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Development of a Fuzzy Logic Based Control Algorithm for Charge-Discharge of a Battery System

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Abstract

In this study, a fuzzy logic controller–based battery charge-discharge control algorithm has been developed to obtain power from a simulation model of an energy system continuously and stably. The current and voltage of the DC busbar, as well as the battery unit, are continuously monitored and used as input data for the algorithm's fuzzy logic controller. And the output of the fuzzy logic controller used as duty ratio for the DC-DC buck boost converter's switching elements. Thus, charge-discharge control of a battery unit to be used as an energy storage unit in an energy system is provided with a developed fuzzy logic-based controller. Also, with the developed simulation model, suitable codes for the TMS320F28335 Digital Signal Processor (DSP) were produced with the embedded code generation method to be used in real world applications.

Keywords. Battery charger, energy storage systems, embedded code generation, the fuzzy logic controller

1. Introduction

These days when we have almost completed the first quarter of the 21st century, many different methods can be used to meet the ever-increasing energy needs. Although the method used to produce energy changes, energy storage systems are needed to ensure the continuity and stability of the energy obtained. When the relevant literature is examined, it is rarely possible to find applications, where the energy obtained, is used directly. However, this way of use greatly reduces the continuity and stability of the energy obtained, especially when it comes to renewable energy sources, which are increasing their popularity today.

For such reasons, it is of great importance to constantly monitor the energy obtained from renewable or fossil-based sources and to store excess energy in cases where there is more energy production than needed to use it in a way to fill the gap in cases where there is less production than needed. For this purpose, many applications have been developed for energy storage systems and the control of these systems. When these applications are examined, it is seen that they are carried out using PI or PID controllers for reasons such as being easier to understand and apply. However, for these controllers, which have a simple structure, the fact that the controller parameters are determined by trial and error also complicates the system design process(Karuppiah, Karthikumar ve Arunbalj, 2018; Haque ve Razzak, 2021; Kumar *vd.*, 2021).

Instead, it may be appropriate to use controllers such as Fuzzy Logic Controller, which can respond quickly to variable system parameters and have adaptive features, to overcome such constraints. Considering all these situations, fuzzy logic controllers are preferred in applications where energy storage system control is desired. In this study, charge-discharge control of a simulated energy storage system is provided by a developed fuzzy logic controller-based algorithm.

In the first section of this article, the general structure of the energy system and the charging and discharging methods of the battery unit, which will be used as an energy storage unit in this system, are discussed. In the second section, the simulation model developed for this energy system and its units is presented. In the third section, the fuzzy logic controller-based algorithm developed for the charging and discharging of the battery unit is presented. In the last section, the obtained results are shared.

2. System Structure

2.1. Battery Charge – Discharge System

As can be seen in Figure 1, the system consists of the battery unit, the load unit, DC-DC buck-boost converter unit and the fuzzy logic-based charge-discharge control algorithm unit. The battery unit used as energy storage while in the charge state or source while in the discharge state. DC-DC buck-boost converter unit responsible for transferring the power from the DC busbar to the battery unit by decreasing while in the charge state, and transferring the power from the battery to the DC busbar by increasing the power while in the discharge state. The fuzzy logic-based charge-discharge control algorithm unit generates the switching signals required for this converter.

