A fuzzy-based Solution for Optimized Management of Energy Consumption in e-bikes

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Abstract

In recent years, electric vehicles (EVs) have performed an increasingly significant role in contemporary smart cities. Among the various classes of EVs, it is reasonable to incorporate electric bicycles (e-bikes) which have encountered a fast spread in the last ten years. An e-bike is a bicycle on which an electric motor, powered through the use of rechargeable batteries, can be used for propulsion. As a consequence, the main issue related to this kind of vehicles concerns the usage of batteries related to distribution and production of the energy to power them. This paper introduces a solution based on fuzzy logic aimed at optimizing the energy management of electric bikes. The retrieved results prove that the proposed approach outperforms another method based on proportional–integral–derivative (PID) controller, significantly prolonging battery life.

Keywords: Fuzzy Logic Control, Energy Management, E-Bikes, Smart City

1 Introduction

ICT (Information and Communications Technology) represents a set of techniques for transmitting, processing, and receiving data and information [15, 24]. ICT-based solutions are used in heterogeneous public and private environments. They can be considered the real general purpose technologies and are increasingly connected to human, social, and economic progress.

The origin of the technologies mentioned above took place in the early nineties from the combination of the Information Technology (IT) and the Communication Technology (CT), coupling different parts from telecommunications, electronics, and media [10]. The spread of ICT has caused the beginning of a real industrial revolution [6, 5], still in progress, in which users find themselves interacting with each other, with information and with the surrounding context, as, for instance, in Smart Cities [7].

A smart city represents a set of organizational strategies aimed at improving and innovating public services by relating physical infrastructure to social and intellectual assets [18, 20, 19]. In these modern cities, the attention is focused not only to traditional services but also to the increasingly fundamental role owned by high technology and environmental heritage, moving towards efficiency [2, 3, 22]. Another peculiarity to take into account is the environmental sustainability, which, in this historical period, becomes crucial, as resources become increasingly limited, and most cities base their economy on the exploitation of natural reserves. This practice must not compromise natural assets and must guarantee the renewability. As a consequence, it is feasible to recognize the prominent importance of renewable energy sources and, also, their applications in the field of low environmental impact vehicles [11].

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In recent years, electric vehicles (EVs) [9] have played an increasingly important role. The environmental impact related to transport infrastructures based on oil has encouraged interest in EVs. The latter can rely on the use of renewable energy sources, also minimizing the environmental impact. Among the various classes of EVs, it is possible to include electric bicycles (e-bikes) [8] which have experienced a rapid spread in the last ten years. An e-bike is a bicycle on which an electric motor can be employed for propulsion [13]. It is powered through the use of rechargeable batteries and can reach speeds ranging from 25 to 32 km/h for the less powerful models, while up to 45 km/h for the most performing ones.

The electric bicycle proves to be useful in cases of rehabilitation from some cardiac pathologies since, thanks to the assistance provided, the user makes a lower cardiac effort. Moreover, e-bikes can be useful in cases of people who are unable to exercise for a prolonged time (for instance, due to injuries or overweight) providing them with adequate assistance to avoid over-exhaustion or excessive strain on the joints. In addition to health benefits, e-bikes certainly offer other advantages related to eco-sustainability and the environment. The e-bikes are considered zero-emission vehicles since they do not release substances from combustion and, as a consequence, have a low environmental impact. This feature makes them desirable within the urban context [17]. The small size of the battery makes it suitable for charging with solar energy or other renewable energy sources. The main issue related to this kind of vehicles concerns the usage of batteries related to distribution and production of the energy to power them [1]. To this end, research has focused on optimizing energy management. Increasing the charge duration of batteries means decreasing the charging frequency and, consequently, improving the average battery life. The approaches used to enhance the performance of e-bikes range from the most traditional, such as based on proportional–integral–derivative (PID) controllers [21], to the most innovative ones that employ Fuzzy Logic Controllers (FLCs) [23] or neuro-fuzzy hybrid control systems.

This paper introduces an approach based on fuzzy logic aimed at optimizing the energy management of electric bikes. Unlike other conventional methods, a FLC allows the development of heterogeneous systems without the requirement of mathematical modeling. This feature also makes it feasible to formulate models that often are too complex from an analytical point of view that, probably, could not be implemented in real scenarios. Besides, less complexity could mean fewer electronic components and, hence, lower costs. Complex hybrid systems, on the other hand, could potentially allow better performance but at the expense of the ease of realization achieved, for instance, though the use of fuzzy logic solely. FLCs provide considerable performance, making the realization of the system much more accessible and, therefore, they could represent the best compromise between several available control solutions.

This paper in organized as follows. Section 2 analyzes the literature works focused on the energy management and battery optimization in e-bikes. Section 3 presents the solution introduced in this paper, while its validation is performed in Section 4. Finally, Section 5 concludes the paper highlighting the obtained results and proposing possible future research improvements.

2 Related Works

The problem of energy management and battery optimization in e-bikes has been addressed in various works in the literature. The goal is to extend battery life through an appropriate control methodology.

The authors of [16] introduce a control system for e-bikes in which the current speed of the bike and the moment generated by pedaling are used as inputs to determine the activation of the engine to assist with the uses. The approach is based on a FLC controller that replaces the PAPC (Proportion Assisted Power Controller) which manages the current speed of the bike and the pedaling frequency as an input to determine the next time of assistance. The two types of controllers are compared on different simulation scenarios, and the obtained results show that the best performance is obtained through the FLC, which provides a more stable final speed. Nevertheless, there is a decrease in performance in the target speed which is lower than the desired one, and there is also the absence of sensors to intercept slope variations or to record the power impressed by the cyclist to be used as input signals for the FLC.

A moment control system generated by a PMBLDC (Permanent Magnet Brushless DC) motor, based on an artificial neural network (ANN) for a low ripple moment, is presented in [14]. A conventional BLDC motor produces large oscillations (ripples) in the electromagnetic moment and is not directly controlled. The motor can lead to some malfunctions in the circuit components as well as to a failure to detect the position due to vibrations caused by large oscillations. This disadvantage is reduced through the control technique proposed by the authors, which consists in adjusting the BLDCMD (brushless dc motor drives) speed through a PI (proportional–integral) controller and the current ripple is reduced through an ANN network. The proposed method is validated through Matlab/Simulink simulations. The results reveal that proposed techniques minimize the oscillations in the PMBLDC engine. However, these techniques can apply advanced methods depending on the accuracy of vehicle parameter information. Besides, to be used, the latter implies that the configuration of the system must be rearranged from time to time. Some techniques require hardware changes or additional steps, while others are algorithm-based techniques. This situation involves a considerable complexity that is variable based on the applicable limitations and the implemented controller.

