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Title: Neural Sliding Mode Control of a Regenerative Braking System for Electric Vehicle

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Introduction

Nowadays, Electric Vehicles (EVs) present an important alternative solution to conventional vehicles, regarding gasoline prices, gas emissions, and climatic changes among other factors [1]. One of the challenges in EVs is the enhancement of energy storage in order to improve the capability to drive longer distances extending the battery cycle of life and state of charge.

The proposed architecture in this work is a regenerative braking system with an Auxiliary Energy System (AES) conformed of a super-capacitor and a buck-boost converter to enhance the Main Energy System (MES) conformed of a battery bank which dynamics are approximated using a Recurrent High Order Network (RHONN) trained with the Extended Kalman Filter [2]. The regenerative braking capability is one of the most important characteristics of EVs, which helps to recover energy during braking and improves the storage system efficiency [3].

A Neural Sliding Mode Controller (NSMC) for a regenerative braking system is used to control the current and voltage of the buck-boost converter related to AES with the objective to recover the waste energy during braking and enhance the MES efficiency.

Regenerative Braking System

A regenerative braking system as illustrate in Fig. 1 allows the recovery of kinetic energy produced during braking and its utilization to improve the energy storage efficiency and extend the operating distance of the EV [4].

This system is composed of a super-capacitor and buck-boost converter, which are part of the AES. In addition, a battery bank is used to administrate the energy to the electrical motor conforming to the MES.

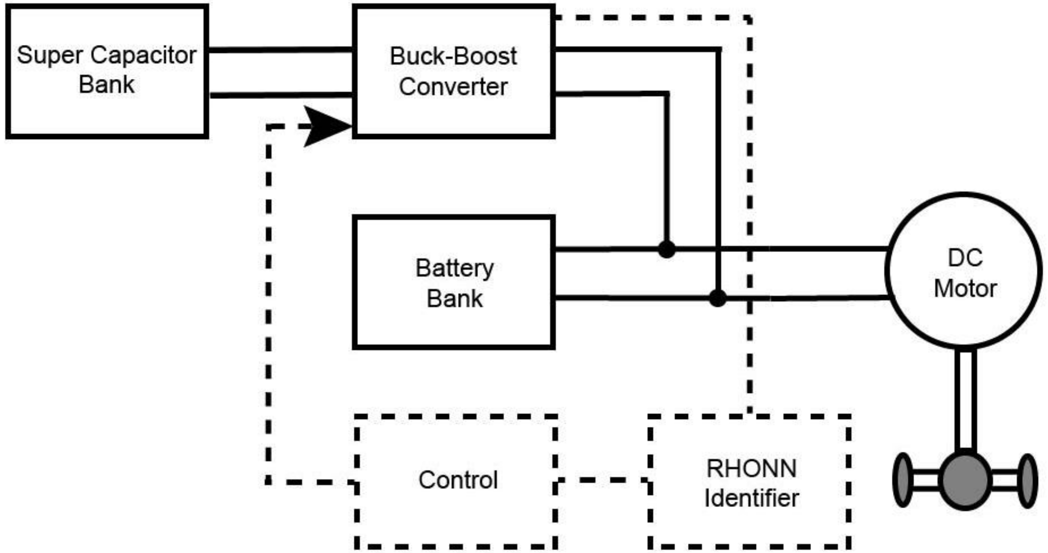

Figure 1 Regenerative Braking System

Regenerative Braking System

The super-capacitor and the buck-boost converter are connected as illustrated in Fig. 2, with the objective of increasing or decreasing the output voltage depending on the following operation modes.

During the braking operation, the brake manages the electricity generated by the motor into the batteries or capacitors. The DC-DC converter operates in **buck function** during the deceleration while the **boost function** is enabled during the acceleration, which will make it easier in charging up the super capacitor.

