cycles NYCC, NEDC, FTP-72 and FTP-75 with and without using the RBS.

Table 3 summarizes the starting, final and drop of SOC% for each driving cycle with and without using the RBS. It can be noted that the percentage increase of the battery SOC% is about 39.3%, 22.4 %, 7.14% and 11.5% for NYCC, NEDC, FTP-72 and FTP-75, respectively. This enhancement of the SOC % will be positively reflected in the longer travel distance and increase the battery lifetime. Figure 6 presents the Energy in KJ (where 1 kWh=3600 KJ) consumed for the different considered driving cycles NYCC, NEDC, FTP-72 and FTP-75 with and without using the RBS.

Table 4 presents the recovery energy generated by RBS and the percentage of the recovery energy backed by the battery for each driving cycle. Moreover, it summarizes the extra travel distance for different driving cycles with and without RBS. It can be noted that the percentage of the recovery energy generated by the RBS is about 22.45 %, 14%, 15.7% and 9.4 % for NYCC, NEDC, FTP-72 and FTP-75, respectively.

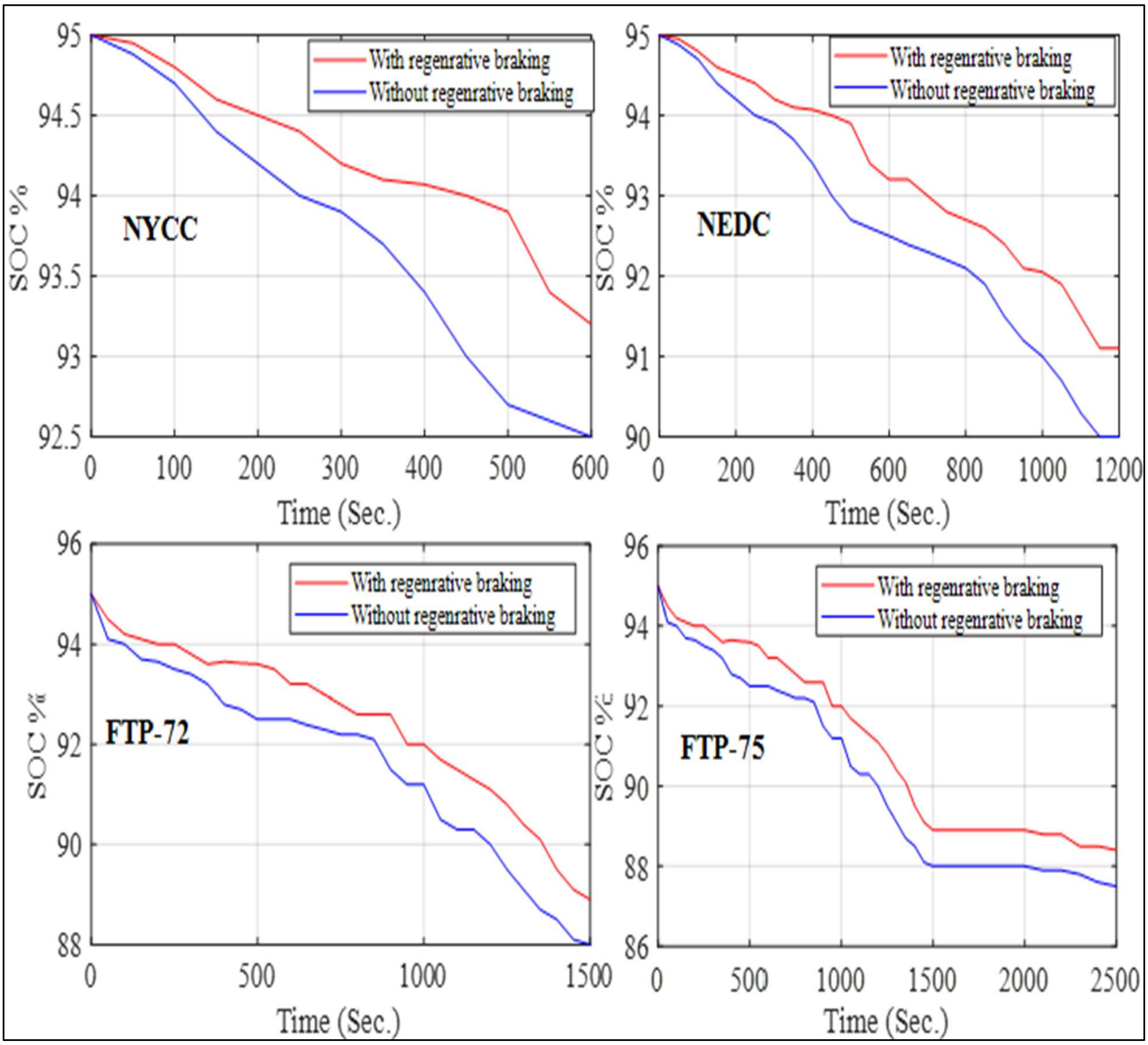

Figure 5. The SOC % of the Battery for the different driving cycles with and without regenerative braking.

Table 3. The drop of SOC % for different driving cycles with and without RBS.

Parameter	Without Regenerative braking				With Regenerative braking			
	NYCC	NEDC	FTP-72	FTP-75	NYCC	NEDC	FTP-72	FTP-75
Starting SOC%	95	95	95	95	95	95	95	95
Final SOC %	92.5	90.1	88	87.2	93.3	91.2	88.5	88.1
Drop of SOC %	2.8	4.9	7	7.8	1.7	3.8	6.5	6.9

This of the SOC % will be positively reflected in the longer travel distance and increase by a range from 11.2 % to 31.3% for the different tackled driving cycles. Moreover, it can be noted that, with the conditions of the tackled four driving cycles, the regenerative braking efficiency of electric vehicles has significantly improved.

Table 4: The percentage of recovery energy by RBS and extra travel distance for different driving cycles.

Parameters	NYCC	NEDC	FTP-72	FTP-75
Total Consumed Energy (KJ)	490	2500	3500	4800
Recovery Energy by RBS (KJ)	110	350	550	450
% Recovery	22.45%	14%	15.7%	9.4%
% More travel distance	31.5%	17.2%	18.6%	11.2 %