The goal of the solution proposed in [12] is to investigate the dynamic characteristics of an e-bike and to optimize its required power. A simulation is performed in Matlab/Simulink to analyze the dynamic and operational characteristics for each change sequence, based on the effect of the input parameters, such as the speed in the gearbox, the front surface and the slope of the course. The results prove how the required power can be optimized by changing the above principal parameters. Besides, another simulation is carried out on a speed control system under the effects of gearbox speed and slope. Experimental results that confirm their validity characterizes the simulations. It is useful to note that the main disadvantage concerns the difficulty of reaching the target speed by the e-bike with the highest gears. The problem could be solved by implementing a FLC alongside the classic PID, but this would have an impact in terms of complexity and construction costs.

The authors of [4] develop and simulate all the main parts of an e-bike's electrical system using Matlab/Simulink. The main components of the proposed system consist of a PMSM (permanent magnet synchronous motor) powered by a 3-phase inverter, the battery, and the central controller. SimPowerSystem is a Matlab/Simulink toolbox used to model and simulate the electrical components. In detail, the system presented in [4] allows evaluating the performance of each component in a global context together with the other electrical components. The adopted speed control system used is a traditional one, ie, a PI regulator. Inevitably, this approach brings with it all the disadvantages related to the use of this type of components:

- strong dependence on the mathematical modeling of the system;
- reduced reliability;
- slowest system response;
- higher costs;
- inability to model non-linear systems;
- lack of adaptive capacity as the system changes.

The solution proposed in this paper is based on the model presented in [4] since it takes into account some similar components, such as the battery, motor, and inverter. However, the proposed approach differs from the one shown in [4] regarding the speed control because it is not implemented through a traditional method but through a FLC controller. The use of a soft computing technique within the proposed method could probably allow a considerable increase in performance. Compared to the works analyzed above, the solution introduced in this paper could improve several features and could represent an excellent compromise between performance, cost, reliability, completeness, adaptability, speed of response, and simplicity. It is necessary to note that the main aim of this paper remains the energy performance optimization reducing the waste, a typical problem that afflicts the emerging electric vehicles.

3 The Proposed Solution

The model proposed in [4] has been taken into account as a starting point for the realization of the system introduced in this paper. The main components of the e-bike (i.e., battery, motor, inverter) have not been modified, while the description of the speed control has been changed since it represents the crucial point to obtain a performance improvement. Consistent with the system shown in [4], the model introduced in this work is also realized through the use of the Matlab/Simulink assisted by the SimPowerSystems toolbox.

Unlike the model introduced in [4], in which the speed control is performed through the use of a traditional technique, or through the use of a PI regulator, in the proposed solution, the fuzzy logic has been selected for control. Fuzzy logic has swiftly matured as one of the most successful approaches for the development of advanced control systems. Through its use, compound requests can be made surprisingly simple and with low price controllers. Many problems are too complex to be addressed from a quantitative point of view. So, sometimes, it is better to use a piece of knowledge based on the relative approximation than on accuracy. The fuzzy logic is based on fuzzy sets which employ approximate information and uncertainty to generate decisions.

Regarding the additional features of this soft computing technique, fuzzy logic can model non-linear systems. The implementation of conventional control systems is based on mathematical modeling. If an accurate mathematical model exists, with known parameters, it can be analyzed, and the controller can be built to perform a specific operation. However, this scheme can be undoubtedly time-consuming. Fuzzy logic controllers have adaptive features. As a consequence, solid performances can be achieved in systems composed by parameters having variable uncertainty and load disturbances. Moreover, it can be achieved more reliability, a high degree of accuracy, fast system response with a low computational cost.

The fuzzy controller introduced in this paper replaces the classic PI controller, presented in [4], regarding the speed control. The use of a traditional FLC, and not, for instance, a neuro-fuzzy hybrid system, or a FLC controller cascaded to a neural network, or a FLC type 2, allows to obtain an advantage even in terms of computational performance. The use of the methods mentioned above could achieve an improvement in the overall performance but would increase the complexity of the system.

The architecture of the proposed solution is shown in Figure 1. The inputs are represented by the speed error (E) and by the speed error variation (CE), both in revolutions per minute (rpm). The output is the control speed in rpm. The membership functions (MFs) for input and output variables have been chosen as follows:

- Positive Big: PB;
- Positive Medium: PM;
- Positive Small: PS;
- Negative Big: NB;