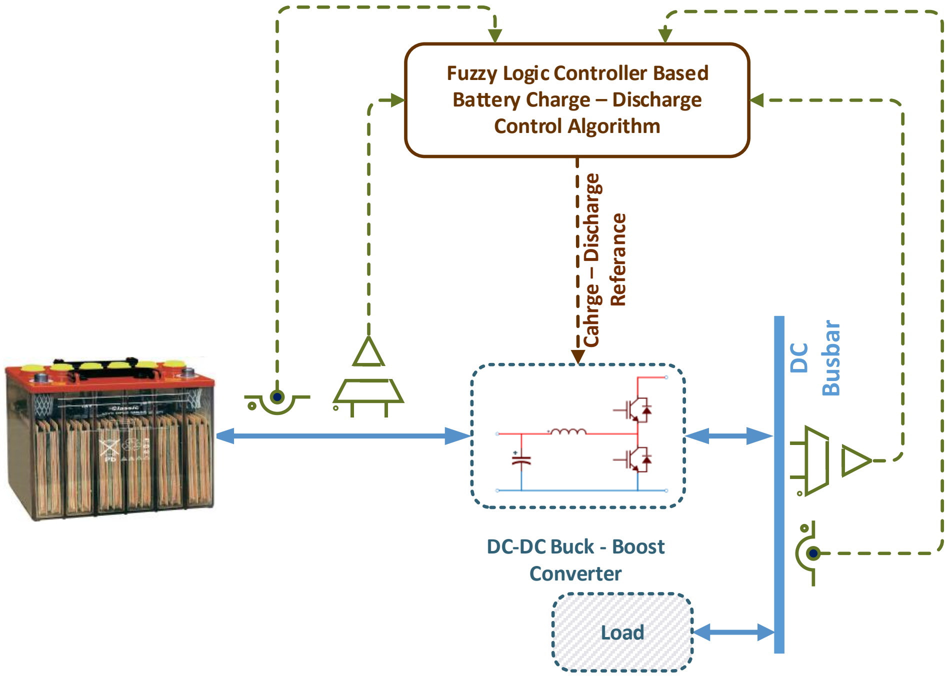

Figure 1. Battery Charge-Discharge System General Schematic.

For a battery, charging is a conversion process that converts electrical energy into chemical energy to be stored in the battery cell. When the relevant literature is examined, it is seen that the Constant Potential Charge method stands out as a battery charging method (Mahmuddin, Yusran ve Klara, 2017). Although the number of stages in the Constant Potential Charge method differs in different approaches, it is the three-stage approach that is mostly used.

Constant Current Charging is the first phase where high constant current charging is applied so that most of the battery charging can be carried out. The constant current applied at this stage is determined as the highest possible current value that will not cause the battery to be damaged by overheating or reduce its lifespan. The current value at which a typical 12V battery can be charged in the constant current phase is determined as C/10. Here C is the capacity value of the battery expressed in Ah.

Constant Voltage Charge is the second stage in which a constant voltage charge is applied until the battery charge current drops to approximately C/50 to C/100 so that the battery can reach a fully charged (100%) state. While the battery voltage remains constant at the determined value (voltage level reached in the previous stage), this stage where the battery current gradually decreases towards full charge is also called the absorption stage.

The third and final stage is the Floating Charge stage, also called the trickle charge. At this stage, a constant voltage is applied to the battery, whose charge state has already reached 100%, in a way that will maintain its 100% state of charge and prevent self-discharge. When the charging process is completed, the voltage at the battery terminals becomes slightly less than the voltage reached during the constant voltage charging Stage (Husnayain, 2017).

Figure 2 shows the charge graph of a battery charged with the three-stage constant potential charging method.

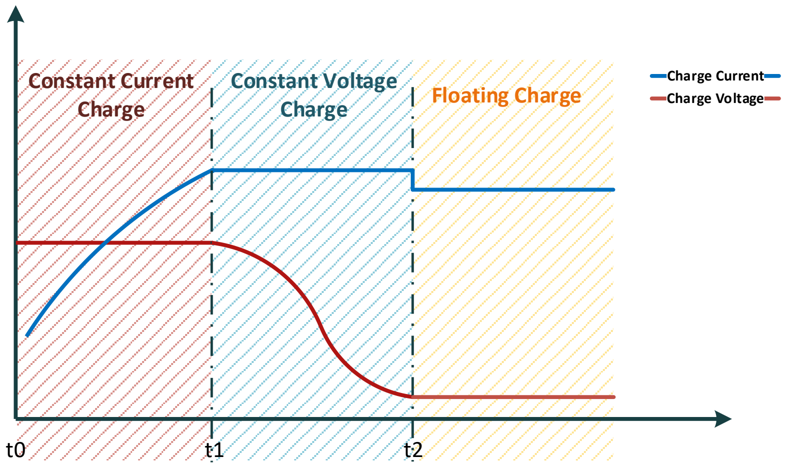

Figure 2. Three Stage Battery Charge (Bhatt, Hurley ve Wölfle, 2005; Armstrong, Glavin ve Hurley, 2008)

The flow chart of the developed fuzzy logic controller-based battery charge-discharge control algorithm is shown in Figure 3. First of all, it is decided whether the battery should be in charge or discharge states.

