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A New Fuzzy Logic Based Battery Management System Proposal for Hybrid Electric Vehicles

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Abstract— *In this study, an original software design of a smart battery management system was studied by examining one of the batteries required for hybrid electric vehicles, knowing its chemistry, and selecting one of the appropriate battery management systems. When the chemistries of batteries used in electric vehicles are examined in the literature; These are known to be nickel cadmium (NiCd), nickel-metal hydride (NiMH), lithium nickel cobalt aluminum oxide (NCA), lithium iron phosphate (LFP), lithium titanium oxide (LTO) and lithium sulfide (LiS). Nickel cadmium (NiCd) was selected from these batteries, and the software studies, equivalent circuit parameters and controller software were developed based on these battery chemistries. It was developed following a statistical analysis-based approach to electronically determine battery chemistry. The management parameters of the battery can be adjusted automatically; In this way, it supports multi-chemistry battery management. The effectiveness of a switching mechanism designed to benefit from these features at the most appropriate moment has also been demonstrated through a simulation study. The developed battery management system is presented in comparison with other battery management systems in the literature on a function basis.*

Keywords— Hybrid Electric Vehicles, Battery Management System, Nickel cadmium batteries (NiCd), Modular battery management system topology.

1. Introduction

Throughout history, various methods, technologies and tools have been developed for transportation, which is a basic need. This process began by domesticating animals and continues today to explore space. The first vehicle capable of self-propellation, the main criterion for transportation, was based on steam power. This first self-propelled vehicle on record is considered to be a military tractor invented by French engineer and mechanic Nicolas Joseph Cugnot in 1769.

These vehicles were based on the principle of turning the vehicle wheels with mechanical apparatus, using steam obtained from a water boiler heated by burning coal or wood, that is, converting heat energy into mechanical energy. One of the most important parameters for the development of electric vehicles is the storage of electrical energy. In other words, in order to make an electric vehicle, it is basically necessary to store electrical energy and convert this stored electrical energy into mechanical energy. 19th century when steam engines were popular. Thanks to the electromagnetism technology developed in the mid-1990s, the first electric motors emerged. However, the 20th century. Throughout history and today, our transportation needs are largely based on internal combustion engine technology. Although internal combustion engines replaced steam as the primary energy source, electric-powered vehicles were produced long before vehicles powered by gasoline or diesel fuel.

Although many studies have been done on electric vehicles in the 19th century. Electric vehicles became popular in the 20th century for various reasons, including the discovery of new oil resources and cheaper oil prices. They lost their popularity in the beginning. Especially thanks to the development of electric starter technology, long range and easy refilling, internal combustion engine vehicles have attracted great attention and created demand because they solve the range problem in electric vehicles [1].

19th century In terms of technical developments, electric vehicles were far ahead of gasoline vehicles. The vehicle named La Jamais Contente broke the 1 mile per minute record in 1899. At the same time, it reached a speed of 106 km/h, becoming the first land vehicle in the world to exceed the 100 km/h limit [2]. Although electric vehicles have not made technical progress for a century and have not received the attention they deserve, they have started to gain value again since the 21st century due to developing battery technologies and especially the environmental problems of internal combustion engines.

Electric vehicles are considered as an alternative solution to the global warming and climate change problem in recent years, in increasing the share of green-renewable energy in production and use with economic incentive approaches and in reducing unnecessary and excessive energy consumption of humanity [3-4]. For a sustainable global energy policy, it is of great importance to increase the share of renewable-green energy sources in individual energy production. Evaluating electric vehicles that use these energies within the zero waste chain can further increase interest in electric vehicles. In this context, electric vehicle charging bills include hydraulic power plants [5-7], wind-based production methods [8-9], photovoltaic-based energy production methods [10-12], different biogas-based production techniques [13-14] and geothermal-based [15] If energy trade with power plants is supported by the public administration with tax incentives and subsidies, the share of electric vehicles in the vehicle market will increase further and the energy used and carbon dioxide gas emissions emitted by internal combustion engine vehicles, one of the main causes of global warming, will decrease. There are many scientific studies on more efficient energy use of electric vehicles [16-21]. For more effective control of electric motors used in electric vehicles, new methods are being developed on DC-DC converters, one of the basic fields of power electronics [22-29]. There is an urgent need for scientific studies on battery technologies to solve the range problem in EV vehicles.

2. Battery Management System (BMS)

In studies on batteries, the cell used is a single battery, the cells are connected to each other in series to meet the system voltage to form groups, the groups are connected to each other in series or parallel to form modules, and the modules are connected to series-parallel combinations according to need to form batteries. Battery management systems (BMS) can be defined as mandatory hardware that performs tasks such as observing, monitoring, controlling and balancing the battery through measurements made from various points on the system in order for the battery of electric vehicles to fulfill its basic functions.

BMS may include any one or more of the functions such as observing and measuring the battery on a cell basis, protecting it from overcharge-discharge, estimating and predicting the current state of the battery, optimizing the performance of the battery and reporting the data to the system and the user [30-31].

The purpose of the BMS is to make the best use of the energy stored in the battery that powers the system and not to damage the battery and the system. To achieve this goal, both charging processes and discharge processes of the battery must be monitored and controlled [32].

BMS are vital systems that enable cells, banks or battery packs to operate within a predefined current, voltage and temperature limit, as shown in Figure 1. While performing this task, two basic outputs, Charge Status and Health Status, are important. While the charge state is important for the vehicle to produce side outputs such as range; the health status is directly related to the total energy storage capacity of the battery group. BMSs can be used in a wide range of areas, from mobile devices to very large powerful applications that feed city networks, to backup of renewable energy sources.