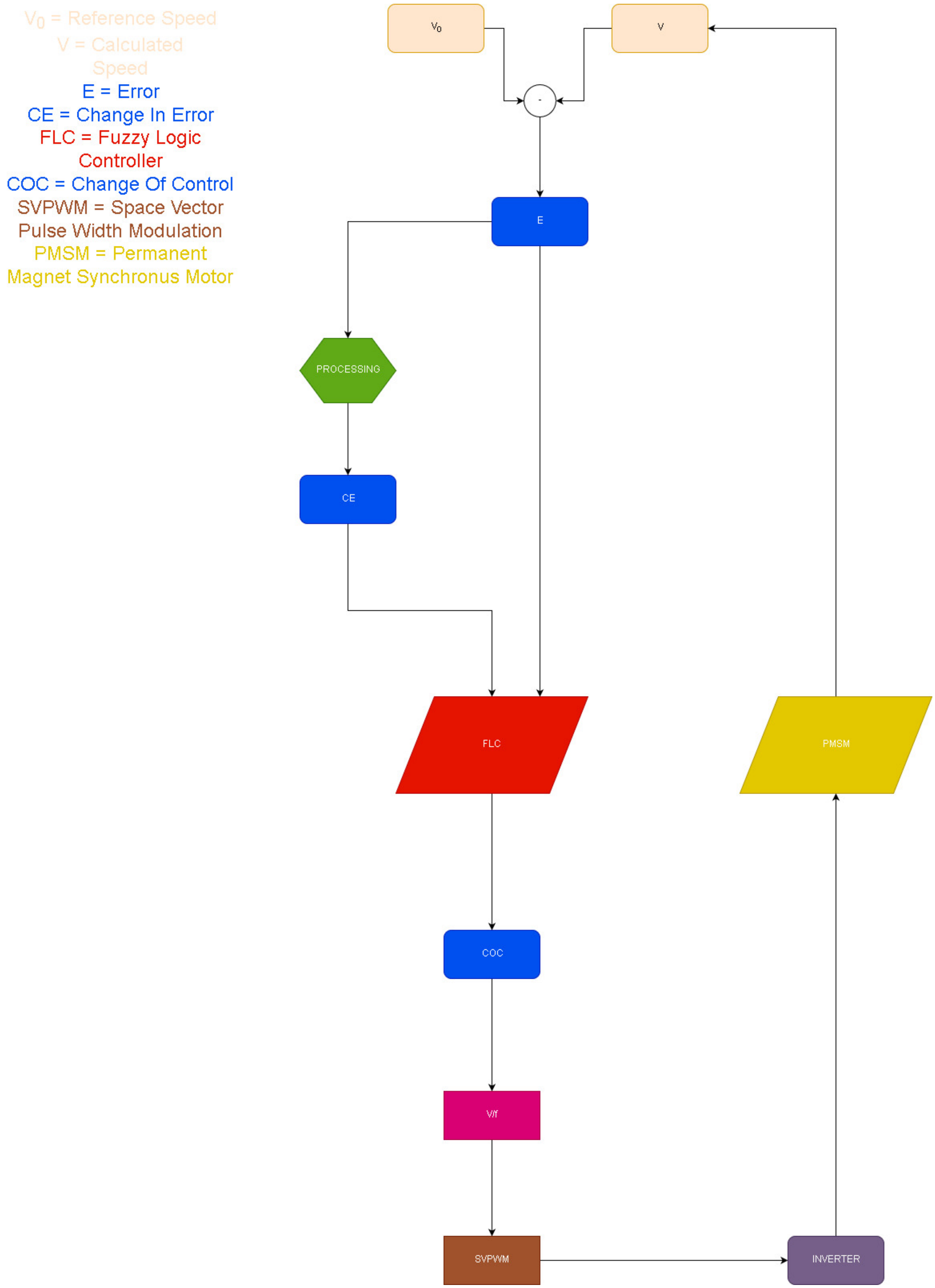

Figure 1: The proposed fuzzy-based architecture.

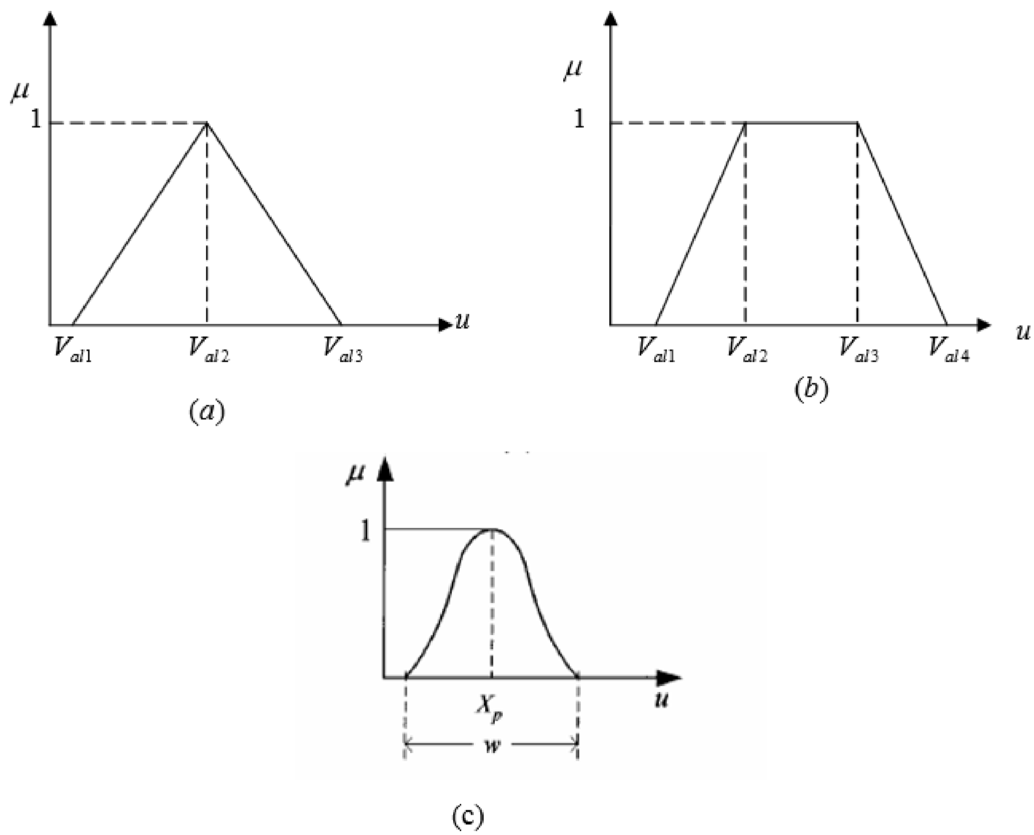

Figure 2: Membership functions: (a) Triangular, (b) Trapezoidal, (c) Gaussian.

- Negative Medium: NM;
- Negative Small: NS;
- Zero: ZE.

Triangular MFs are employed in the proposed FLS. It is useful to note that a MF is a particular graphic representation exploited during the fuzzification process. They are defined by using linguistic variables that are often expressed as logical implications of the *if-then* construct. For instance, as shown in Figure 2, MFs can be triangular, trapezoidal, Gaussian, or in another appropriate shape. In this paper, the choice fell on triangular MFs since they are the most versatile, the simplest ones to be processed, and, therefore, offer a benefit regarding the computational complexity, and, consequently, an increase in overall performance. The triangular MF is defined in eq. (1). The limits are defined as V_{al1}, V_{al2}, V_{al3}.

$$\mu(u_i) = \begin{cases} \frac{u_i - V_{al1}}{V_{al2} - V_{al1}} & \text{if } V_{al1} \leq u_i \leq V_{al2} \\ \frac{V_{al3} - u_i}{V_{al3} - V_{al2}} & \text{if } V_{al2} \leq u_i \leq V_{al3} \\ 0 & otherwise \end{cases} \tag{1}$$

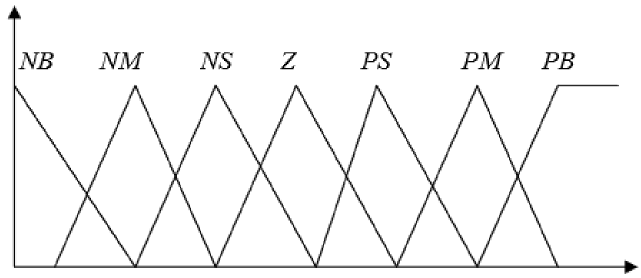

Figure 3: Membership functions subdivision.

Table 1: Values used for the definition of triMF and "E" variable.