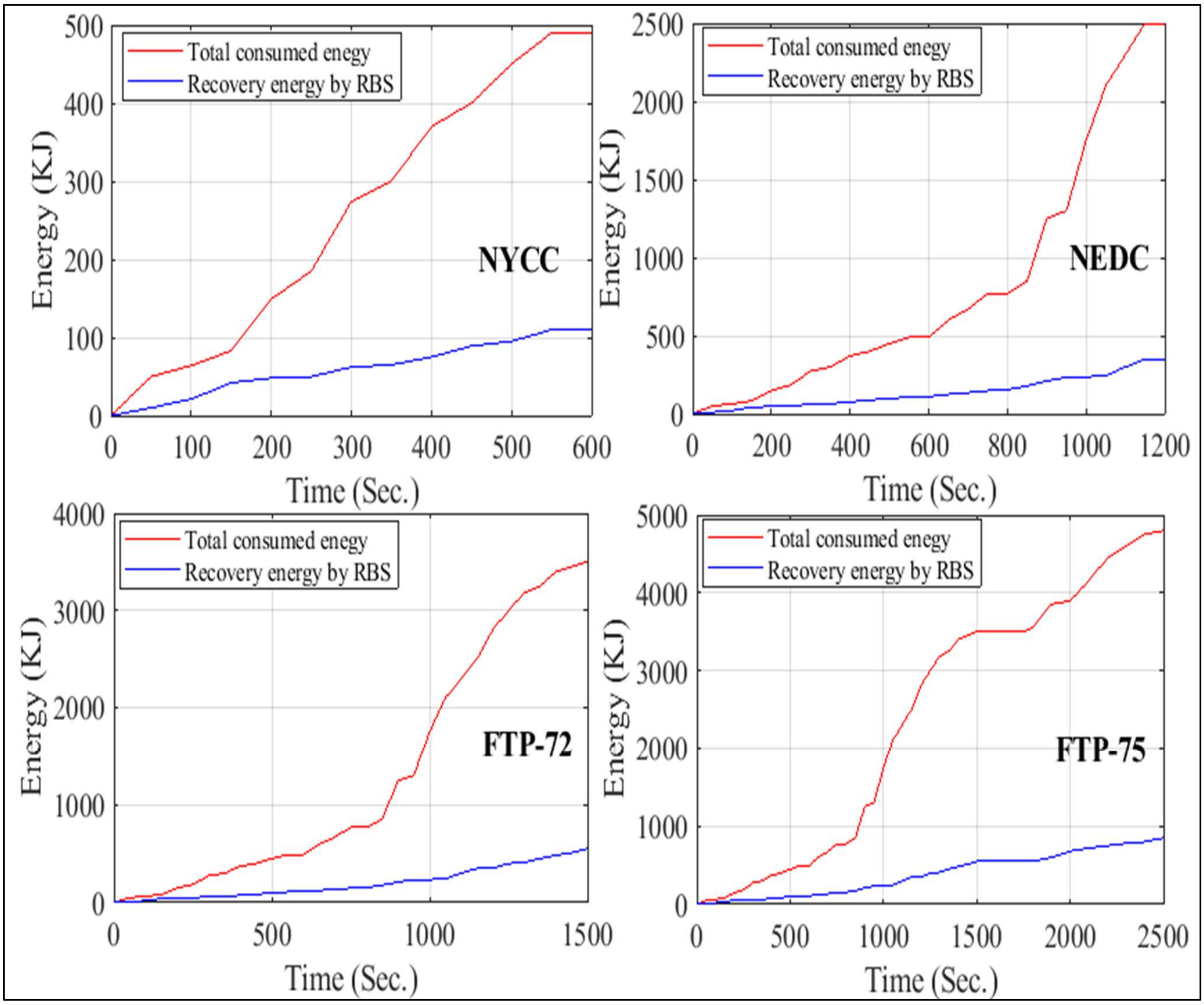

Figure 6. The energy consumed and recovered for the different driving cycles.

Table 5 presents a comparison of the obtained simulated results with different control algoriths found in literature [3],[39]. it can be noted that the ANFIS contrl algorithm relatively provides higher energy recovery effeciency for (NYCC, NEDC and FTP-72). Meanwhile for FTP-75, ANFIS provides relatively higher value due to the losses of the two driving motors used in the current model and longer travel distance.

Table 5: Comparison of the percentage of energy recovery efficiency for different driving cycles using different control algorithms.

Control algorithm	% Energy Recovery efficiency			
	NYCC	NEDC	FTP-72	FTP-75
Minimum Loss [38]	1.18 %	-	-	-
Fuzzy optimization [39]	-	13.5 %	-	-
Optimization neural network [13]	-	-	14.2%	12.5 %
ANFIS (Proposed algorithm)	22.45 %	14%	15.7 %	9.4 %

4. Conclusion

The electric vehicles performance has been demonstrated using a developed MATLAB/Simulink model to investigate the different effects of the regenerative braking systems. Artificial neural fuzzy control systems (ANFIS) is used to control the different conditions to determine the optimal utilization of the regenerative braking systems. Four different driving cycles are used to verify the implementation of the developed control strategy with the simulated electric vehicle's model.

The total braking force of the motor is used as an input threshold in the utilization of mechanical braking force and regenerative braking force to optimize the usage of the regenerative braking. The obtained results reveal that the developed control strategy of regenerative braking force can significantly increase the energy saving efficiency of electric vehicles, with an energy recovery efficiency within a range from 9.4% to 22.45 % for the different tackled driving cycles.

Nevertheless, by employing the developed control strategy, the battery SOC% is increased by a range from 11.5 % to 39.3% and travel distance is increased by a range from 11.2 % to 31.3% for the different tackled driving cycles.

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