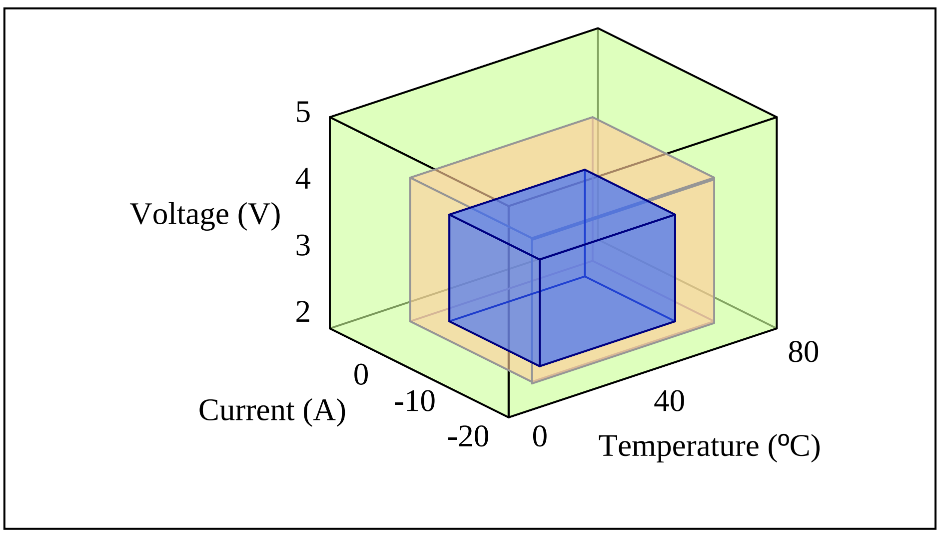

Fig. 1. *Operating zones of an example battery.*

2.1. Fuzzy Logic Based Energy Management Systems

As it is known, fuzzy logic-based Energy Management Systems are based on the fuzzy logic theory, which broke new ground in control systems and whose foundations were laid by Lotfi Zadeh (Zadeh 1965) [33]. In fuzzy logic-based control philosophy, unlike deterministic rule-based control, strict rules and limits are removed. The inputs and outputs of the control system are designed with various membership functions and based on verbal judgment expressions. Since a certain amount of contribution to the membership function may be sufficient, the “High” membership function can be determined by another amount. Therefore, sharp boundaries and discrete output values do not occur in the method. Due to this feature, it is more flexible and tolerant to incorrect measurements than deterministic rule-based Energy Management Systems.

The basic principle diagram on which fuzzy logic-based systems are based is shown in Figure 2. The input values of the system are first blurred with various mathematical membership functions. The input values are then processed according to the established rules. Finally, a numerical output value is obtained through the defuzzification process.

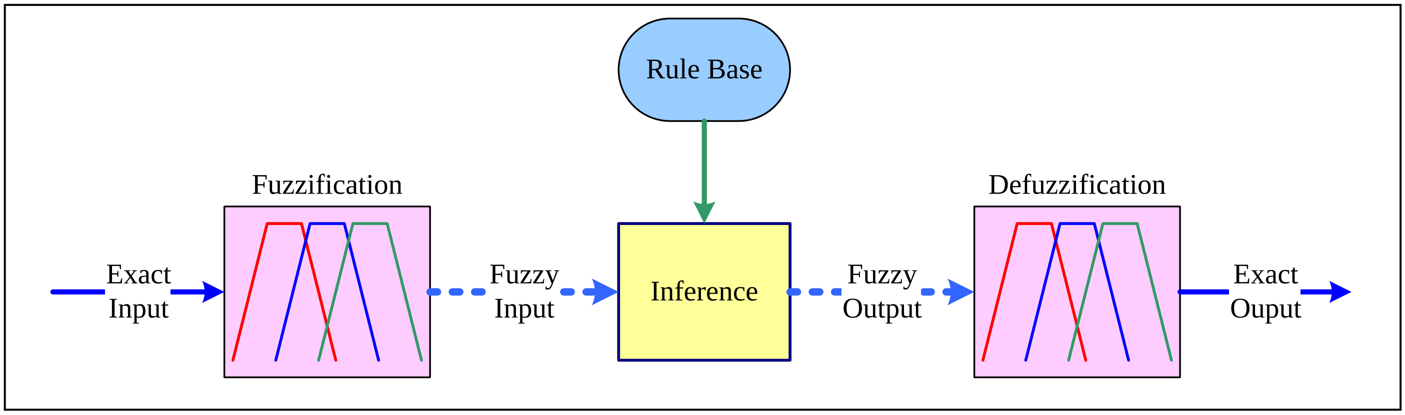

Fig. 2. *Fuzzy Logic based controller Simulink model.*

In this article, Zadeh introduced the "fuzzy set theory" of objects with imprecise boundaries [34]. Fuzzy set theory was developed to solve problems where imprecise, ambiguous definitions pass. A fuzzy set is characterized by a membership function with a membership degree between 0 and 1. Purpose of fuzzy set theory; It is to assign a degree of membership to concepts that express uncertainty, which are difficult to define or difficult to understand, to bring certainty to them. The specificity approach arises from the transformation of the bivalued set theory into the multivalued set theory. With the use of fuzzy sets, which are the numerical representation of imprecise information, new mathematical techniques have been developed to be used in modeling the uncertain structure of real world problems. The methods developed in this uncertainty are quite different from classical linear programming. It can be said that fuzzy sets are sets with fuzzy boundaries compared to classical sets. Because of this feature, fuzzy sets are compatible with real life and have a wider application area compared to classical sets [35]. Fuzzy set theory is about a subset of A in the universe X. The fuzzy subset does not have well-defined boundaries when universe X covers a finite class of elements. For A, which is a classical subset of the X universe, the membership is represented by the characteristic function $\mu_A(x)$ and varies between [0,1] as follows [36].

$$\mu_A(x) = \begin{cases} 1, & If\ x \in A \\ 0, & otherwise \end{cases} \quad (1)$$

If the cluster value is indeed allowed to be in the range of [0,1], then the set A is called the "Fuzzy Set". $\mu_A(x)$ is the "membership degree" of X in set A, and for values of $\mu_A(x)$ close to one, the membership of x in set A increases. A fuzzy set is characterized by a set of ordered pairs. The fuzzy set A in the universal set X is represented as a set of ordered pairs. The ordered pairs of a fuzzy set A are shown in equation (11). The meaning of this expression is expressed as follows; The first of the elements of a fuzzy set, A, consisting of ordered pairs, is the element of the set, and the second is the value indicating the membership degree of this element [37-40]. The degree of belonging or membership of x to A is denoted by $\mu_A(x)$.

$$A = \{(x, \mu_A(x)) \| \ x \in A\} \quad (2)$$

As a result; fuzzy sets help to express ambiguous and fuzzy concepts in language mathematically. Fuzzy set theory was developed to describe and solve problems with no clear boundaries. The symbols and expressions used in fuzzy sets and most of the expressions used in classical sets are similar to each other. For a Fuzzy Logic based Matlab/Simulink model, the behavior of the system to be controlled should be observed first. Appropriate membership functions and rule table are obtained by considering the control signal applied to the system, the error signal produced by the system and the changes in the error. Figure 4 shows the Simulink block diagram of fuzzy logic control [41-42].