Universe of Discorse	Set	a	b	c	d
Error (E)	**NB**	-3.44	-2	-1	-0.7
	NM	-1	-0.7	-0.4	
	NS	-0.7	-0.35	0	
	ZE	-0.2	0	0.2	
	PS	0	0.35	0.7	
	PM	0.4	0.7	1	
	PB	0.7	1	2	3.44

The input of the FLC are organized in different intervals. As it is possible to note in Figure 3, these intervals are expressed as *Positive Big* (PB), *Positive Medium* (PM), *Positive Small* (PS), *Negative Small* (NS), *Negative Medium* (NM), and *Negative Big* (NB). Both the input and output variables assume values included in the range from -2 to 2. They are fully defined in tables 1, 2, and 3.

Table 4 shows the 49 rules used in the FLC. The steps for speed control are the following:

- motor speed signal sampling;
- error and its variation calculation;
- estimation of the fuzzy and MF sets for the error and for its variation;
- estimation of the control action according to the fuzzy rule;
- calculation of the control speed with the centroid defuzzification method;

Table 2: Values used for the definition of triMF and "CE" variable.

Universe of Discorse	Set	a	b	c	d
ChangeInError (CE)	**NB**	-3.44	-2	-1	-0.7
	NM	-1	-0.7	-0.4	
	NS	-0.7	-0.35	0	
	ZE	-0.2	0	0.2	
	PS	0	0.35	0.7	
	PM	0.4	0.7	1	
	PB	0.7	1	2	3.44

Table 3: Values used for the definition of triMF and ”COC” variable.

Universe of Discorse	**Set**	**a**	**b**	**c**	d
	NB	-3.44	-2	-1	-0.7
	NM	-1	-0.7	-0.4	
	NS	-0.7	-0.35	0	
ChangeOfControl (COC)	**ZE**	-0.2	0	0.2	
	PS	0	0.35	0.7	
	PM	0.4	0.7	1	
	PB	0.7	1	2	3.44

Table 4: Rules used in the system.

e/ce	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

- transmission of the control signal to the system after the speed calculation.

The FLC employed in the proposed solution has been developed as a less precise component than the PI regulator. However, its accuracy improves with the increase of the rules. As a consequence, in the case under examination in this paper, it can be entirely accurate and more precise than the PI regulator. This goal can be achieved thanks to the use of 49 rules which cover all possible combinations.

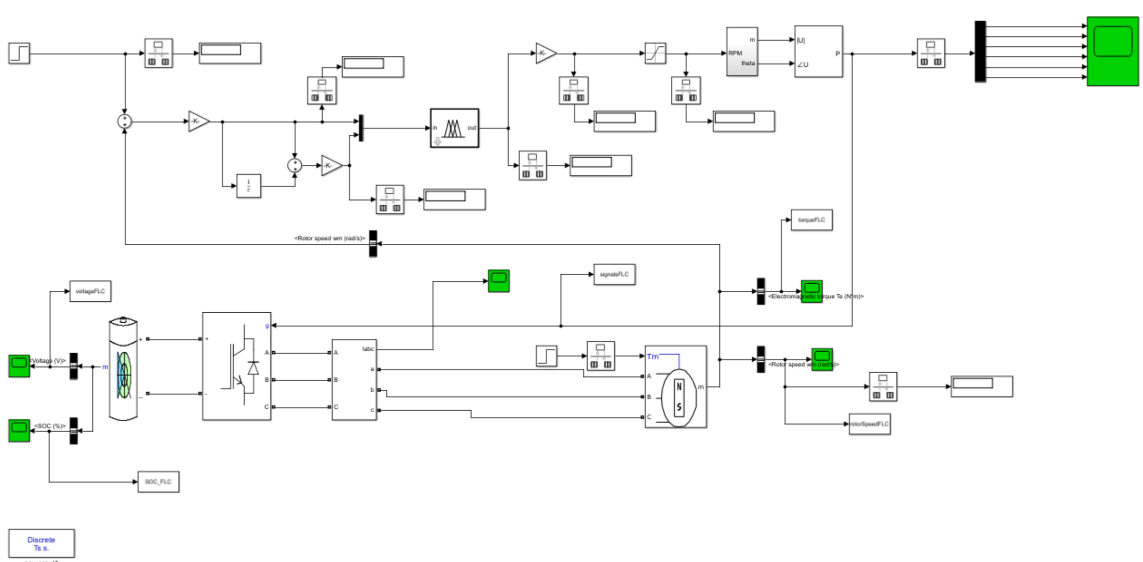

Figure 4: The electric model developed in Matlab/Simulink.

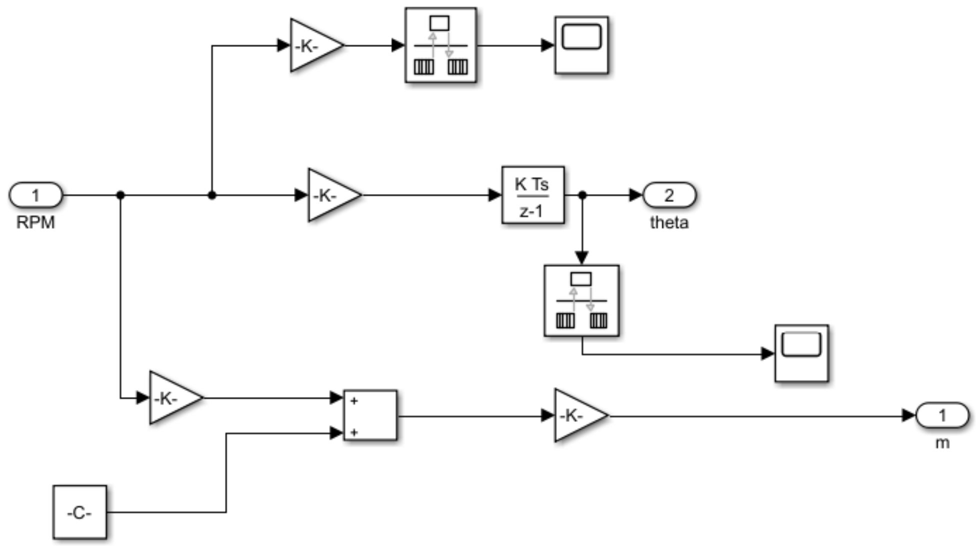

Figure 5: Simulink model of the ”V/f” block.

Table 5: Summary table of the FLC characteristics.

