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Development of regenerative braking in an electric vehicle using a neural controller with an auxiliary power system

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Abstract:

Electric vehicles (EV) have recently spread because of their benefits, such as reducing pollution, as they are environmentally friendly because they use clean energy instead of fossil fuels. The braking system in EV is considered one of the most important systems studied and under development in many researches. It has a significant impact on the stability of the performance of the electric vehicle, and a great benefit in increasing the battery life of the electric vehicle, by recharging it through regeneration braking, and maintaining a large state of charge relatively.

This research presents a development of the regeneration braking system by developing a neural controller consisting of two layers and using it to drive the braking process instead of the proportional integrative (PI) controller with an auxiliary power system. The latter is stable and enables its engine to generate suitable torques at relatively high speeds, without a decrease in the speed of the vehicle from the required speed, and the improvement rate was more than 10%, where the state of battery drain when using the PI controller was about 87%, while when using the neural controller more than 97% .

Keywords: Neural networks - boot- battery-circuit-vehicle - performance.

تطوير الكبح بإعادة التوليد في المركبة الكهربائية باستخدام متحكم عصبوني مع وجود نظام طاقة مساعد

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الملخص:

انتشرت العربات الكهربائية في الآونة الأخيرة لما لها من فوائد كالتقليل من التلوث باعتبارها صديقة البيئة بسبب استخدامها الطاقة النظيفة بدلاً من الوقود الأحفوري، ويعتبر نظام الكبح الخاص بها من أهم الأنظمة المدروسة وقيد التطوير في العديد من الأبحاث، لما له من تأثير بالغ على استقرار أداء العربة الكهربائية، وفائدة كبيرة بزيادة مدة بطارية المركبة الكهربائية، من خلال إعادة شحنها عن طريق الكبح بإعادة التوليد، والحفاظ على حالة شحن كبيرة نسبياً.

يقدم هذا البحث تطوير لنظام الكبح بإعادة التوليد عن طريق تطوير متحكم عصبوني يتكون من طبقتين واستخدامه لقيادة عملية الكبح بدلاً من المتحكم التكاملي التناسبي (PI) مع وجود نظام طاقة مساعد، حيث استطاع المتحكم العصبوني المطور زيادة نسبة حالة شحن بطارية العربة الكهربائية مما انعكس على أداء الأخيرة واستقرارها ومكن محركها من توليد عزوم مناسبة عند سرعات عالية نسبياً، دون حدوث انخفاض لسرعة العربة عن السرعة المطلوبة، وكانت نسبة التحسين أكثر من 10% حيث كانت حالة شحت البطارية عند استخدام متحكم PI حوالي 87% أما عند استخدام متحكم عصبوني أكثر من 97%.

كلمات مفتاحية: شبكات عصبونية – اقلاع – بطارية – دارة– عربة – أداء.

تاريخ الايداع: 2022/10/24

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Introduction:

The electric car industry has thrived due to its environmental and energy considerations. As for the environment, it does not have any negative impact, as in the case of diesel cars. For energy, it depends on electric energy and no needs fossil fuels. The process of braking by regeneration is one of the most important ways to save electric energy for electric vehicles, because of its positive role in recharging the battery. In addition to the advantage of soft braking of the vehicle through its electric motor instead of mechanical braking. Therefore, researches in this field take many directions. Because the regeneration braking is not limited to the issue of braking the electric vehicle, but it goes beyond that to many concepts related to its performance, where the performance developed in modern electric vehicles can affect the efficiency and stability of the vehicle, and environmental factors.

-Related works:

The braking system not only stops the vehicle, but it affects the accuracy of the work of many systems on the control panel of the vehicle, such as the thermal and mechanical systems in the electric vehicle. So one study proposed a method for performing generation braking for two wheels at the same time and studied the speed of the vehicle in the cases of mechanical braking and braking by regeneration, and the response to each of them (Pugi et al. , 2019). The study (Xu et al., 2020) proceeded from the important and essential role of regeneration braking control technology in electric vehicles to save energy and protect the environment. It considers that the presence of two basic factors is very important in the process of braking by regeneration; the first: maintaining the stability of the vehicle during the braking process to safe it, and the second: reducing the energy consumed to operate the vehicle and recovering as much energy as possible. A strategy for performing regeneration braking to achieve the previous two factors is proposed, based on a predictive controller design to distribute braking torque between hydraulic and electric braking on four wheels, and a simulation was carried out using Matlab/Simulink for four-wheel drive models separately.