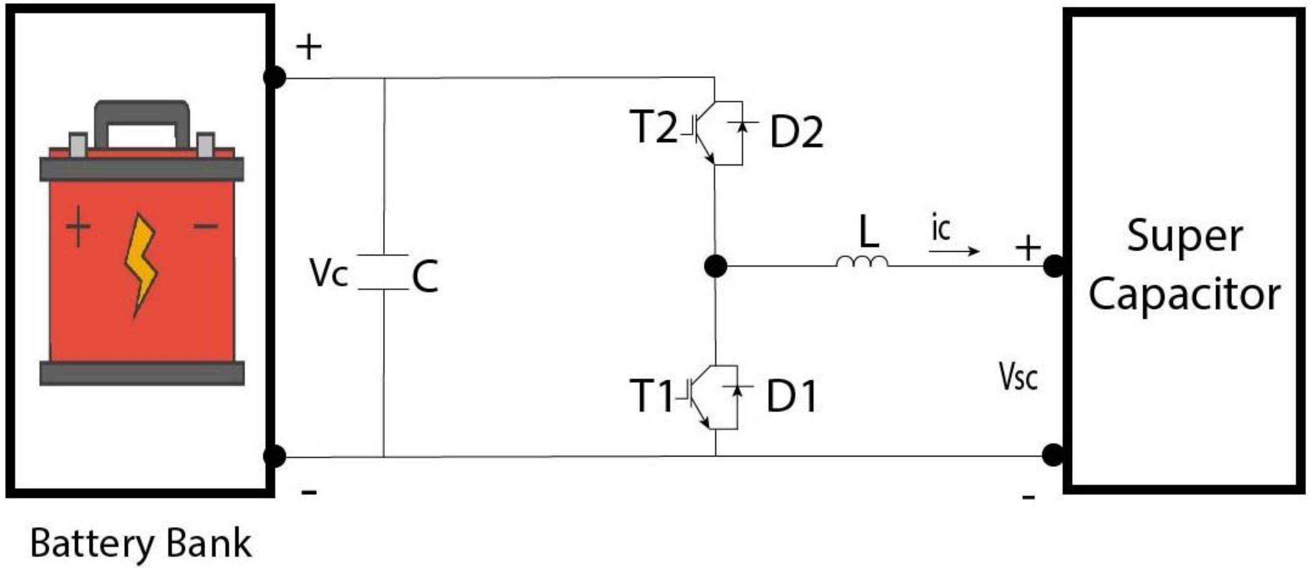

Figure 2 Buck-Boost Converter

Buck-Boost Converter Model

The boost converter model is defined as [5].

$$x_{1,k} = \left(1 - \frac{ts}{RC}\right) x_{1,k} - \frac{ts}{c} x_{2,k} \quad (1)$$

$$x_{2,k} = x_{2,k} + \frac{ts}{L} U_{btt} u_c \qquad (2)$$

The buck converter model is given as:

$$x_{1,k} = \left(1 - \frac{ts}{RC}\right) x_{1,k} + \frac{ts}{c} x_{2,k} \quad (3)$$

$$x_{2,k} = x_{2,k} + \frac{ts}{L} U_{btt} u_c \qquad (4)$$

where $x_{1,k}$ is the Buck-Boost converter output voltage, $x_{2,k}$ is the Buck-Boost converter output current both with the inductance L(H), resistance load R (Ω), capacitor (F) C, and t_s sampling time.

Neural Controller Design

To control the current flow and ensure the charging and discharging operation modes, an RHONN has been used to approximate the buck-boost converter behaviors and then the sliding mode controller is synthesized. Knowing the adaptive nature of the RHONN, and the similitude between the buck and boost converter models a single identifier is proposed for both cases as

$$\widehat{x_{1,k}} = \omega_{1,1}(k)S(x_1) + \omega_{1,2}(k)S(x_2)$$

$$+w_{1,3}S(x_1)S(x_2) + \varpi_1 x_2 \qquad (5)$$

$$\widehat{x_{2,k}} = \omega_{2,1}(k)S(x_2) + \omega_{2,2}(k)S(x_1)$$

$$+w_{2,3}S(x_1)S(x_2) \qquad (6)$$

Equations (5) and (6) can be rewritten as follows

$$\widehat{x_k} = \hat{F}(x_k) + \hat{B}u(x_k, k) \qquad (7)$$

$$\widehat{y_k} = x_{2,k}k \qquad (8)$$

And the NSMC is implemented as follows.