FLC type = Mamdani
Input = 2
Output = 1
Rules = 49
AND method = min
OR method = max
Defuzzyfication = centroid

4 Performance Evaluation

Consistent with what has been done with the model presented in [4], the solution introduced in this work has also been realized through the use of Matlab/Simulink, (Figure 4) and with the cooperation with the SimPowerSystems toolbox. The Fuzzy logic controller output signal is normalized, then is managed by the ”V/f” block which calculates its module and phase and these are evaluated by the ”SVPWM” block (space vector pulse width modulation), which generates the pulses for the three-phase inverter. Figure 5 illustrates the mathematical model of the ”V/f” block developed through the Simulink software while the type and characteristics of the fuzzy logic controller are summarized in the Table 5.

The main aim of section 4 is to present the simulation results obtained through Matlab/Simulink. The duration of the simulations has been 17619 seconds, and they have been carried out under the same conditions. The parameters that have been taken into account for the performance evaluation are the following:

- rotor speed;
- electromagnetic moment output;
- battery charge status.

The rotor speed depends, in part, on the rotor diameter. Typically, it is in a range from 120-210 m/s, but mainly between 150 and 190 m/s, with a tendency to be higher with a smaller rotor diameter. Currently, the smallest achievable diameter for a rotor is 20 mm with speed up to 150000 rpm, although some machines can reach up to 160000 rpm. An increase in rotor speed results in better rotational stability up to a specified maximum speed. However, too high speed results in poor rotation stability due to the enormous centrifugal forces acting on the rotor recess. A reduction in the diameter in the range of 56 mm to 28 mm results in higher productivity and lower energy consumption at the expense of reduced rotation stability. In this paper, for a motor with a nominal power of 250 W, a rotor has been used with a diameter of about 45 mm. This value allows a rotation speed up to 100000 rpm to obtain assistance even in the most challenging situations.

The electromagnetic moment can be calculated using different techniques. The main of these is the Finite Element Method (FEM), which is considered particularly flexible, reliable, and effective in the analysis and synthesis of electromagnetic and electromechanical devices. This solution is the one used for determining the electromagnetic moment in this paper. Even adopted by inexperienced users, FEM packages are easy to use and allow the calculation of the electromagnetic field distribution and integral parameters without detailed knowledge of applied mathematics. Another essential advantage of the finite element method is the possibility of calculating reinforcement reactions, inductances, and electromagnetic moments through the rotor position. The estimation of forces and moments using the FEM is one of its most significant applications. Three methods can be used:

- Maxwell's stress tensor;
- co-energy;
- the Lorentz force equation.

The most appropriate method depends on the problem considered, although the most frequently used are the Maxwell stress tensor and the co-energy.

The use of the Maxwell stress tensor is computationally simple since it requires only the local flow density distribution on a specific contour line. Using the Maxwell stress tensor definition, electromagnetic forces can be determined based on the magnetic flux density:

- total force

$$F = \int\int \left[\frac{1}{\mu_0}B(B \cdot n) - \frac{1}{2\mu_0}B^2 n\right] dS \tag{2}$$

- normal force

$$F_n = \frac{L_i}{2\mu_0}\int [B_n^2 - B_t^2] dl \tag{3}$$

- tangential force

$$F_t = \frac{L_i}{\mu_0}\int B_n B_t dl \tag{4}$$

where n, L_i, B_n e B_t are respectively the normal vector at the surface S, the length of the winding, the normal component of the magnetic flux density and the tangential component of the magnetic flux density. The moment $T = r \times F$, according to equation 4, is:

$$T = \frac{L_i}{\mu_0}\oint_l r B_n B_t dl \tag{5}$$

where r is the radius of the circumference that lies in the interspace. The accuracy of the model depends on the discretization and selection of the integration line.

Forces and moments can also be calculated as derivatives of the stored co-magnetic energy W' if it is possible to consider a small displacement. The infinitesimal incremental ratio is approximated with the finite incremental ratio, so the instantaneous component of the force F_s in the direction of the displacement s becomes:

$$F_s = \frac{dW'}{ds} \approx \frac{\Delta W'}{\Delta s} \tag{6}$$

or, for an instantaneous moment T with a sufficiently small angular displacement:

$$T_s = \frac{dW'}{d\theta} \approx \frac{\Delta W'}{\Delta \theta} \tag{7}$$

The problem with finite incremental ratios is that they must be calculated, and this doubles the computation time and also the most suitable value of angular increase $\Delta\theta$ is unknown and must be estimated using an iterative procedure. Using the Lorentz force theorem, the instantaneous moment, instead, is expressed as a function of the phase of the electromotive forces and the phase currents:

$$T = \sum_{l=A,B,C} i_l(t) \left[2pN \int_{-\frac{\pi}{2m_1 p}}^{\frac{\pi}{2m_1 p}} rL_i B(\theta,t) d\theta \right] = \frac{1}{2\pi n} [e_A(t)i_A(t) + e_B(t)i_B(t) + e_C(t)i_C(t)] \tag{8}$$

where p, θ, n, and N are the pairs of poles, the mechanical angle, the angular velocity and the number of conductors in phase, respectively. The latter represents the specific method used to calculate the electromagnetic reference moment.

The charge of the battery is defined as the available capacity expressed as a percentage concerning a reference. It can be sometimes be expressed through the nominal capacity or is often represented through the current capacity. This ambiguity can lead to confusion and errors. The preferred reference should be the nominal capacity of a new cell rather than the current capacity of the cell under consideration. This motivation is related to the cell's capacity that is gradually reduced due to aging. The temperature and the discharge frequency reduce the actual capacity even more significantly. The use of the current capacity compared to the nominal capacity is usually a design choice or a compromise to avoid the calculation of complex adjustments related to aging that are conveniently ignored.

Knowledge of SOC is particularly crucial in lithium batteries. Lithium is the most reactive chemical element compared to all the other elements used for these applications, and it is the only one that needs an electronic Battery Management System (BMS) so that the battery is used in the area working time to ensure a long average life. The control of the SOC is one of the main functions of the BMS. In the EVs, the SOC is used to determine the range. So, given the importance of this parameter, it should be calculated precisely on a new cell, not as a percentage of the current capacity that could deviate from the real value by as much as 20% or more due to aging. Different methods are used to calculate the SOC, and some are specific for particular electrochemical cells, others depend on the most convenient parameter to be measured that changes as the SOC changes. The Coulomb measurement depends on the current flowing from the battery to the external circuits, so it is not affected by the effects of the self-discharge currents or the Coulomb efficiency of the battery. This method is the one used for the calculation of the SOC of the model that has been created in this paper.