A new strategy has been developed to distribute the braking force from the front axle to the rear axle to control the regenerative braking of a high-speed electric vehicle. The proposed method adapts the energy recovery from the electric motor during braking and meets the safety requirements. The method of controlling the braking process by regeneration is characterized by the presence of a control unit for the forces generated during the braking process, which has a prominent role in enhancing braking performance and electrical efficiency. The regeneration braking control was implemented with high accuracy, as the effectiveness of the system and the performance of regeneration braking were analyzed. The results proved that the regeneration braking system improved the efficiency of the electric vehicle's energy recovery, and the study concluded that a proposed controller could be designed for the regeneration braking process that achieves the concepts of safety and high yield. (Karyotakis et al., 2021).

The study (Xu et al., 2011) also showed that the regeneration braking method is very effective in increasing the time of driving electric cars and suggested a smart method for the regeneration braking based on the fuzzy logic to obtain a high level of electrical energy conservation and saving. Taking into account the concept of electric vehicle security during regeneration braking operations, to prevent the occurrence of the two phenomena of vehicle skidding or vehicle locking during the braking process. Italian researchers have proposed a methodology for the braking process in electric cars in order to recover the energy resulting from the braking process by regeneration in an optimal way. The application was carried out using two motors, one for each rear wheel, and the process of regeneration braking was applied with and without the proposed strategy, as it was found that under optimal conditions, energy could be recovered at each specific speed (Rizzo et al., 2021).

Regeneration braking was not limited to induction motors but was used in three-phase brushless DC motors to extend battery life in electric vehicles

(Long et al., 2014). Based on the concept of the possibility of recovering electrical energy by braking by regeneration in many electric cars, a control strategy has been proposed to achieve that. This strategy consisting of three levels to control the process of braking and regeneration. It includes several paths and possibilities for driving the vehicle starting from the driver and his commands in the upper layer to optimal algorithm in the middle layer down to the bottom layer including the hydraulic system to perform the regeneration braking process (Li et al., 2020). Due to the large number of researches related to the topic of regeneration braking, some studies have presented a comprehensive review of studies that dealt with regeneration braking in terms of advantages and disadvantages, based on the importance of increasing the effectiveness of braking in vehicles and reducing heat losses in the mechanical braking system (Jamadar and Jadhav, 2021). The principle of regeneration braking is based on the principle of converting mechanical energy into electrical one by converting the work of the electric car motor into the principle of generation and making it work as a generator by converting the mechanical energy of braking into electrical. The electric energy is converted from alternating to direct through the commutator and then goes to charging the batteries (Totev et al., 2019). Another study suggested a strategy for regeneration braking to achieve two primary goals. They are to restore as much energy as possible, and to maintain the safety and stability of the vehicle. It provided mathematical modeling of the regeneration braking process and developed the braking algorithm, and came to a conclusion that included increasing the battery life cycle before charging it again (Ping et al., 2021).

The essence of research in the field of regeneration braking in electric vehicles is to propose a control algorithm capable of dealing with difficult situations without affecting the system ant to achieve a high yield of the current produced by regeneration braking.

Where we find that the control algorithm based on a neural network has been adopted by (Manriquez et al., 2021) and the controlled variable is torque, while in most of the reference articles it is speed. It is also worth noting that, some studies focused on the issue of reducing the return current during the braking process by regeneration, to prevent the combustion of the electric vehicle battery using a hydraulic system. This hydraulic system represents an auxiliary driving system to perform the braking process to mitigate the impact of the return current from the braking process by regeneration on the battery with the presence of a fuzzy controller (Zhao and others, 2021).

The importance of research in the topic of regeneration braking in electric vehicles can be summarized by maintaining the stability of the vehicle at high torques while storing a return current by recharging the battery, which prolongs its operating time. This article falls within this field of research and its idea is to design an intelligent neural controller capable of regulating the braking by regeneration, taking into account the presence of an auxiliary power system to protect the battery from large currents and maintain the stability of the vehicle at high torques. Where the intelligent controller works instead of the PI one to perform the braking with regeneration in the presence of an auxiliary power system. This is necessary to prevent the battery burning when the car is braking when moving at relatively high torques, where the generated currents are relatively large. Model simulation was conducted using the MATLAB environment for both systems braking by regeneration in the presence of a PI and a neural controller. The results are founded and comparing between them.