2.2. BMS in Electric Vehicles

With the development of battery technology, the need for batteries to work together more efficiently has begun to emerge. BMS offers a solution to the instability and burning problem of lithium-doped batteries due to their electrochemical properties. BMS is also needed for memory formation or optimal energy management in other battery chemistries. There is no need for a unique BMS in classical lead acid batteries, as they are very safe and have a mature technology. Studies have shown that the efficiency of lead acid batteries must be increased in order to be used in automotive and electric vehicles [43]. As a result of these studies, the idea emerged in the 1960s that the parameters affecting the efficiency of lead acid batteries should be observed and controlled through a separate system.

2.2.1. BMS Basic Functions

BMS requires several inputs to manage the energy storage system of the electric vehicle. Based on these inputs, it can analyze and therefore manage the state of the system. Some of these inputs can be listed as cell voltage, group voltage, total voltage, charge-discharge current, cell temperature, ambient temperature, thermal cooler inlet-outlet temperature, pedal status, throttle, brake coil, accelerometer, smoke-gas sensor values. The main outputs produced by the BMS according to these inputs are charge-discharge, main circuit contactor control signal for emergency, electric fan or heater signal for heat control, capacitor or balancing resistor for balancing, communication signal, error signal. The functions of the BMS that reveal the relationship between these inputs and outputs can be listed as detecting battery parameters, on-board fault detection, estimation of battery states, battery safety control and alarm, balancing, charge control, thermal management and communication.

2.2.2. BMS Design Topologies

Battery management systems can basically be grouped into four basic classes. The first is the centralized topology, where all operations are performed in a single center [44-45]. The opposite of this situation is also possible. This is called decentralized topology [46-47].

The third is distributed topology, where sensors and processors are located in different units [48-51]. The last group is the modular topology, where each module can do every job [52-53].

2.2.2.1. Central topology

Systems where all operations are integrated into a single module connected to the battery or battery cells with several cables are called central battery management systems [54]. There are even some applications where a single integrated circuit can perform all battery management functions [55].

The disadvantage of this topology, presented in Figure 3, is that it significantly increases the risk of short circuits because it involves a large number of long cable connections. Additionally, connections can become loose and inputs can easily be confused or connected incorrectly. This significantly increases sensitivity to errors.

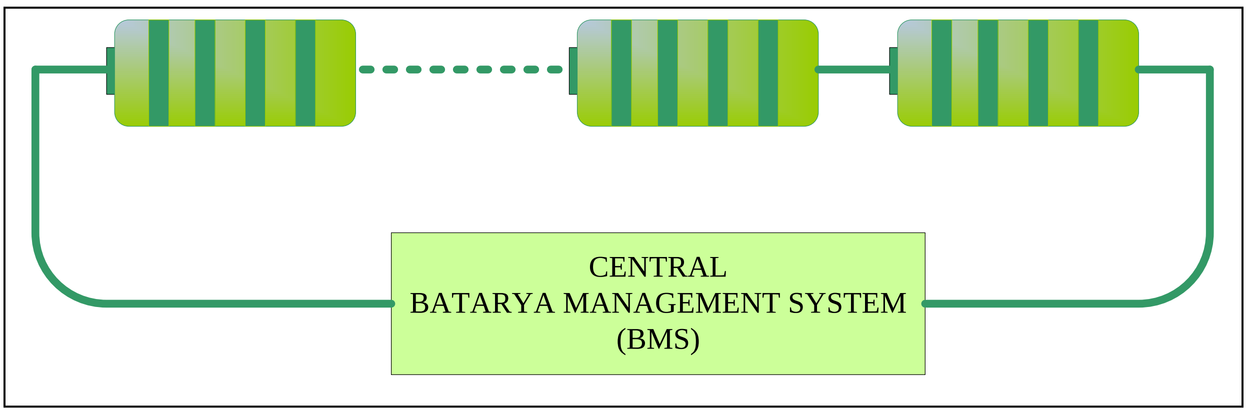

Fig. 3. *Central battery management system topology.*

2.2.2.2. Decentralized topology

To overcome the disadvantages of centralized control structures, transforming battery management systems into a decentralized structure is seen as a suitable option. In this type of decentralized battery management systems, all functionality consists of several equal units that are local and autonomous, as presented in Figure 4. Separate BMS units can operate independently of each other. In fact, in some decentralized battery management systems, the need for communication between units has been eliminated [46-47].

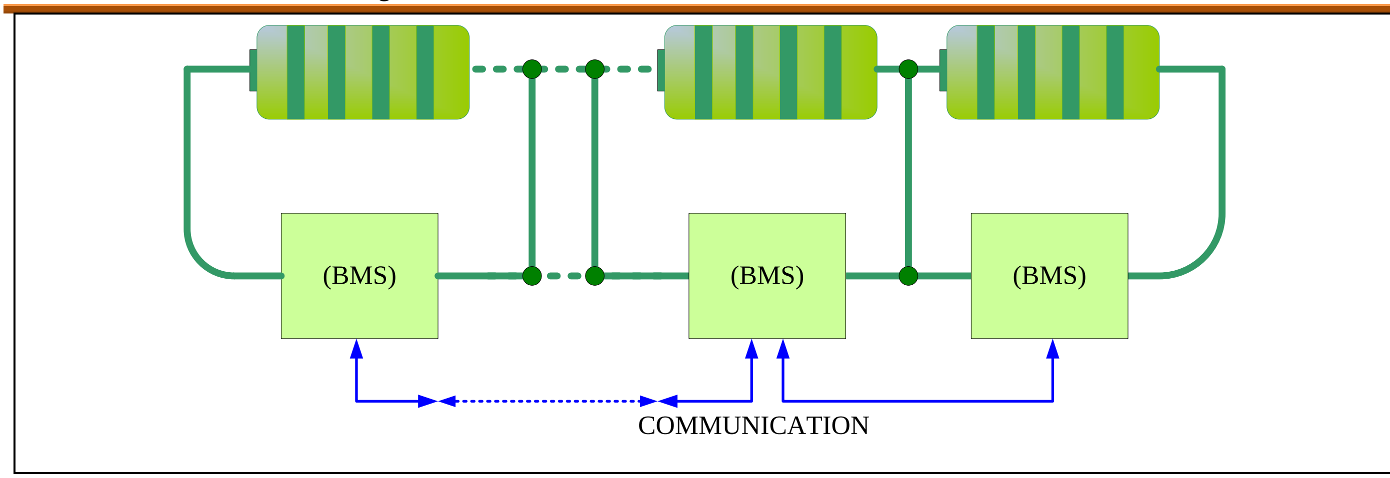

Fig. 4. *Decentralized battery management system topology.*

2.2.2.3. Distributed topology

In distributed battery management systems, individual battery cells or battery groups are controlled by a separate BMS auxiliary module, as presented in Figure 5. BMS auxiliary modules provide measurement and control of communication, balancing and operating parameters. BMSs in this topology consist of several auxiliary and one main BMS modules for real-time monitoring and reporting of the operating conditions of each battery cell [56]