When the battery is in charge state;

If the battery voltage is below the reference voltage value determined for constant voltage charging, it is charged with the current value determined for constant current charging until it reaches this value (Constant Current Charge).

When the battery voltage reaches the reference voltage value determined for the constant voltage charging, the battery is switched to the constant voltage charging stage so that this voltage value is constant. At this stage, while the voltage at the battery terminals remains constant, the battery charging current gradually decreases (Constant Voltage Charge).

When this current value falls below a determined value, the floating charge stage is started. At this stage, it is ensured that the battery voltage remains constant at the specified reference voltage value so that the battery remains fully charged (Floating Charge).

In charging mode, the DC-DC buck-boost converter operates in buck mode from DC busbar to the battery.

When the battery is in discharge state;

Since the power demanded by the load cannot be met, this missing power is tried to be completed by the discharge of the battery. The developed algorithm generates the switching signals and sends them to the switching elements to transfer the required amount of power to the load. Here, the discharge process is carried out in accordance with the references determined to protect the battery from deep discharge or going out of the discharge current limits.

In discharge mode, the DC-DC buck-boost converter operates in boost mode from the battery to the DC busbar.

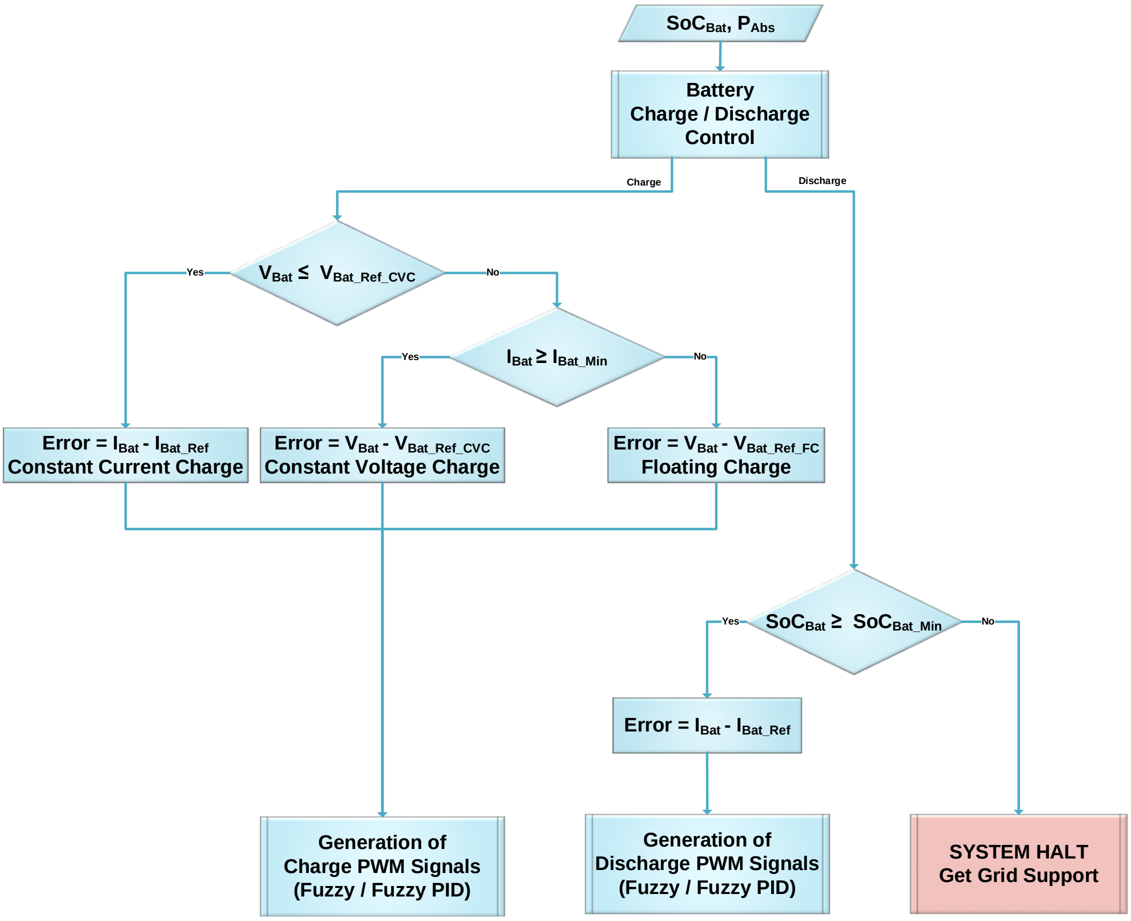

Figure 3. Flowchart of The Proposed Fuzzy Logic Controller Based Battery Charge – Discharge Control Algorithm.

2.2. Simulation Model

The battery unit has been simulated on the PSIM program by using the catalog values given in Table 1. In the same direction, a simulation model was created in the PSIM program for a typical DC-DC buck-boost converter shown in Figure 4. The developed battery charge-discharge control algorithm is written in the Simplified C block in the PSIM program using the C programming language. The load unit is modeled with a resistor. The system simulation model created is shown in Figure 5. In this simulation model, the battery unit and DSP environment are represented by blue and yellow regions, respectively.

Table 1. Yuasa NPW45-12 Industrial VRLA Battery Catalog Data

Nominal voltage (V)	12
10-hr rate Capacity to 10.8V at 20°C (Ah)	6.6
Float charge voltage at 20°C (V)/Cell	2.275 (±1%)
Capacity loss per month at 20°C (% approx.)	3
Cyclic (or Boost) charge Voltage at 20°C (V)/Cell	2.42 (±3%)
Float charge current limit (A)	No limit
Cyclic (or Boost) charge current limit (A)	2.125
Measured at 1 kHz (mΩ)	24