-Materials and working methods:

This research was carried out according to the following steps:

1- Explanation of the components of the electric vehicle in terms of the electric drive system.

2- Study of the classical regeneration braking system in the presence of a PI controller.

3- Presentation of the regenerative braking system with an auxiliary power system using a proposed neural controller.

4- Clarifying the structure of the used neuron controller.
5- Carrying out a simulation of the classical and proposed regeneration braking system using the MATLAB environment, collecting the final results and discussing them to know the extent of the improvement.

1- Electric vehicle

Figure (1) shows the components of the electrical parts of the process of driving an electric car. The driver adjusts the speed through the car pedal, which is a variable resistance through which a reference voltage signal is generated. The reference voltage is expressing the required reference speed from the controller, which in turn controls with the inverter by means of the DTC (Direct Torque Control) algorithm. In order to rotate the drive motor (M) in the desired direction and speed with torque suitable for the load, the power source is supplied from a battery with an APS (Auxiliary Power System) and regenerating braking unit. The purpose of which is to brake the motor at low speed or stop while charging the battery from the return current from the regeneration braking process is done. The driver can also control the steering wheel of the car, which is a variable rotational resistance that gives an electric voltage signal to the controller in the required amount of turn with the direction, which in turn gives commands (which are electrical impulses) to the drive circuit of the steering motor drive (Motor for Direction) Md. More specifically, the driver has the steering wheel, the accelerator pedal, the stop pedal and the transmission; Through the steering wheel, the driver determines the direction and amount of the car’s rotation, the pedal determines the amount of speed, and through the transmission, the direction of the car’s travel forward or backward. If he wanted to stop, he stepped on the stop pedal. The steering wheel is a rotational variable resistance that gives a voltage signal by the amount of rotation to the controller through an analog input, which in turn - the controller - generates control pulses for the "drive circuit", which in turn ensures the rotation of the steering motor Md in the right direction and amount.

The pedal is a variable resistance connected to an analog input in the controller and gives the reference voltage signal representing the amount of reference speed that the driver wants the vehicle to move. While the transmission is, an electric switch connected to the digital input of the controller to know the direction of the vehicle going forward or backward. The driver steps on the pedal at the speed he wants. The controller receives the voltage signal generated from the variable resistance connected to the pedal and reads the signal connected to the digital input to determine the direction of movement of the vehicle. After that, the controller generates PWM pulses to the inverter by the DTC algorithm programmed within it with Note: Receiving the necessary feedback signals for the DTC algorithm from the measurement unit via analog inputs or digital counters located within the microcontroller.

If the driver wants to stop, he steps on the stop pedal, which is also a variable resistance. Then the amount of stepping determines the stopping speed and the amount of braking required by generating a reference voltage signal expressing that. The controller reads reference voltage signal by an analogue input, then starts operating Regenerating Breaking unit with APS. The controller generates control pulses for the braking process with regeneration according to its programming (either the PI controller is programmed or the neural network). These pulses make the braking system with regeneration work to brake the thrust motor M, while taking advantage of the current generated by the braking process to recharge the battery, with performance and efficiency determined according to the efficiency of the controller used. The results later show that the ANN controller gives higher performance and efficiency than the PI one as will be clarified in the discussion and results section.

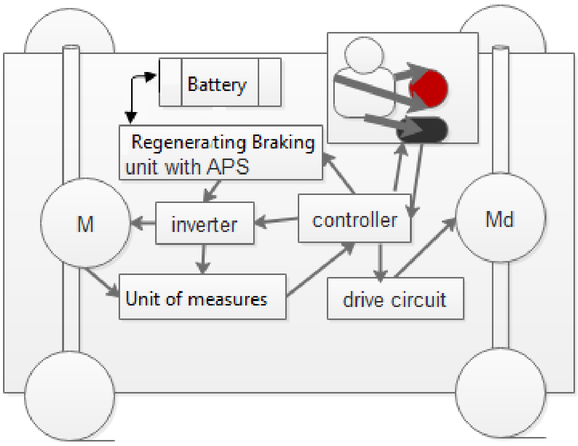


Figure (1) Components of the electric vehicle driving system

2- The regenerative braking system

The regenerative braking system is based on the presence of a battery connected in parallel with an auxiliary power system consisting of a capacitor in parallel with a charging resistance connected in series with a diode and an electronic switch controlled by a controller. This capacitor is high power industrial capacitor. This system has been simulated using the Matlab program as shown in the figure (2) in both cases:

A- With PI controller

Figure (2-A) shows a simulation model of the regenerative braking system with a PI (Proportional Integral) controller, whose equations are given by the following relationship:

$$g = k_p V + k_I \int V dt \qquad (1)$$

Where:

g : The controller output which is the voltage applied to the electronic switch base.

k_p : Proportional constant.

k_I : Integral constant.