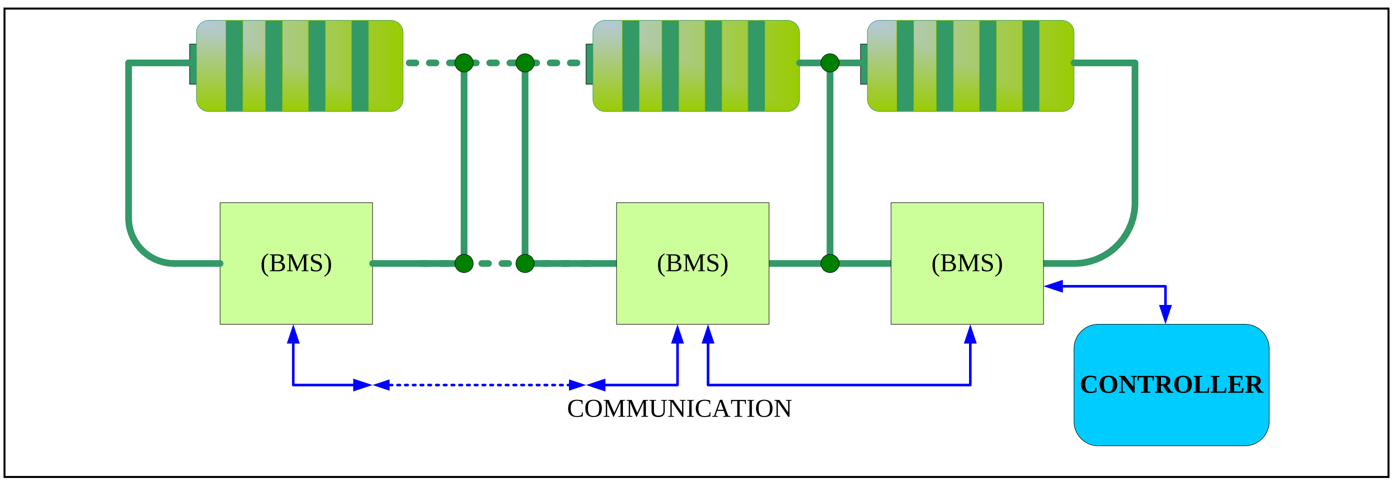

Fig. 5. *Distributed battery management system topology.*

2.2.2.4. Modular topology

Modular battery management systems consist of several identical modules equipped with cables that are individually connected to individual batteries or battery cells, similar to a central BMS. In this topology, presented in Figure 2.7, usually one of the modules is assigned to the administrator role or a separate module acts as the administrator. The main module controls the entire battery pack and communicates with the rest of the system, while the other modules only record the measured data and transmit it to the main unit [52-53].

2.3. Simulation Model of the Battary-BMS System

Different topologies are used in Battery Management Systems [57]. In this study, the distributed topology logic presented in Figure 6 was preferred in the Matlab/Simulink environment. In distributed battery management systems, it consists of auxiliary modules that connect to each battery cell, group or cell, providing measurement and control of them, and a main module that controls the entire system with auxiliary models. While the main module administrator controls all battery packs, auxiliary modules are only responsible for the group they are connected to. While the main module communicates with the rest of the system, the slave modules are only responsible for recording and transmitting the measured data to the main unit.

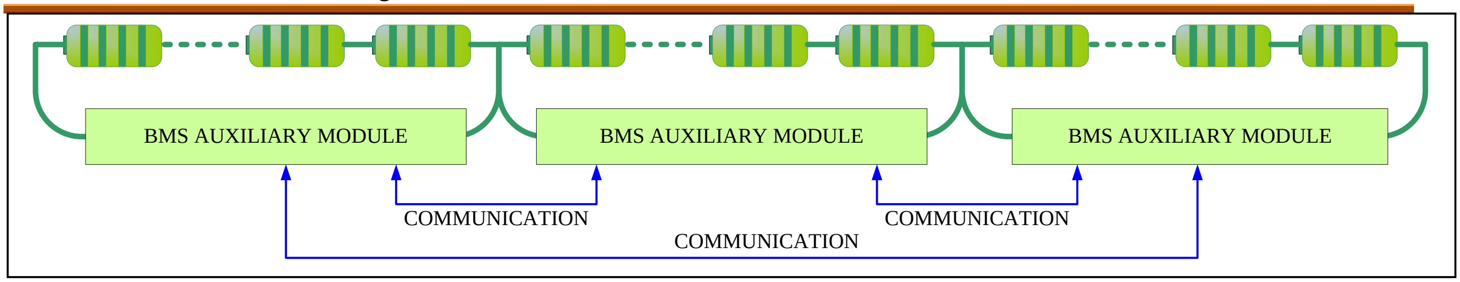

Fig. 6. *Modular battery management system topology.*

2.3.1. Batteries Used in Simulation

The batteries used in the simulation have naming and labeling determined by IEC 60086 and ANSI C18.1 standards, like other standard batteries on the market [58-59]. In this context, batteries are labeled according to their chemistry, packaging style and size. Nickel cadmium batteries (NiCd) is a type of rechargeable battery that uses nickel oxide hydroxide and metallic cadmium as electrodes. Compared to other types of rechargeable batteries, they offer good cycle life and performance at low temperatures with a reasonable capacity. However, their main advantage is that they can offer their full capacity even in applications with high discharge currents. However, the materials they are made from are higher cost compared to lead-acid batteries. Self-discharge rates of NiCd battery cells are also high [60]. NiCd AA; It means that the battery has Nickel Cadmium chemistry and is 14.5 x 50.5 mm in size. Battery Mathematical Model The mathematical model of the electrochemical Nickel Cadmium battery used in the simulation study is presented in Figure 7.