4.1 Obtained Results

The simulations have been carried out in three different scenarios to make the argument as complete as possible:

1. scenario with no slope;

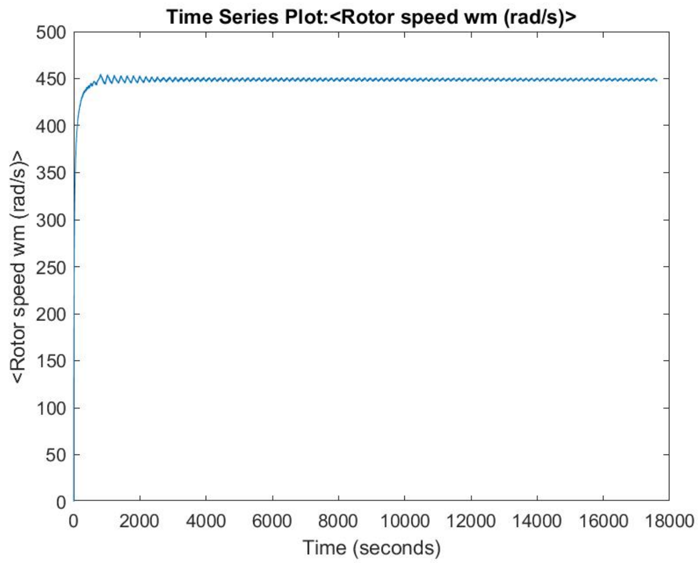

Figure 6: Rotor speed of the PI controller [rad/s] - scenario 1.

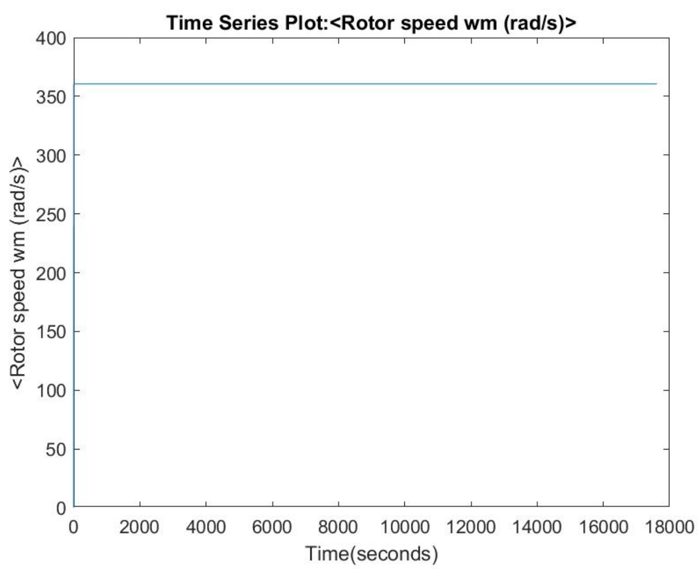

Figure 7: Rotor speed of the FLC controller [rad/s] - scenario 1.

2. scenario with constant slope;

3. scenario with mixed route.

In all scenarios, the system adapts dynamically. As a consequence, the rotor speed and electromagnetic moment values ad kept constant, so the treatment of these parameters is performed only once. This feature determines a change in consumption based on the circumstance under consideration.

In the scenario 1, analyzing figures 6, 7, 8, 9, it is possible to emphasize some advantages related to the use of soft computing techniques. Since the linear path, the rotor speed in both models settles after a certain time at a constant value. The rotor speed of the PI controller, compared the FLC, is coupled with a delay of a few seconds and it is also possible to note not only the presence of noise on the desired value

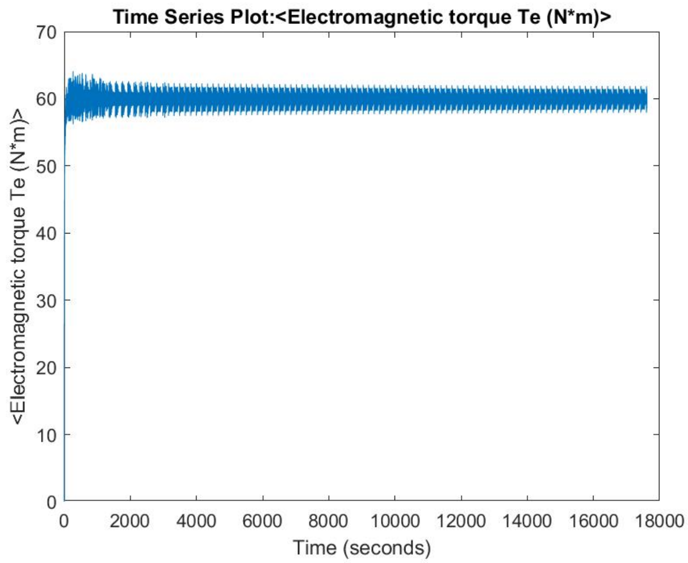

Figure 8: Electromagnetic moment generated by the PI controller [N*m] - scenario 1.

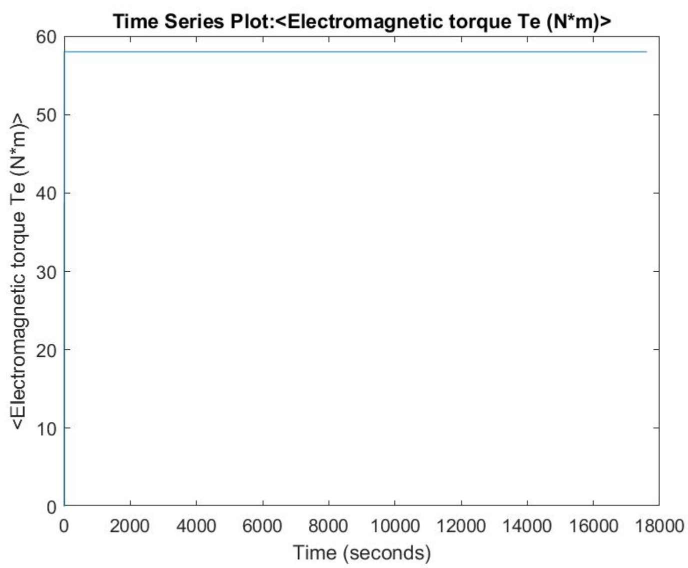

Figure 9: Electromagnetic moment generated by the FLC controller [N*m] - scenario 1.

in the first with respect to the second, but also a difference of about 90 [rad/s] between the two speeds, since the best evaluation of the input error by the FLC controller leads to an evaluation of the more efficient regime speed, which, as it is possible to note see, is also reflected in a better energy efficiency.