$$u(x_k, k) = \begin{cases} u_c(x_k, k) \quad if \;\; ||u_c(x_k, k)|| < u_0 \\ u_0 \dfrac{u_{eq}(x_k, k)}{\left\| u_{eq}(x_k, k\,) \right\|} \;\; if \;\; ||u_c(x_k, k\,)|| \geq u_0 \end{cases} \textbf{(}9)$$

with $\mathrm{u_c(x_k, k) = u_{eq}(x_k, k) + u_n(x_k, k)}$, $u_n(x_k, k) = -(ks_k)$, where k is Schur matrix, and u_0 is the control upper bound and s_k is defined as:

$$s_{k+1} = \omega_{2,1}(k)S(x_2) + \omega_{2,2}(k)S(x_1) + w_{2,3}S(x_1)S(x_2)\varpi_2 u(x_k, k) - x_{ref,k+1} \text{ , and}$$

$$u_{eq}(x_k, k) = -\frac{1}{\varpi_2}\left[\omega_{2,1}(k)S(x_2) + \omega_{2,2}(k)S(x_1) + w_{2,3}S(x_1)S(x_2) - x_{ref,k+1}\right]$$

Simulation Results

The proposed control scheme as well the respective MES and AES are implemented and evaluated using the SimPower System toolbox of MATLAB. The parameters of the AES and MES are listed in Tab. 1

Description	Unit
Converter Resistance R.	$50\ \Omega$
Converter Inductance L	$1.5\ e^{-3}H$
Converter Capacitance C	$100\ e^{-3}\ F$
Super-capacitor voltage V_{sc}	$350\ V$
Battery Bank Voltage V_c	$450\ V$
Initial SOC	80%
Sampling time (t_s)	$1e^{-5}s$

Table 1. *Parameters of the AES and MES*

Neural Identification

The implemented RHONN identification allows to achieve adequate estimation of system states, which are in this case, the voltage x_1, k and current x_2, k during different operation modes. Fig.3 illustrates the neural identification of the voltage $(x_1, k)$and their respective neural weights evolution. Fig. 4 presents the neural identification of the current $(\mathrm{x}_2, \mathrm{k})$ and their respective neural weights dynamics.

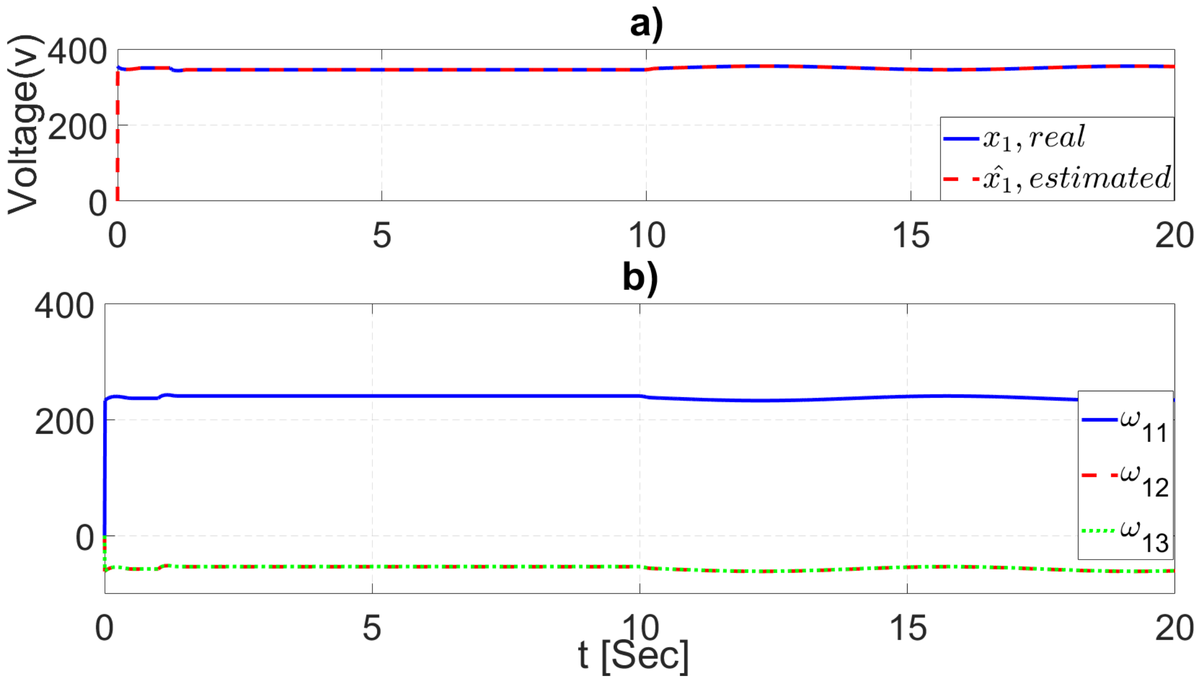

Figure 3. a) Voltage identification (x_1, k) b) $\mathrm{NN_s}$ weights.