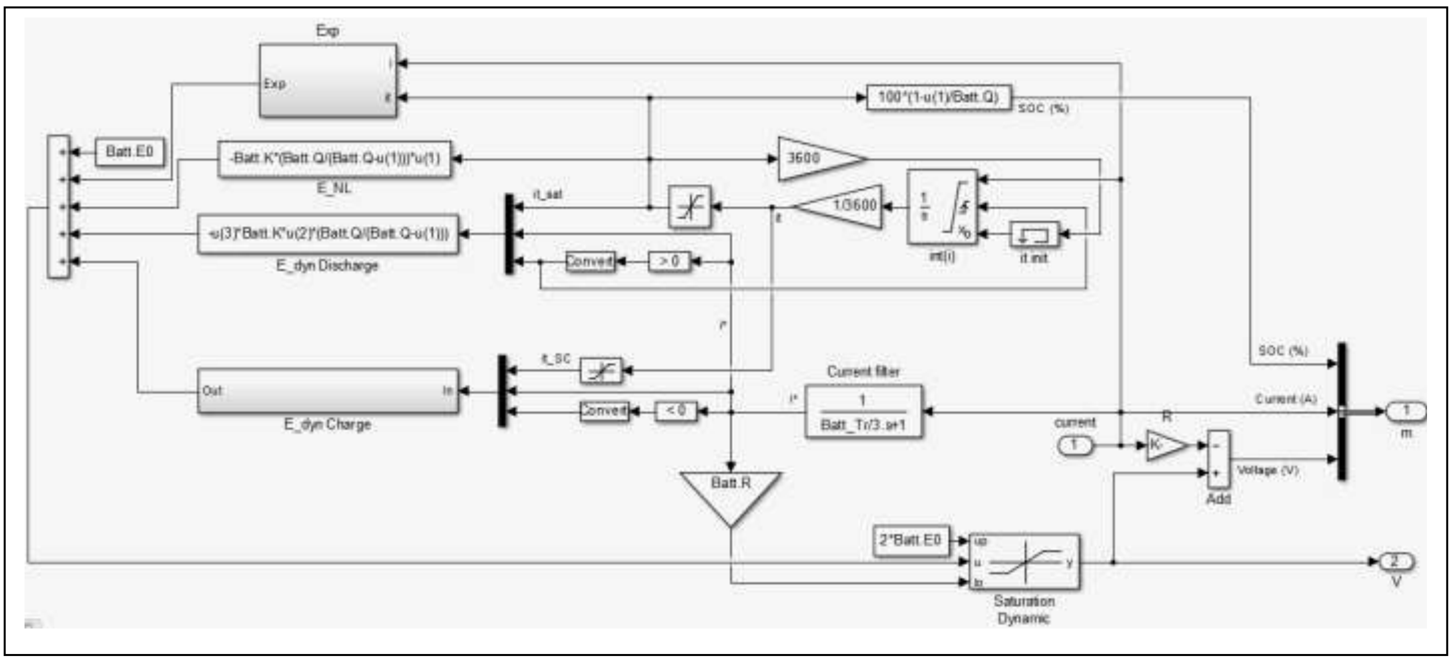

Fig. 7. *Simulink diagram of the battery mathematical model.*

2.3.2. BMS Simulation

The simulation study was carried out in MATLAB/SIMULINK 2014b environment. The simulation consists of blocks that perform five basic functions: Battery Management System (BMS), Electrical System (ES), Internal Combustion Engine (ICE), Gear Subsystem (GS) and Vehicle Dynamics (VD). The general view of the blocks is presented in Figure 8.

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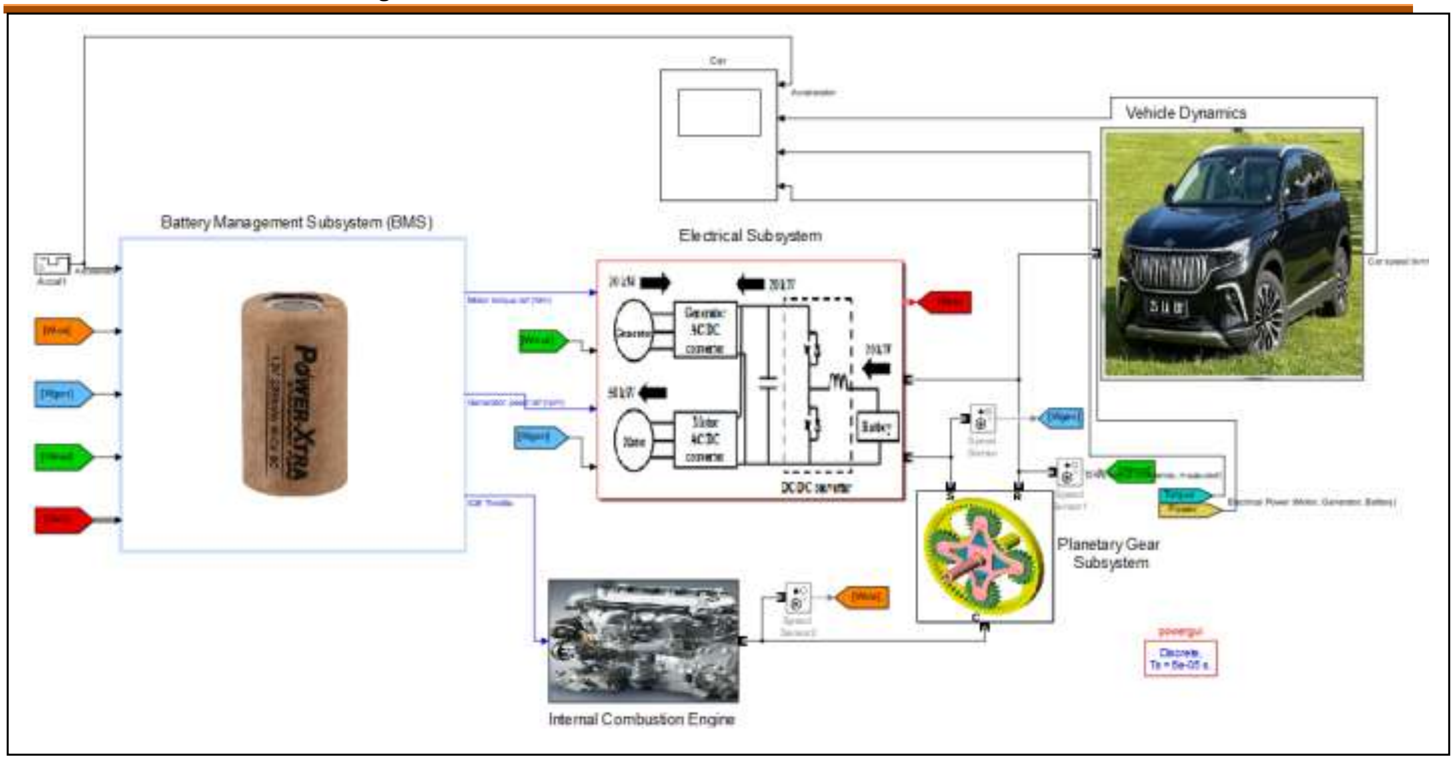