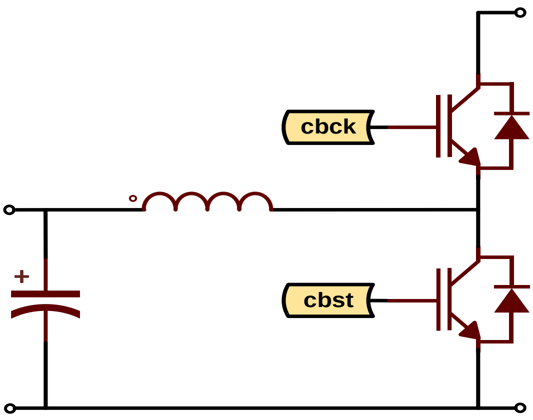

Figure 4. DC-DC Buck-Boost Converter

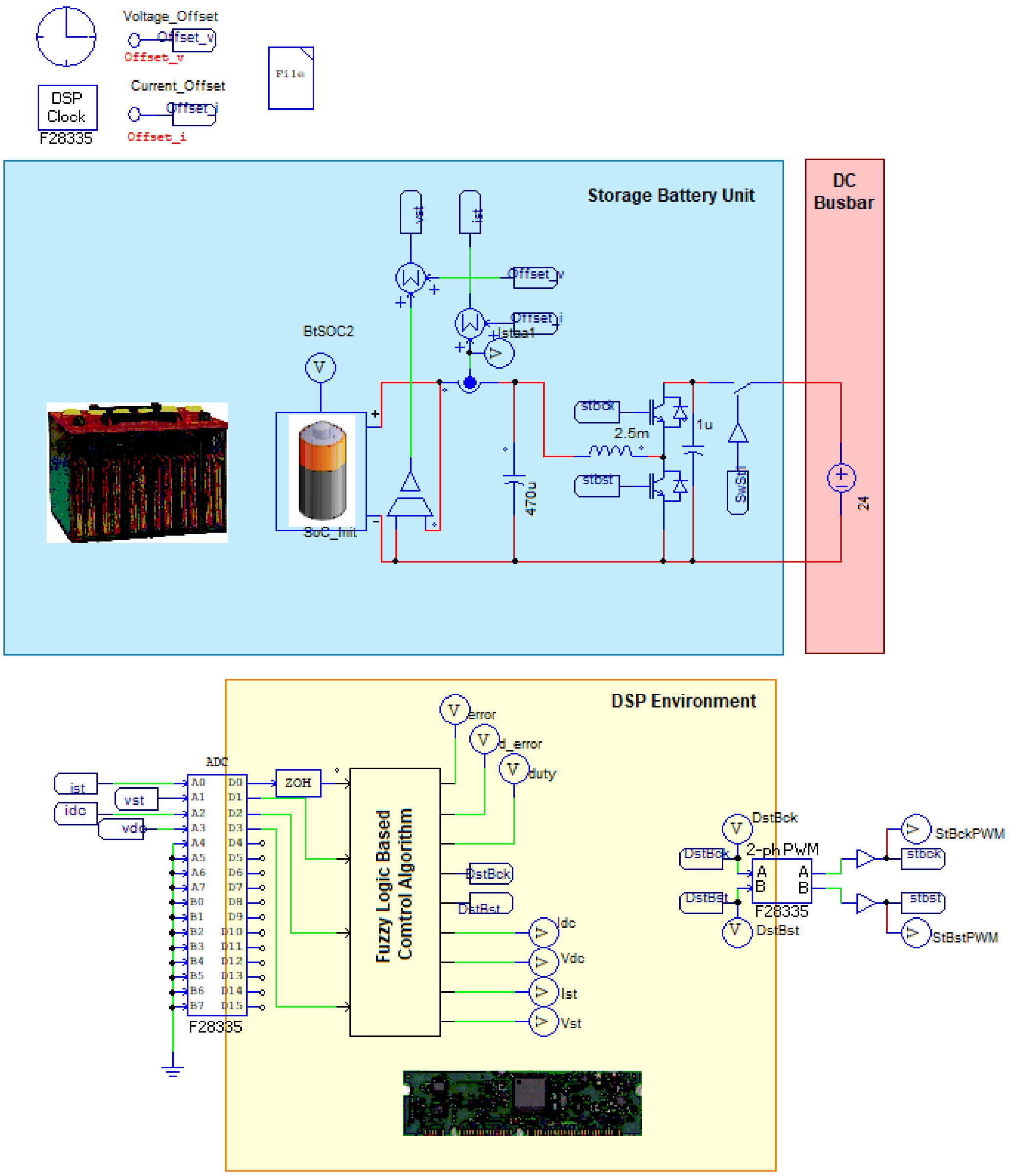

Figure 5. The Simulation Model of The Battery Charge – Discharge Control System

In this simulation model, the battery block has three outputs that represent the positive and negative terminals and State of Charge (SoC) value of the battery. The SoC can be defined as the ratio of the difference between the capacity discharged from a battery since the last fully charged battery's state of charge (full SoC) and the nominal capacity to the nominal capacity, given in Equation 1 (Sauer *vd.*, 1999). Here, C_N is the nominal capacity and Q_b is the charge balance which is a term meaning capacity expended per unit time. The SoC data of the batteries, which will assume the task of storing the energy while in the charge state and providing backup energy while in the discharge state, is very valuable for the system to continue its operation healthily and stably.

$$SoC = \frac{C_N - Q_b}{C_N} \quad (1)$$

A resistor is used to represent the loads to be connected to the system. In addition, the current and voltage values at the output of the battery and on the DC busbar, which are very important for the developed algorithm, were determined using the relevant sensors. The DSP environment has also been simulated so that the microcontroller embedded codes can be automatically generated. To process the measured analog values by DSP, an analog to digital converter (ADC) block, to generate DC-DC buck-boost converter switching signals according to the determined duty ratio value a pulse width modulation (PWM) block, and to write the developed algorithm in C language a Simplified C block was used.