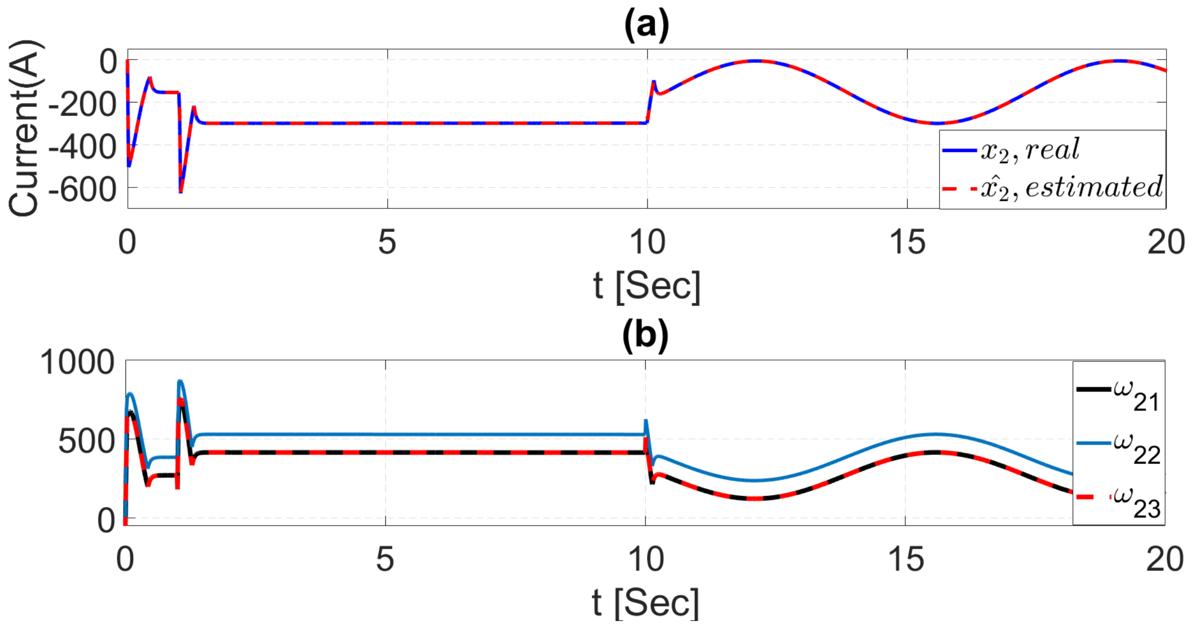

Figure 4. a) Current identification (x_2, k) b) $\mathrm{NN_s}$ weights.

Trajectory Tracking

The tracking of a desired trajectory of the AES voltage and current is demonstrated using a varying-time voltage reference x_1, r is used where it is initiated in $350\,V$ and then decrease to $345\,V$ after $10\,s$ and then, this reference is changed to a sinusoidal function. Fig 5 presents the obtained results for the voltage (x_1, k) at the output of the Buck-boost converter used in the AES system. Fig 6 demonstrates the behavior of the current (x_2, k) as measured at inductor of the Buck-boost converter