Fig. 8. *BMS simulation study.*

Engine, reduction gear, shaft etc. made with Simscape blocks in the vehicle block. mechanical equipment and engine cooling system. The modeled vehicle presented in Figure 9 weighs 1325 kg. Horizontal distance from CG to front and rear axles are 1.35 m, It is a vehicle equipped with a 150kW engine and a wheel radius of 30cm. The power/weight ratio is 93.75. The vehicle model was run with a WLTP Class 3 drive cycle based on the power/weight ratio. This cycle consists of three parts presented in Figure 4.44. These are low, medium and high power sections. While there is relatively low speed and acceleration in the low section, high speed and acceleration are applied in the high section.

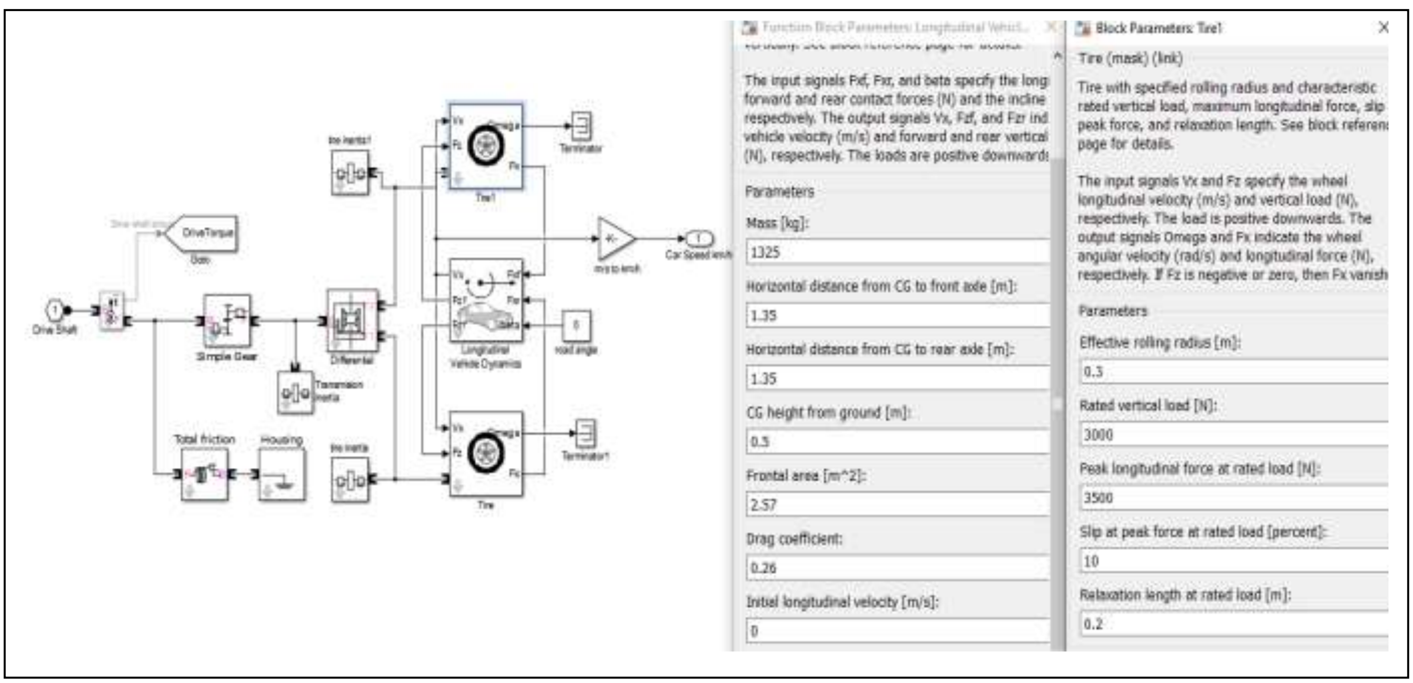