2.3. Fuzzy Logic Controller Based Battery Charge – Discharge Control Algorithm

The voltage and current values on the battery and the DC busbar are measured with sensors and converted into digital data with the ADC block. One or more of the values such as maximum charging voltage or current, maximum discharge current given in the catalog values of the battery (preferred according to being in charge or discharge state) are determined as reference values. The power between the terminals of the battery and the DC busbar are calculated. The error and the change of error, which are the input values of the designed two inputs and one output fuzzy logic controller, are determined. Here, the error is determined as the difference between the battery voltage or current and the reference voltage or current. The change of error was determined as the difference between the current error value and the previous error value. Subsequently, these entries were fuzzified using the Mamdani method by using membership functions in the fuzzify step (Haj-Ali ve Ying, 2002). Seven triangular type membership functions determined for each entry were created as given in Figure 6, and these functions were defined in a matrix in C language. Membership function was selected between -1 and 1 for error entry, while a smaller range of -0.1 to 0.1 was selected for change of error. In the rule base step, it is calculated which rule in the rule base corresponds to the fuzzy values obtained in the previous step. The rule base used is shown in Figure 7. Thus, active rules and the activity levels of these rules were determined.

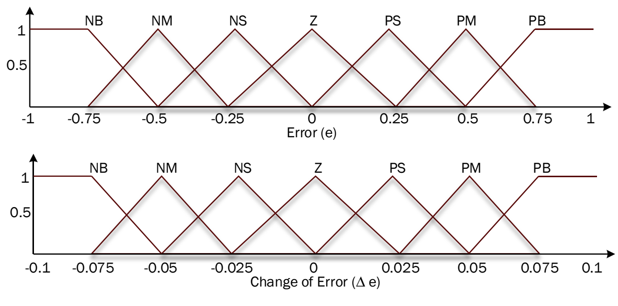

Figure 6. Input Membership Functions For Error and Change of Error.

dE \ E	NB	NM	NS	Z	PS	PM	PB
NB	0 PB	7 PM	14 PS	21 Z	28 NS	35 NS	42 NS
NM	1 PB	8 PM	15 PS	22 Z	29 NS	36 NS	43 NM
NS	2 PB	9 PM	16 PS	23 Z	30 NS	37 NM	44 NM
Z	3 PB	10 PM	17 PS	24 Z	31 NS	38 NM	45 NB
PS	4 PM	11 PM	18 PS	25 Z	32 NS	39 NM	46 NB
PM	5 PM	12 PS	19 PS	26 Z	33 NS	40 NM	47 NB
PB	6 PS	13 PS	20 PS	27 Z	34 NS	41 NM	48 NB

Figure 7. Rule Base of Fuzzy Logic Controller Model.

In the defuzzification step, the defuzzification process was carried out using Equation 2 by using the center of gravity method. As can be seen from Figure 8, seven triangular membership functions for output have been selected so that their value range is 0.1 to 0.7. Since the duty ratio to be obtained at the output of this step takes a value below 0.1 or above 0.7, it will affect the switching process negatively, so a range has been determined so that these values will not be exceeded. The defuzzified value obtained is sent to the PWM block of the microcontroller to generate the switching signals of the DC-DC buck-boost converter. The error and the change of error values, as well as the current, voltage and power values of the battery and the DC busbar, are saved as previous values for the next cycle. Then the algorithm returns to the beginning. Thus, the algorithm recalculates the duty ratio according to the new voltage, current, and power values.

$$Defuzzified\ Output = \frac{\sum \mu_o(i).i}{\sum \mu_o(i)} \quad (2)$$

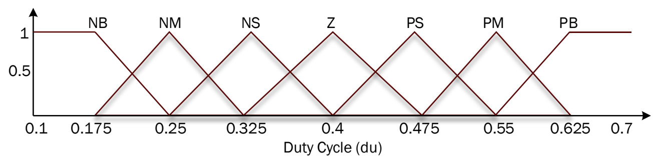

Figure 8. Output Membership Functions for Duty Cycle.