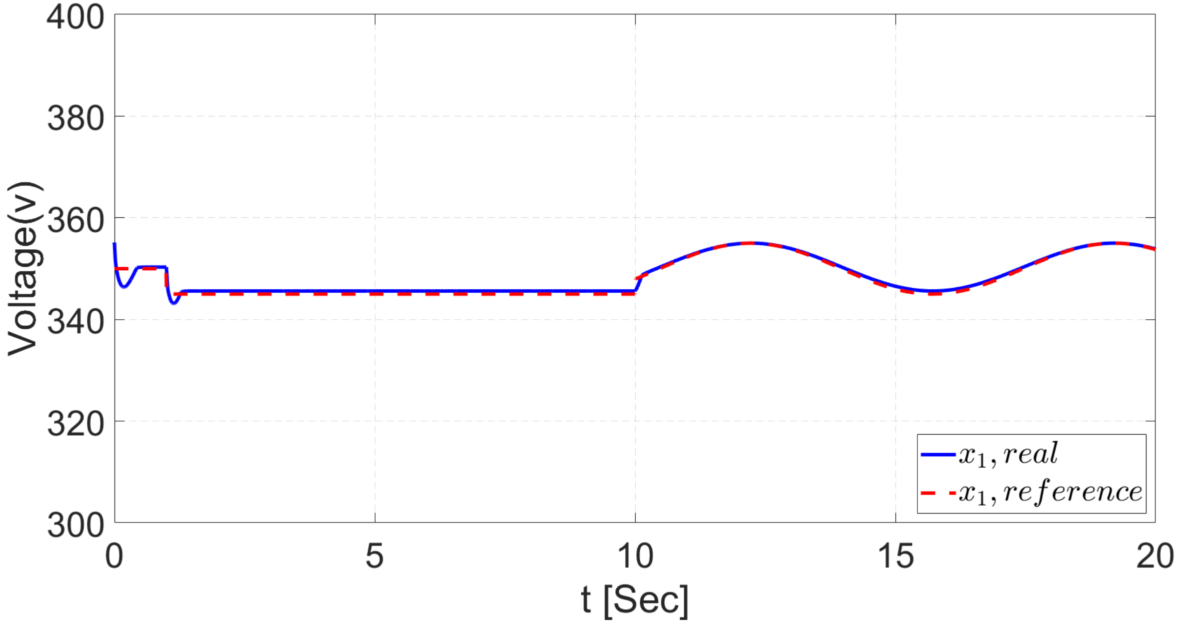

Figure 5. Voltage Trajectory Tracking

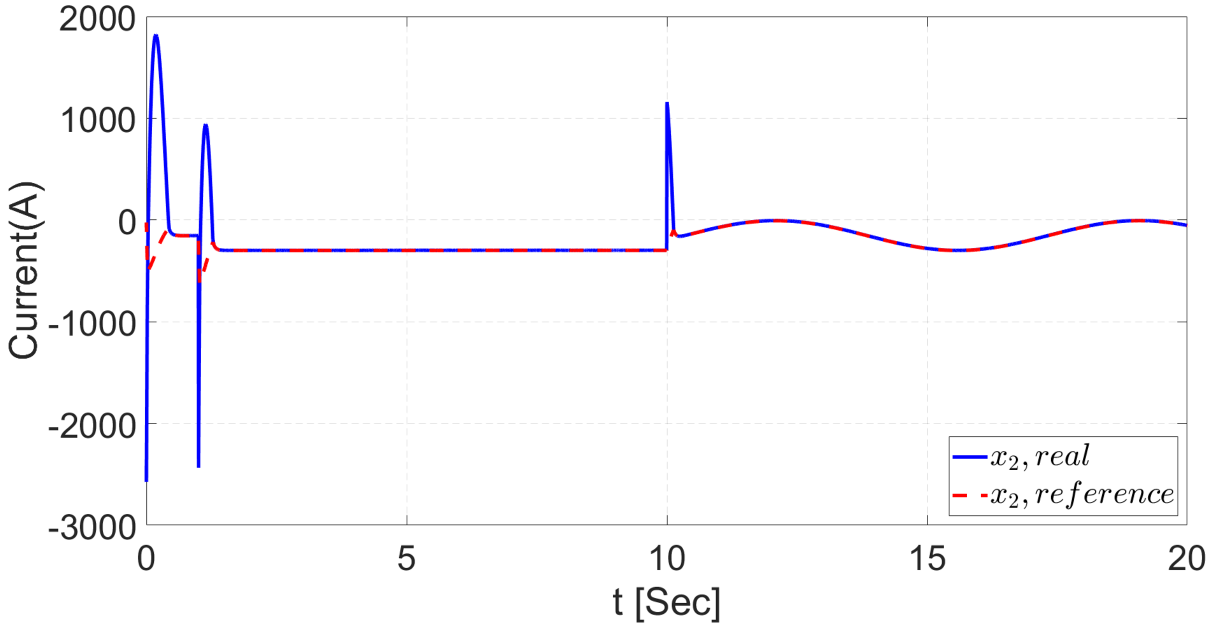

Figure 6. Current Trajectory Tracking

State Of Charge

In the charging operating mode, $t = 0\ s$ to $t = 10\ s$, the boost mode is selected while the buck mode is used during the discharging mode $t = 10\ s$ to $t = 20\ s$. The proposed control scheme (NSMC) ensures adequate trajectories tracking of the AES voltage and assures the charge and discharge operation modes of the AES. Fig. 7 displays the charging and discharging modes of the AES.