Fig. 9. *Mechanical parameters within the tool block.*

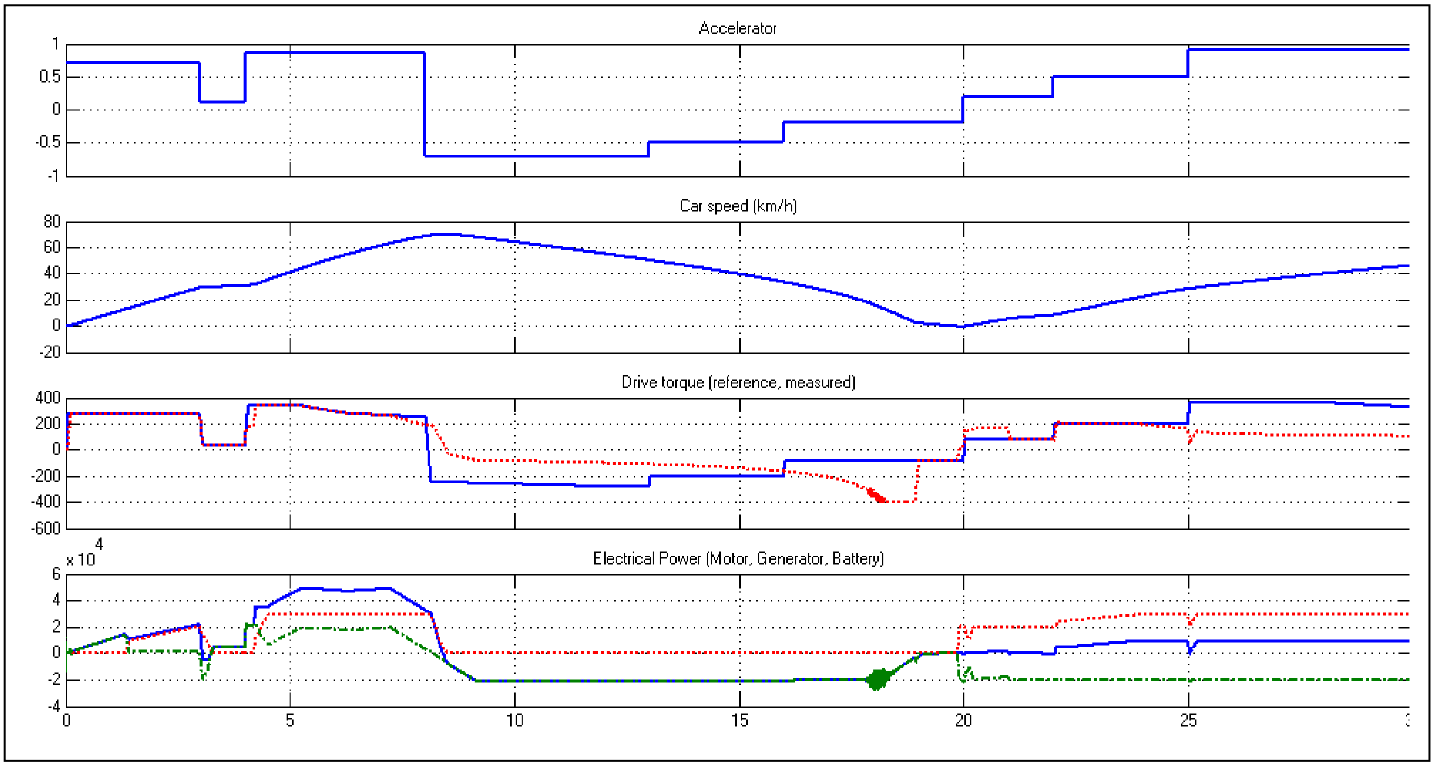

Fig. 10. *Acceleration, speed, torque and power data of the proposed hybrid vehicle.*

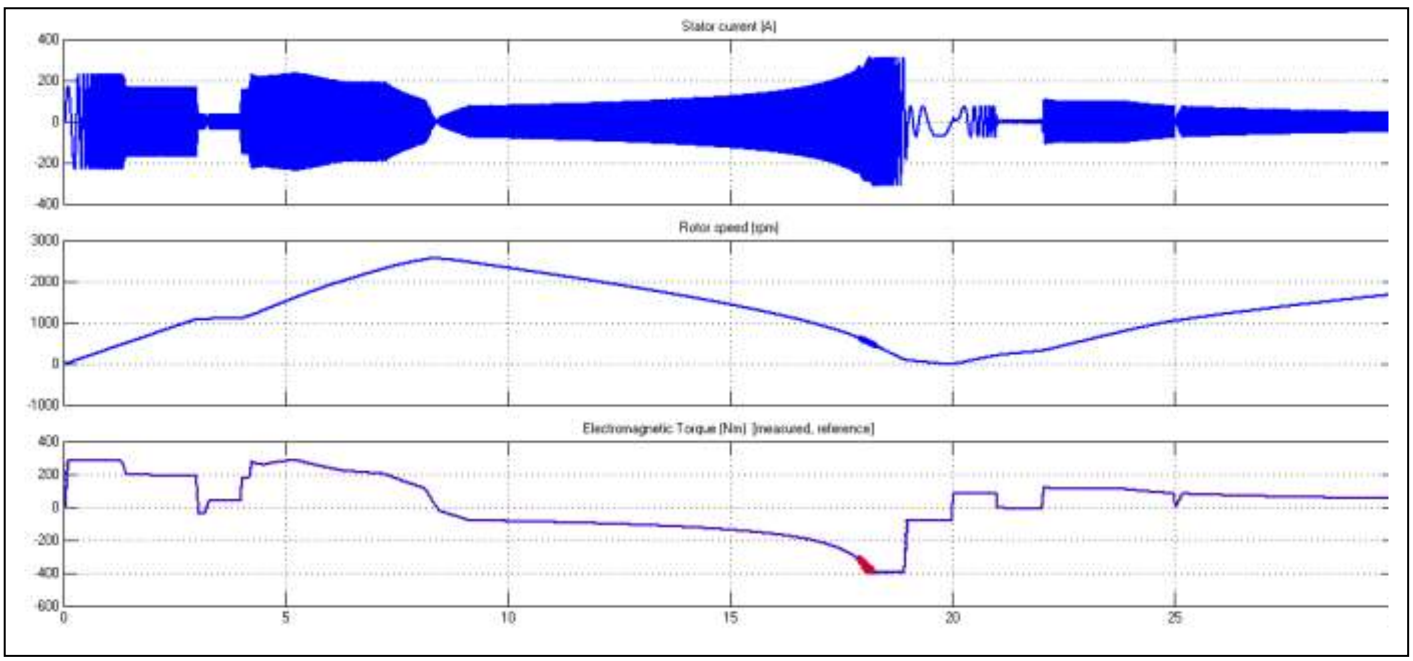

Fig. 11. *Change of some parameters of the electric motor in the proposed hybrid vehicle.*

Figure 10 shows the speed change of the proposed hybrid vehicle with a 30-second variable acceleration input, the torque change it produces following the reference torque, and the power provided by the internal combustion engine, generator and battery during this period. Picture 11 shows the torque change measured by the stator current, rotor speed and reference torque of the electric motor. Picture 12 shows the 30-second change produced by the generator against the same variables.