In the comparison of the electromagnetic moments, it can be recognized how the coupling speed is almost equal, while the difference in the precision of the coupling is clear. In fact, in Figure 9, it is possible to highlight the almost total absence of noise as opposed to Figure 8. The advantages noted above are of lesser importance compared to the benefits brought by the improvements from an energy point of view. As already discussed in Section 1, one of the main problems concerning the use of e-bikes is the charge duration of accumulators (or batteries). Being the disposal of those mentioned

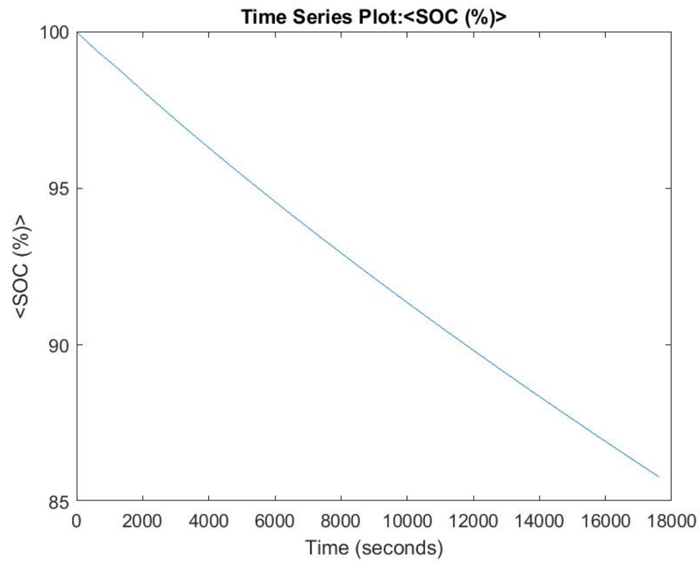

Figure 10: Battery charge in the system with PI controller - scenario 1.

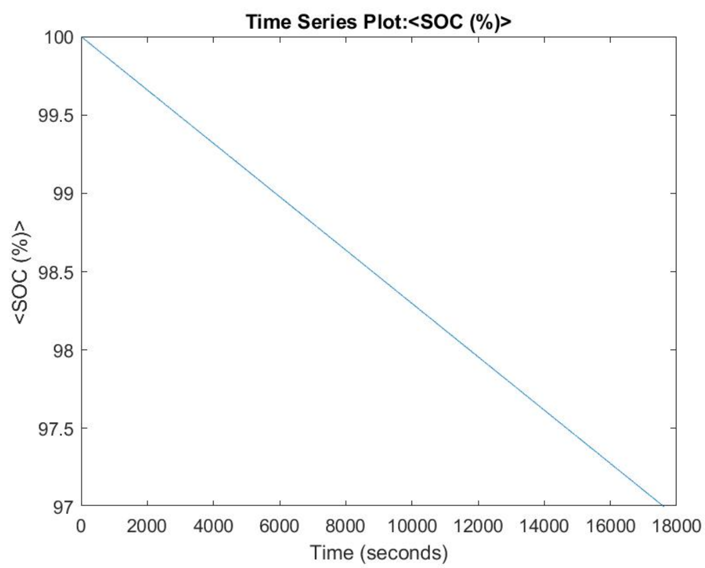

Figure 11: Battery charge in the system with FLC - scenario 1.

above burdensome, the increase of the battery charge cycle means decreasing the charging frequency and, therefore, growing the "average life" of the battery. In Figures 10 and 11, the state of charge of the battery in the respective systems is evaluated. At the end of the simulation, there is a difference in charge of 12%. This value represents a rather significant increase in terms of energy performance.

In the scenario 2, unlike the previous one, a constant slope of 15% has been introduced. In the Figures 12 and 13, the state of charge, in the respective systems, is evaluated. At the end of the simulation, there is a charge difference of about 7%. The use of the model with the FLC is still beneficial even if there is a slight deterioration in performance. This issue is due to the particular configuration of the route.

In the scenario 3, a mixed route is configured in such a way as to avoid fictitious random values,

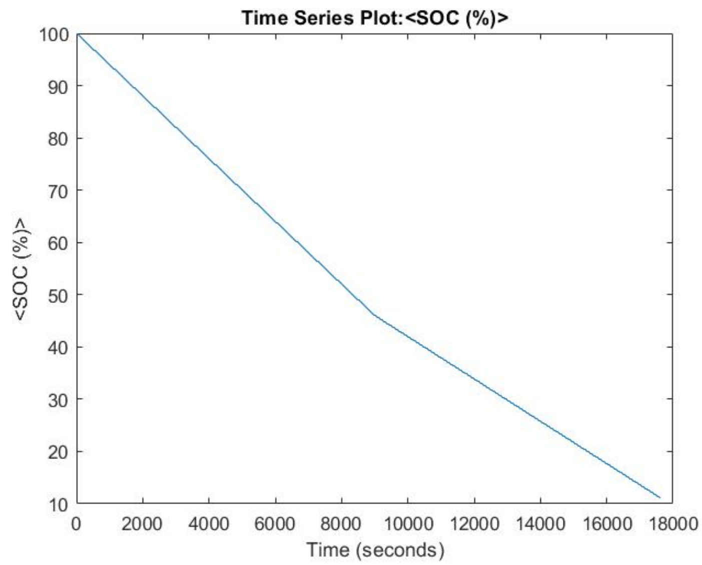

Figure 12: Battery charge in the system with PI controller - scenario 2

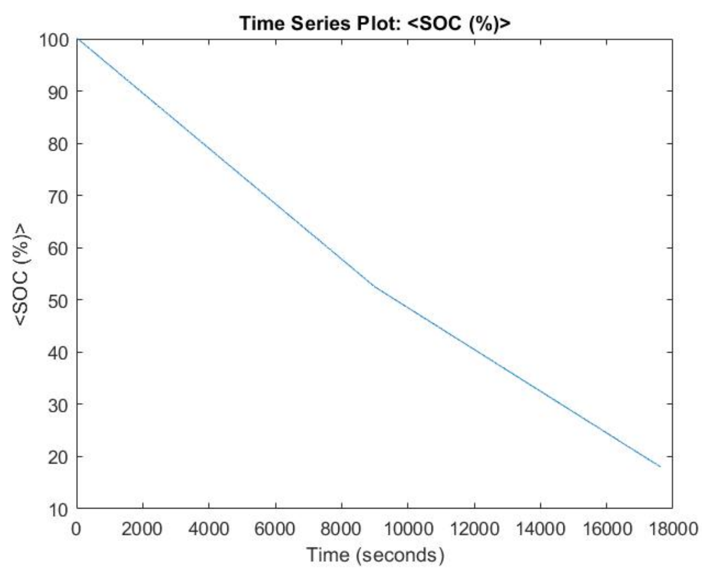

Figure 13: Battery charge in the system with FLC - scenario 2

while instead it is considered a path that could easily be tackled in a real situation, which presents uphill sections, stretches downhill and linear sections. This scenario is what could be called "the most frequent one." Rarely the user would face full uphill or linear routes. Figures 14 and 15 confirm the validity of the proposed model, as high energy performances are maintained with a difference in residual charge of about 11%.