3. Simulation Results

The developed algorithm was run on the simulation model and the results are shown in Figures 9 – 11. Figure 9 shows the current, voltage and battery state of charge graphs obtained for the 3-stage charging system when the energy storage unit is in charge state. Accordingly, in the first graph, the red curve represents the battery current, the blue and pink curves represent the battery charging current references, and the green curve represents the stage of the 3-stage charging system of the charging process. In the second graph, the red curve represents the battery voltage and the blue curve represents the battery charge voltage reference. In the third graph, the battery state of charge value is seen.

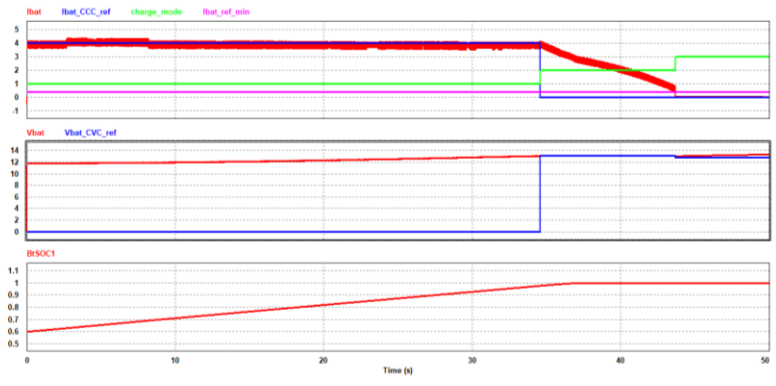

Figure 9. Simulation Results - 3 Stage Charge.

When the results are examined, it is seen that approximately the first 35 seconds of the 50-second simulation period is the 1st stage in the charging system, that is, the constant current charging stage, the next 10 seconds are the 2nd stage, that is, the constant voltage charging stage, and the remaining time is the 3rd stage, the floating charge stage. In the constant current charging phase, it is desired to charge the battery with the specified reference charging current, which is determined as 4A. It is seen that the battery is charged with a slight oscillation of around 4A. At this stage, while the battery voltage reference is zero, the battery voltage increases rapidly, and in this direction, the battery state of charge value approaches 1 from the initial value of 0.6. When the battery voltage reaches the determined reference value, which is determined as 13.1V, in approximately 35 seconds, the constant voltage charging phase is started. The state of charge value, which is very close to 1 in the previous stage, reaches 1 at this stage. At the same time, the battery continues to be charged with the specified reference voltage, which is determined as 13.1V, until the voltage drops to the minimum current reference value, which is determined as 0.4A. When the battery charging current drops to reference value, the battery is fully charged. The battery is kept in the floating charge stage with a value slightly below the voltage it reached in the previous stage, which is determined as 12.8V, in order to maintain this situation without allowing it to self-discharge. At this stage, the battery can be kept stable in a way that it will maintain the fully charged state it has reached even for very long periods of time.

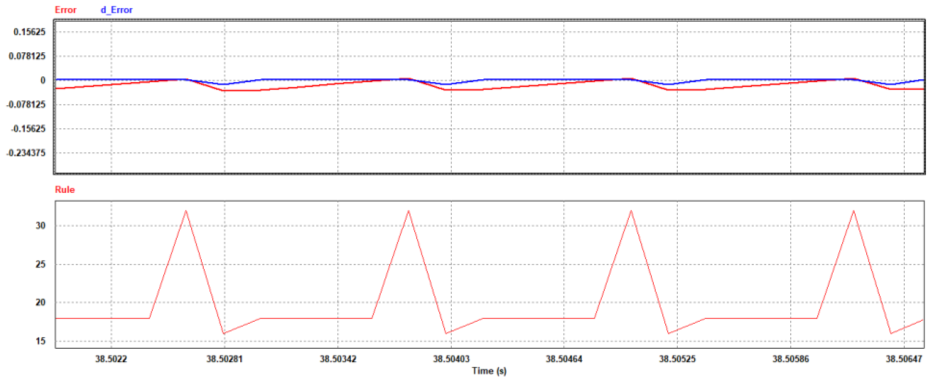

Figure 10. Simulation Results - Error, Change of Error and Rules of Fuzzy Logic Controller

In Figure 10, for a very short moment of the simulation around 38.5 seconds; In the first graph, the red curve represents the error and the blue curve represents the change of the error, while the second graph shows the change in the active rules of the fuzzy logic controller.