V : Output voltage, which is the voltage of the battery and capacitor.

B- With ANN controller

Figure (2-B) shows a simulation of the braking system in the presence of an artificial neural controller. This controller consists of two layers of neurons as shown in Figure (2-C) and is given by the following equation:

$$g = f_2\left(w_2 f_1\left(w_g g_{-1} + w_u u_{-1} + w_r r + b_1\right) + b_2\right) \quad (2)$$

Where:

w_2 : The weight of the second layer.

b_2 : Displacement of the second layer,

f_2 : function of activation of the second layer, which is a linear function, is given by:

$$y = x \qquad (3)$$

w_g : The weight of the first layer connected to the output of the controller after being delayed by one g_{-1} (the output of the controller is the mug pulses connected to the gate of the electronic switch g

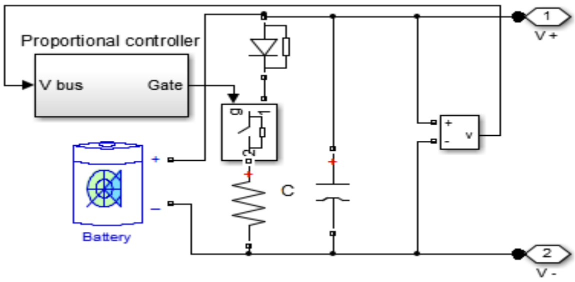
w_u : The weight of the first layer connected to the output of the controlled model after being delayed by one, u_{-1} which is the voltage on both ends of the battery

w_r : The weight of the first layer connected to the output of the reference model (reference signal) r

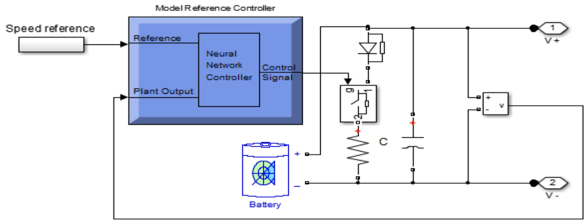
f_2 : The second layer activation function, which is the tansig function, is given by the relationship (Vogl et al., 1988) (Kafarnawi, 2021):

$$y = (2/(1+e^{-2x})) - 1 \qquad (4)$$

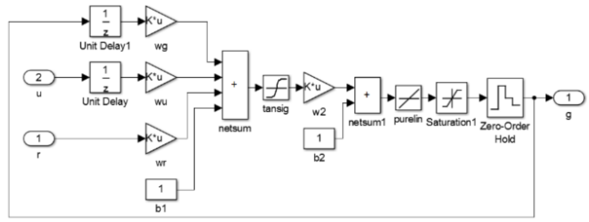
Layer 2 activation function output connected to saturation1 to prevent over value of electronic key g opening effort with first-order zero order hold to convert intermitted signal to continuous signal that fits electronic key input g



A- PI controller



A- ANN controller



C-ANN controller structure

Figure (2) Regenerative braking unit with auxiliary power system

For the battery model, it is the lithium battery model, and it is given by the following equation (Tremblay et al., 2009):

$$I_{bat} = V_{bat} + R_{int} E_{bat} \quad (5)$$

Where:

I_{bat} : Battery current

V_{bat} : Battery voltage.

R_{int} : The internal resistance of the battery.

E_{bat} : The electromotive force of the battery, which is a controlled voltage source that changes according to the state of the battery, where we distinguish two cases; discharge state: in which the current is in the transient state $i^* > 0$. and state of charge: the current of the transient state $i^* < 0$ is given by:

$$E_{bat} = \begin{cases} E_0 - K\dfrac{Q}{Q-i_t}i^* - K\dfrac{Q}{Q-i_t}i_t + Ae^{-Bi_t} & i^* > 0 \\ E_0 - K\dfrac{Q}{0.1.Q+i_t}i^* - K\dfrac{Q}{Q-i_t}i_t + Ae^{-Bi_t} & i^* < 0 \end{cases} \quad (6)$$

Where:

E_0 : The constant voltage is estimated in volts.