In conclusion, considering table 6, it is possible to gather a precise and immediate idea of the obtained results. The proposed model is better in the estimation of the rotor speed since the input signals to the FLC controller are evaluated in a more precise practice, guaranteeing the same results at a lower effort regime (about 90 [rad/s] of difference). Concerning the electromagnetic moment, both models measure

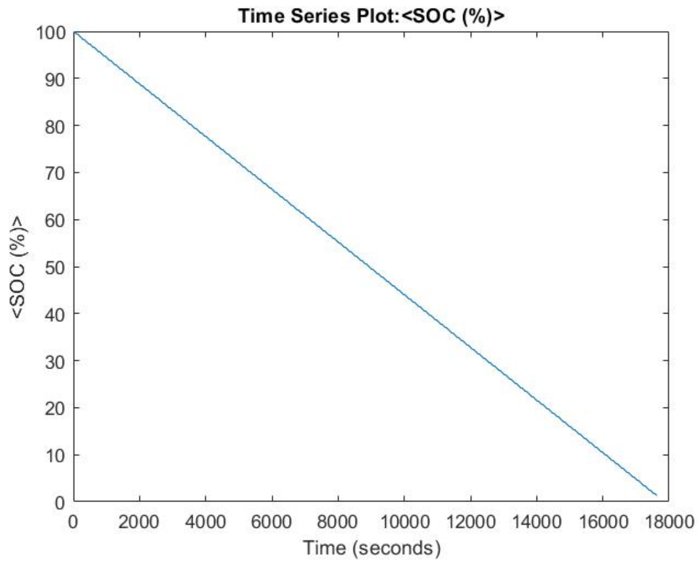

Figure 14: Battery charge in the system with PI controller - scenario 3

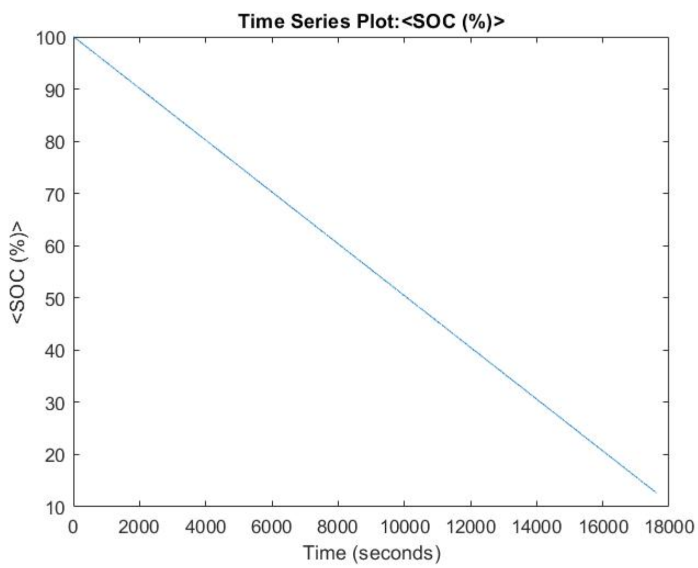

Figure 15: Battery charge in the system with FLC - scenario 3

an almost identical value, but the proposed solution reaches the latter with a clear difference in precision and coupling speed. Furthermore, in the three scenarios, it is possible to note a substantial improvement in the behavior of the energy management system installed on the e-bike. In scenario 1, at the end of the journey, the model presented in this paper retains 12% more charge, while, in the scenario 2, the one mentioned above retains 7% more charge, presenting a slight deterioration of the performances. Even in the scenario 3, it obtains a consistent performance advantage of about 11% on a route which is one of the most easily found cases in a real situation.

	Scenario 1 (with no slope)		
Model of Choi et al [4]	Rotor speed as [rad/s]	Electromagnetic moment as [N*m]	Residual charge as percentage
	450	60	85
The proposed model	Rotor speed as [rad/s]	Electromagnetic moment as [N*m]	Residual charge as percentage
	360	58	97
	Scenario 2 (with costant slope)		
Model of Choi et al [4]	Rotor speed as [rad/s]	Electromagnetic moment as [N*m]	Residual charge as percentage
	450	60	13
The proposed model	Rotor speed as [rad/s]	Electromagnetic moment as [N*m]	Residual charge as percentage
	360	58	20
	Scenario 3 (with mixed route)		
Model of Choi et al [4]	Rotor speed as [rad/s]	Electromagnetic moment as [N*m]	Residual charge as percentage
	450	60	2
The proposed model	Rotor speed as [rad/s]	Electromagnetic moment as [N*m]	Residual charge as percentage
	360	58	13

Table 6: Summary table of the obtained results.

5 Conclusions

The use of a FLC controller has allowed the development of a system with a high degree of precision compared to traditional PID controllers. This achievement has been obtained thanks to an exhaustive definition of the inference rules that cover all possible cases, allowing a gain in terms of accuracy of the reference speed coupling value. Furthermore, the proposed solution would involve the realization of the real system with lower costs. The improvements, regarding the energy efficiency, are due to the use of the fuzzy logic that permits not only to perform a more precise and more flexible error control but also to obtain an equally fast and optimized circuit response, to guarantee the lowest possible consumption of charge.

A further advantage that could be introduced thanks to the use of the FLC is related to the absence of purely mathematical modeling of the system. This feature can be noticed by comparing the two systems. The representation of the comparison model present in the literature is based on the purely analytical description of the circuit components. On the contrary, the model proposed therein relies on the use of fuzzy logic control, which does not require a purely analytical formulation. However, the use of this soft computing technique also has some potential disadvantages, such as, for instance, the difficulty in identifying all the inference rules necessary for data evaluation or even the risk of creating an incomplete knowledge base.

Fuzzy logic is a relatively recent approach and still not very well established in various fields, such as the one that has been taken into consideration in this paper. This work has aimed to provide an innovative approach, open to possible future developments, and, consequently, to subsequent improvements. In this direction, a possible improvement could be that of using a neuro-fuzzy hybrid system or the possibility of training a fuzzy expert system through a neural network. The latter represents only one of the many possibilities that can contribute to the realization of a more precise and more efficient model.

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