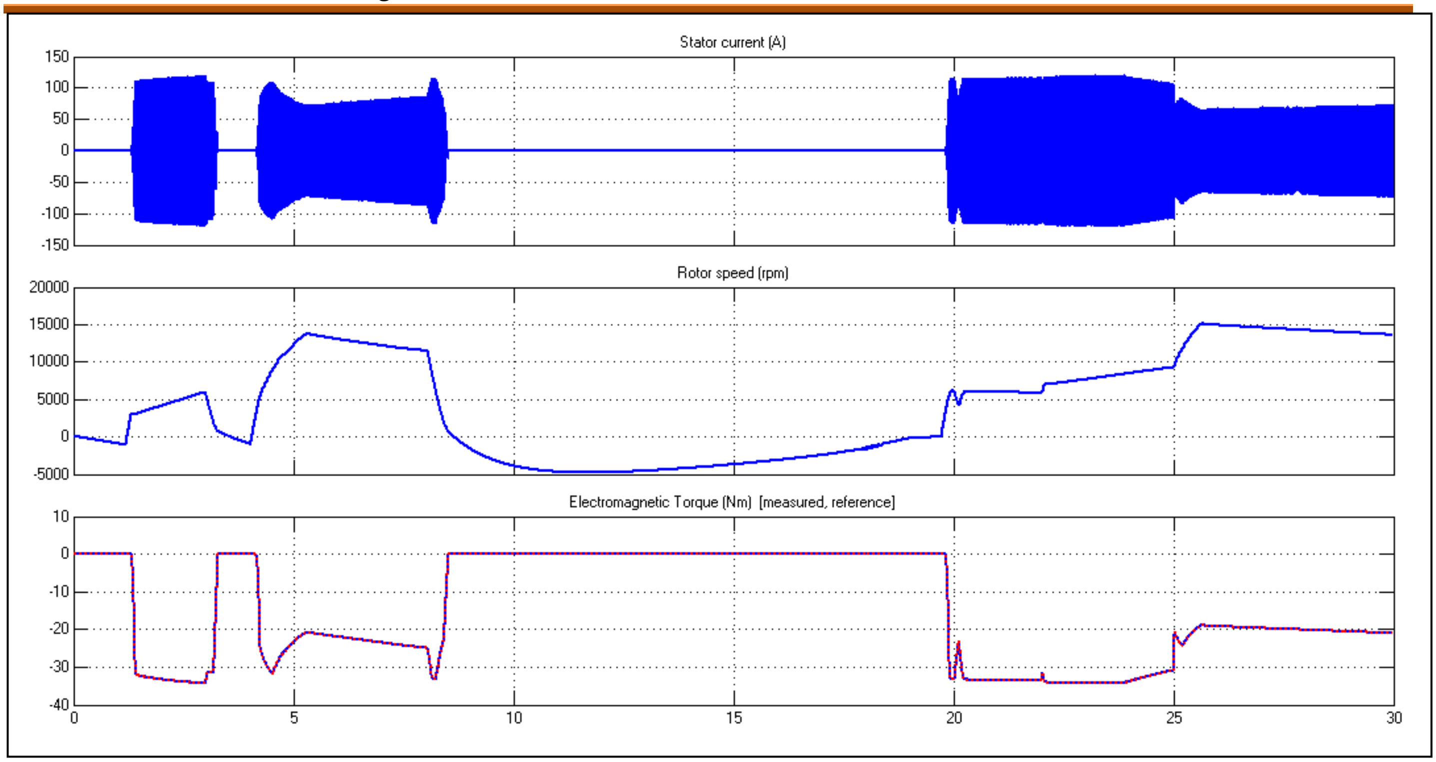

Fig. 12. *Change of some parameters of the generator in the proposed hybrid vehicle.*

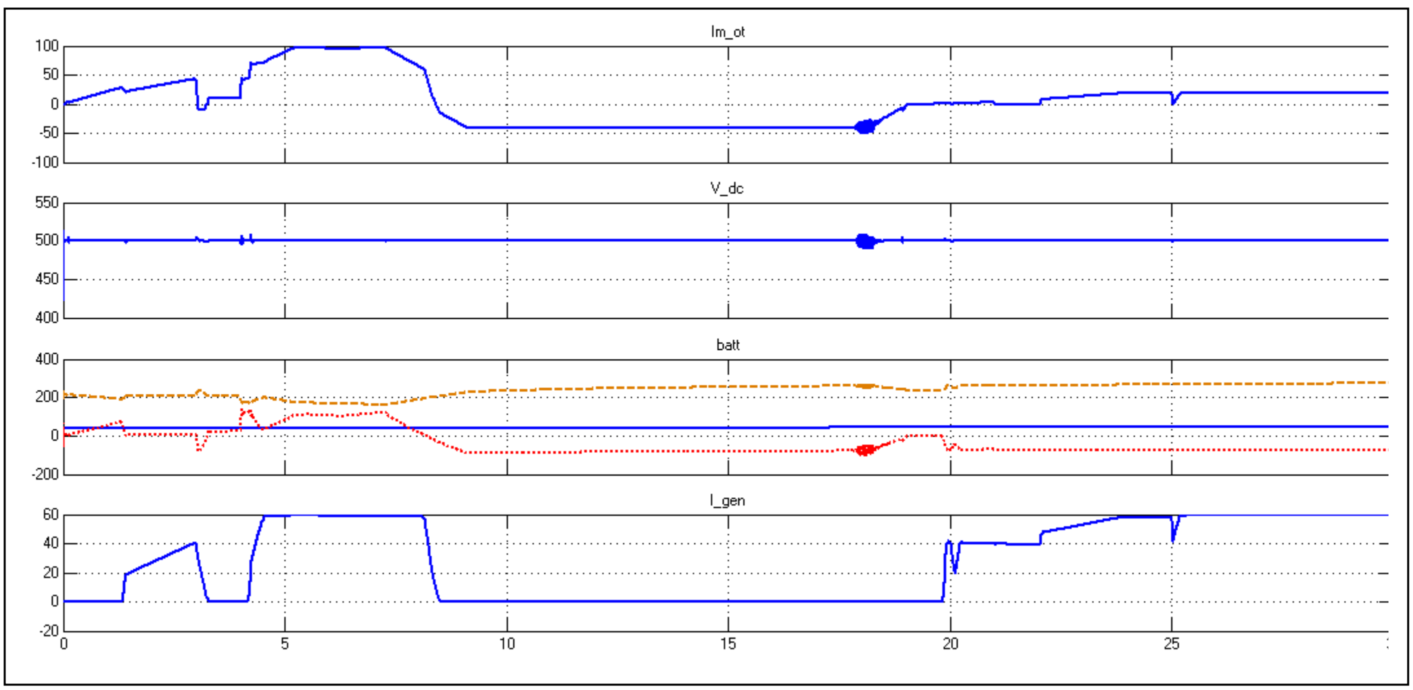

Fig. 13. *Change of battery parameters..*

3. CONCLUSIONS

In Examining the innovations and problems brought by electric vehicle technologies will continue to be an important topic in the world of science and technology in the near future. On the other hand, it is predicted that the conversion of fossil fuel systems to electric and the development of sustainable technologies will be of critical importance in order to overcome environmental problems such as global warming caused by greenhouse gas emissions. The biggest obstacle to electric vehicle technology continues to be the problems of storing electrical energy. However, serious progress has been made in the development and application of appropriate and sufficient energy storage capability. Following these steps of success, many scientists have, over time, developed lithium batteries, which have higher energy density and are the biggest factor that enables electric vehicle technology to exist today. It requires careful and careful use of the lithium element. Therefore, lithium batteries' inherent need for a good management system has necessitated much more work on BMS. However, all these studies are insufficient for today's rapidly developing electric vehicle technology. In this study, the effect of BMS on a hybrid vehicle is presented in detail by developing a smart battery management system while fulfilling the functions of existing BMSs through software.

With the proposed BMS topology, the hybrid electric vehicle successfully produced the power data requested by the load under variable acceleration.

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