K : Boltzmann constant (Ah^{-1}) or Boltzmann resistance (Ω).

Q : The maximum capacity of the battery, estimated in amperes-hours Ah

i_t : The capacity of the battery is drawn in amperes-hours Ah

A : Exponential voltage, measured in volts.

B : Exponential amplitude estimated (Ah^{-1}).

The battery operates in a charging system by regenerating braking, where the current is negative, that is, the direction of the current from the electric vehicle's motor to the battery. When the vehicle is running, the battery operates in a state of discharging and is the source of supplying for the motor car.

4-Results and Discussion

The performance of the electric vehicle was simulated in the MatLab software environment as shown in Figure (3), using a three-phase induction squirrel cage drive motor, according to the specifications given in the following table (Krause et al., 2022):

Table (1) electric vehicle motor, battery and capacitor specifications.

The parameter	
Nominal power	150Kw
nominal voltage	380v
Frequency	50Hz
number of pairs of poles	2
stator resistance	14.85mΩ
stator lecture	0.3027mH
Rotor resistance	9.295mΩ
rotor lecture	0.3027mH
moment of inertia	3.1Kg.m2
coefficient of friction	0.08N.m.s
Battery capacity	600Ah
Battery type	Lithium
Capacity of capacitor	5200µF

The user selects the desired speed through the accelerator pedal (in our experience it is 8.4m/sec and the total torque required is 20N.m), which is translated to a reference speed for the controller that

works according to the DTC methodology with a speed controller.

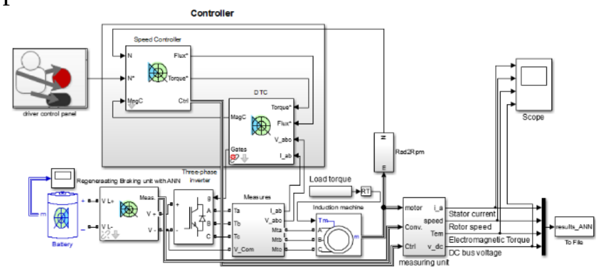


Figure (3) a simulation model of the performance of an electric vehicle using a three-phase drive motor with regeneration braking

The speed controller generates the desired torque* and flux* according to the given reference speed. The desired torque and flux values are passed to the direct torque control methodology that generates pulses for the trigger gates of the three phase inverter. The inverter is a three-phase gantry block whose function is to convert DC voltage into three phase alternating voltage to drive the induction motor at the required speed with a unit of measurement between the inverter and the motor to measure the currents and voltages required for the direct torque control methodology. This model contains the Regenerating Braking Unit with APS with an auxiliary power system. This unit has been simulated according to two working mechanisms. The first one: presence of an integrative proportional controller, and the second one: presence of artificial neural network controller according to the scheme shown in Figure (2). All of that in order to know the extent of the development of the regeneration process of braking when developing this unit using artificial neural network controller instead of an integrative proportional controller. The movement of the electric vehicle was simulated at an increasing speed with different torques and in the presence of the regeneration braking system with the auxiliary power system, for the following two cases:

The first case: Using an integrative proportional controller as shown in Figure (4-A), where the results show that the speed of the electric vehicle reaches 5.8m/sec, while the required speed is

8.4m/sec because the kinetic torque of the vehicle oscillates at 14N.m and does not reach to the required torque of 20N.m.

The second case: Using a neural controller as shown in Figure (4-B), the results show that the car is traveling at the required speed with the required torque.

It is noticed from the results shown in Figure (4) that the performance of the electric vehicle exceeded the performance of the electric vehicle when using a neural controller (ANN) over the case of using a proportional integrative controller (PI). Because when using an ANN neural controller, the actual speed of the electric vehicle reached the required reference speed that the driver wanted while maintaining the required torque. While when using PI controller, the actual speed of the electric vehicle do not reach the required speed and the torque of the vehicle fell below the required limit. And this superiority is due to the increase in the amount of battery charge when using the ANN controller, Where the current generated by regeneration braking is greater than in the case of using a PI controller as shown in Figure (5-A). Where we find that the current generated as a result of regeneration braking when using a neural controller exceeds 150A. While the current generated by regeneration braking when using a proportional integrative controller does not exceed 120A. Which causes a weak electric vehicle battery current due to decrease in the charge percentage of the battery when using the PI controller, and because the total capacity required from the feeding system is constant, which in turn leads to a drop in the battery voltage when the vehicle is moving as well. It is shown in Figure (5-B). So the battery voltage during the movement of the vehicle is higher when using the ANN controller than when using the PI controller in the regenerative braking system of the electric vehicle. The battery voltage do not suffer from a decrease when using the ANN controller in the braking system By regeneration, as when using a PI controller. The battery voltage while operating the vehicle was a minimum of 11.8volt when using the ANN controller, with it oscillating and reaching 12volt while operating the electric vehicle. However, when using the PI controller, the voltage fluctuated around 10.5volt, reaching lower voltage levels and not exceeding the battery voltage while the electric vehicle is in motion is 11.2volt, as shown in Figure (5).