Figure 11 shows the voltage, current, the active rules of the fuzzy logic controller and battery state of charge graphs obtained when the energy storage unit is in discharge state. Accordingly, in the first graph, the red curve represents the DC busbar voltage; the blue curve represents the battery discharging voltage reference. In the second graph, the red curve represents the battery current and the blue curve represents the battery voltage. In the third graph, the change in the active rules of the fuzzy logic controller is seen. In the fourth graph, the battery state of charge value is seen.

For the discharge simulation, the initial state of charge of the battery is set as 0.8. In this direction, there is a voltage of around 12.5V at the battery terminals. Firstly, a voltage of 24V is demanded in the DC busbar and the fuzzy logic controller discharge algorithm increases the voltage at the battery terminals to this value. The reference DC busbar voltage is then reduced to 20V and increased back to 26V. As desired, it is seen that the DC busbar voltage follows the reference voltage values given, by the voltage transferred from the battery by boosting it. During the entire discharge process, it is observed that the battery current constantly changes in negative values to create a voltage at the demanded values in the DC busbar. The negative values of the battery current and as well as the decrease in the battery state of charge are due to the discharge of the battery.

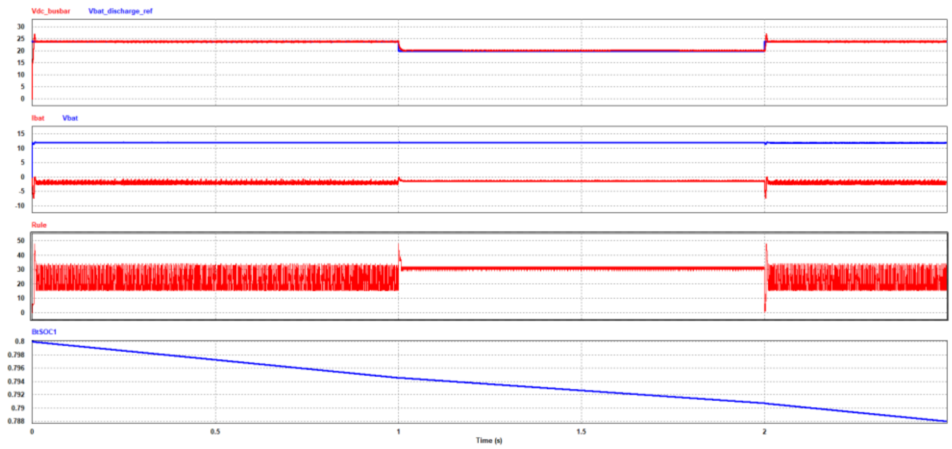

Figure 11. Simulation Results - Discharge

4. Conclusion

The performance of the proposed fuzzy logic controller-based battery charge-discharge control algorithm is monitored. When the results obtained are examined, it is seen that while the battery is in the charging mode, the charging process is completed in accordance with the 3-stage battery charging method, and the discharge process can be performed within the appropriate limits in the discharge mode. In the constant current charging phase, which is the first phase of the 3-stage battery charging method, a 4 Ampere charging current reference was determined and the battery could be charged with small oscillations around this current value; In the second stage, the constant voltage charging stage, a 13.1 Volt charge voltage reference was determined and it was observed that the battery could reach full charge with this voltage value, and a voltage reference of 12.8 Volts was determined in the floating charge stage, which is the last stage, and it was observed that the battery maintains its full state with this reference.

In the discharge mode, voltage reference values of 24, 20 and 26 Volts are given for the DC busbar, respectively. The voltage obtained by discharging the battery within the discharge current limits was transferred to the DC busbar by boosting, thus ensuring that the DC busbar voltage is at reference values.

As a result, the usability of a fuzzy logic-based control algorithm instead of classical control algorithms, which are inadequate and nonlinear system parameters in storage unit included energy system applications, has been confirmed.

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