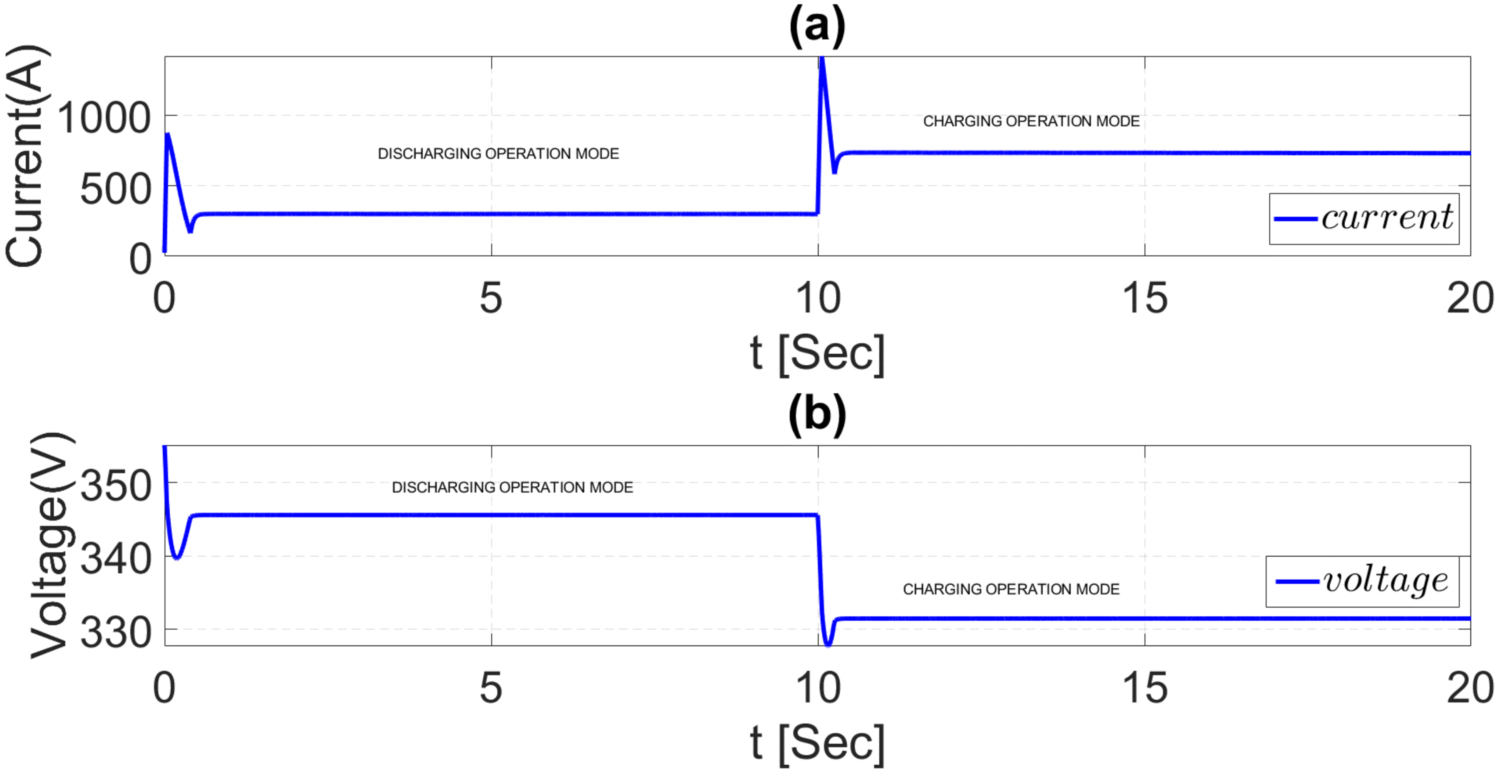

Figure 7. AES charging and discharging

State Of Charge

Fig. 8 illustrates a comparison between the MES discharging behavior with and without AES. Form the obtained results, the MES performance is improved by using the AES since the MES discharging behavior without AES is fast than when this last is activated.