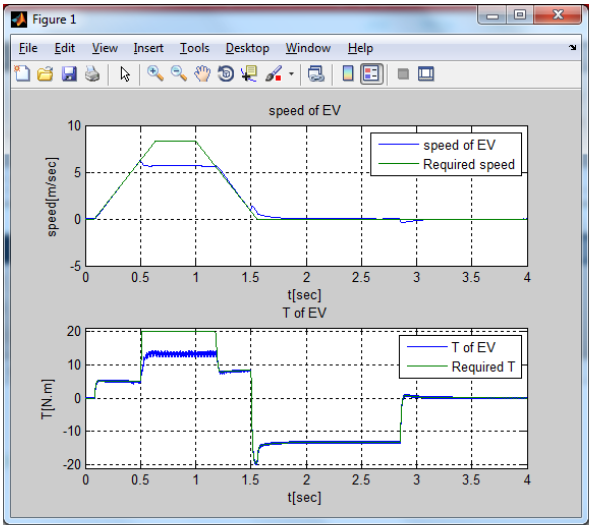
The figure (6) shows torques: required T, T with Pi controller and T with ANN controller. The last one close to the required T but the second one cannot close specially at starting change at time t=0.5 sec. This confirms importance of ANN controller. The torque is related with current taken from battery. If the current is enough to make motor generate enough torque, the torque will be more close to required torque. The entail conditions are set like final state of simulation to see effect recharge current in the change of torque. The braking begins at t=1.5 sec and finishes at t=2.8 sec like shown in figure (4). This period from 1.5sec to 2.8 sec is final state for battery. After 2.8 sec, battery is not used. The T with ANN controller is closer then T with PI controller to required torque. This improves the current taken from battery is bigger in ANN controller than one in PI controller. When the generated torque is not enough, the speed will be reduced especially at high required torque like in state of PI controller shown in figure (4-A) at t=1.5 sec.

The previous results confirmed by comparison made between the performance of the two regeneration braking systems according to the SOC (State of Charge) standard, as shown in Table (2), which is given by the following relationship (Tremblay et al., 2009),(Mu and Xiong, 2018):

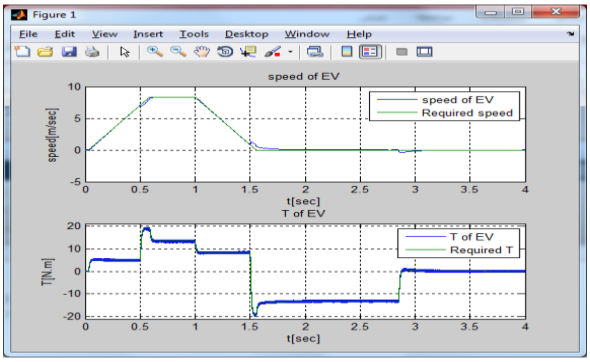
$$SOC = 100\left(1 - \frac{1}{Q}\int_0^t I_{bat}\,dt\right) \qquad (7)$$

The above equation shows that state of charge for battery is related by drained current and time of draining from battery. For example if we have battery 400Ah so that mean if we run battery for half hour 200 Ah so $SOC = 100(1-0.25) = 75\%$

The comparison shows that the performance of the system of braking with regeneration with the presence of an auxiliary feeding system when using the ANN controller is better than the case of using the PI controller. The battery charge state is 97.96% when using the ANN controller, which proves that the process of charging during braking with regeneration is more feasible when using the controller ANN than when using a PI controller where the charge state is 87.22%.

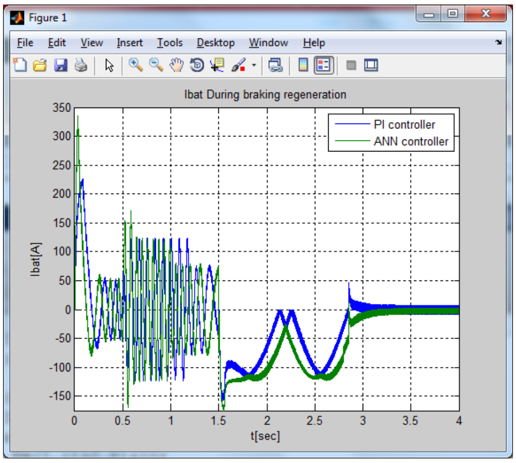


A- Speed and torque curves with a PI Controller

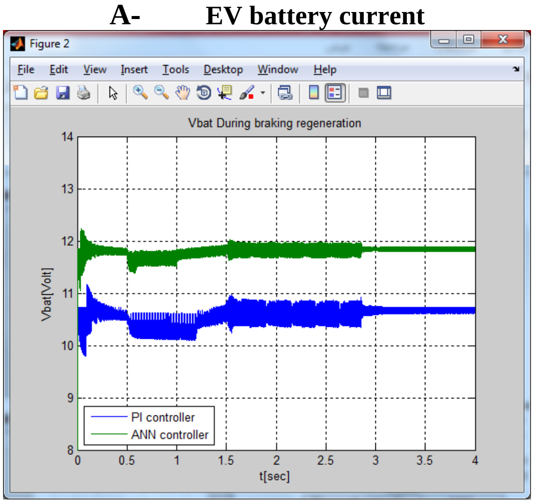


B- Speed and torque curves with ANN Controller

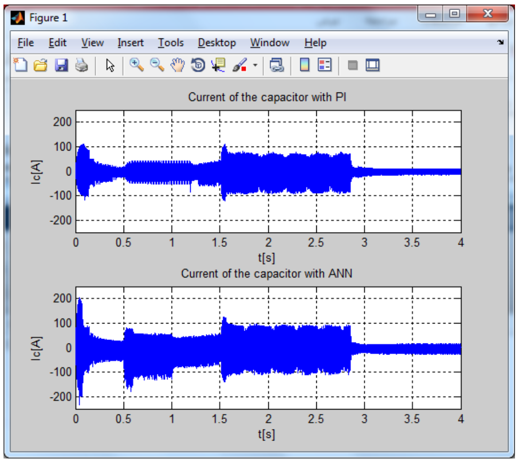
Figure (4) Velocity and torque curves resulting from driving an electric vehicle in the presence of regeneration braking.



A- EV battery current



B-EV battery voltage



B- EV capacitor current

Figure (5) the current and voltage curves of the electric car battery in the presence of the regeneration braking system with the presence of APS in two cases: using the PI controller and using the ANN controller.

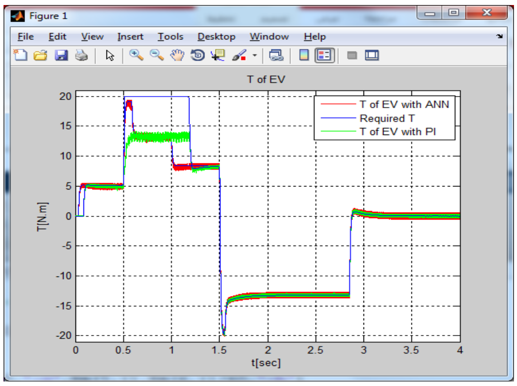


Figure (6) torque curves resulting from driving an electric vehicle in the presence of regeneration braking for ANN and PI with required torque.

Table (2) Comparison of the SOC of the electric vehicle battery in the two regeneration-braking states

The used controller	SOC
PI	87.22%
ANN	97.96%

5-Conclusion:

In this paper, the performance of an electric vehicle is developed by increasing the torque of its motor and its response to levels of relatively high speeds without a shortfall in performance or a decrease in its speed, as a result of the reduced torque required for its movement, by maintaining appropriate voltage levels for the electric vehicle's battery. The battery is charged by current, which results of the regeneration braking with the presence of an auxiliary power system. A neural controller instead of an integrative proportional controller develops the performance of the regeneration braking system. The battery charge state increased to 97%, and the improvement rate in the regeneration braking system exceeded 10% over the regeneration braking system in the presence of a PI controller and not over a drive system without a regenerative braking system.

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