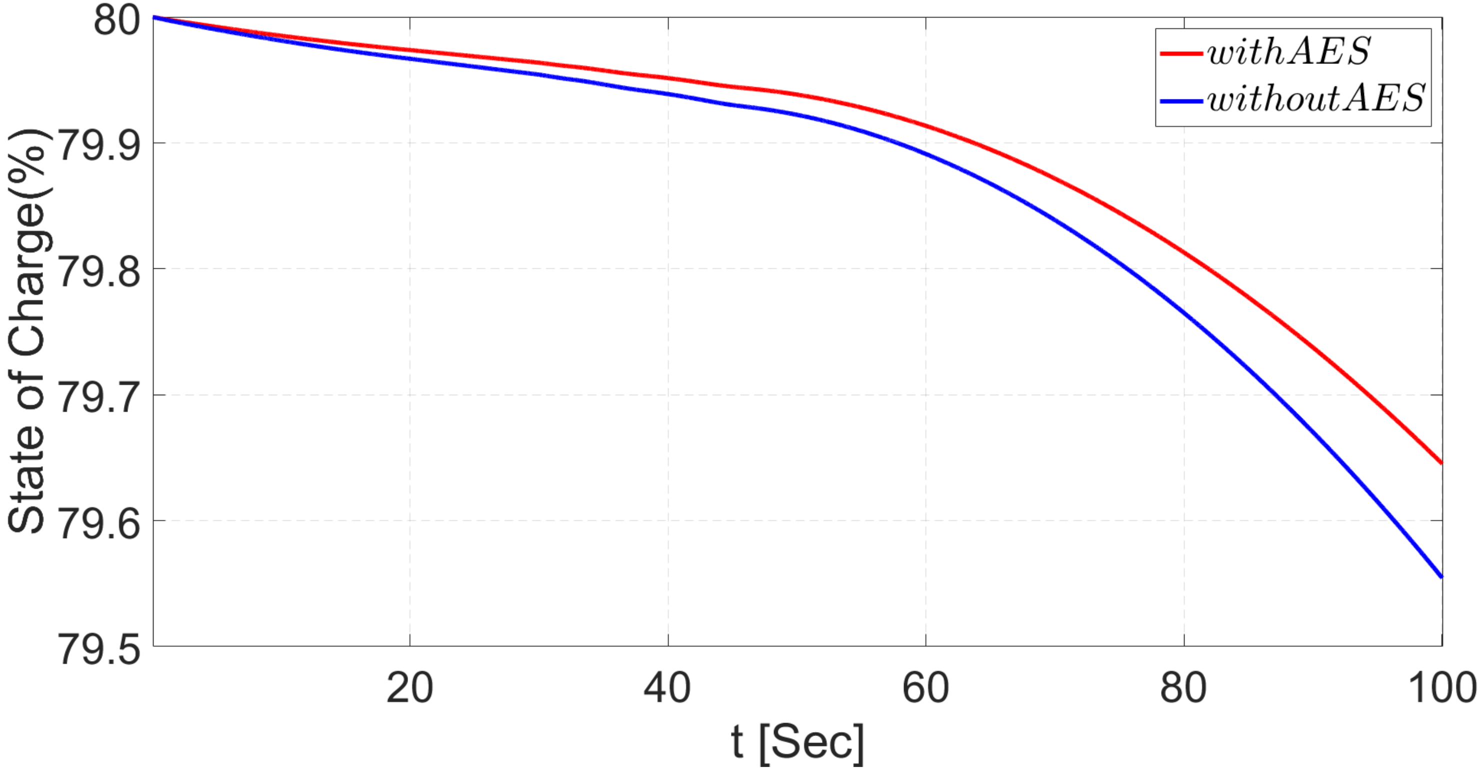

Figure 8. Comparison of variables with and without the regenerative braking

Conclusions

A NSMC of a regenerative braking system scheme is used to control the AES composed of a buck-boost converter and super-capacitor with the objective to recover the energy during breaking and participating in power supply of the MES

The obtained results illustrate the effectiveness of the proposed control scheme where the trajectories tracking of AES voltage and current are achieved and the charging and discharging mode is ensured. In addition, the MES behavior is enhanced by using the AES, which helps to improve the discharging time of the MES and extend the operation time of the EV.

In conclusion, the used controller in this paper presents a simple control algorithm, which can be used in the industrial EV applications.

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