Three-Stage Charging of Lead Acid Batteries by Artificial Intelligence Fuzzy Logic Controller

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Abstract. The traditional methods of charging lead-acid batteries depend on stabilizing the current or voltage through simple electronic circuits, which causes the shorten the life of the batteries due to damage to the electrodes or the hot and dry batteries. To achieve the best charging efficiency, this paper has adopted artificial intelligence represented by (Fuzzy Logic Control (FLC)) to achieve three charging stages through which the current and voltage are controlled together. Using three algorithms of this type, the batteries are charged when a constant voltage source is available, while the charge is discharged when the source is cut off while preserving the nominal voltage and current limits of the battery to prevent damage.

Keywords: Fuzzy logic control(FLC), state of charge (SOC), lead-acid battery,

1 Introduction

In remote areas that lack the electricity grid, the facility that needs an emergency power source, or in electric cars and other uses, the need for batteries has emerged as source of energy storage [1]. Lead-acid batteries of all kinds are relatively cheap and can be produced in large quantities with high power and capacity [2], so they are preferred over other types of batteries, especially in photovoltaic systems. Using diesel generators despite their low initial cost, but they are considered expensive in the long run due to the cost of fuel and maintenance in addition to pollution [3]. In this paper, artificial intelligence is used as an algorithm that checks for optimal battery charging to keep batteries safe from damage and to increase battery life. In the research presented by [4], he relied on charging, discharging, or standby without specifying the charging stages that ensure that the battery is not damaged. Despite the research presented by [5], artificial intelligence was used to obtain the maximum power from a photoelectric cell (using P&O algorithm), but the algorithm that he used to charge the battery was not considered efficient because it did not use artificial intelligence as it either passes or does not pass a signal from (P & O algorithm circuit) to (Plus with Modulation (PWM)) where it is compared with zero or one always. Although the paper presented by [6] reviews different methods of charging batteries, it is traditional and does not include any artificial intelligence or taking into account the charging stages to control the amount of current and voltage according to the manufacturer's data. It also did not take into account the (MPPT) of the photovoltaic cell, as it will not benefit from about 40% of the solar energy.

In this paper, three stages of charging and one stage of discharging were used using (Fuzzy Logic Control), and it was taken into account that the current is fixed at the beginning of charging to avoid the large surge of current at the beginning of charging. Upon reaching 80% of the charging state, the voltage is fixed because the current starts to reach the saturation state and decreases with the increase in the state of charge (SOC) as it approaches a full charge. When the (SOC) reaches 100%, the voltage is reduced to the limits that allow only the battery to remain always charged during the standby period without causing damage to the battery. The method used allows charging and discharging according to the state of the source if it is connected or disconnected through an algorithm that connects three stages of (FLC). The DC source can be replaced by a photovoltaic cell with a Maximum Power of the circuit or any other power source.

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2 Solar batteries

In most cases, batteries are used to store the energy generated by photovoltaics(PV), in order to be used later when the sun sets or on cloudy days, especially in remote areas that are not connected to the electrical grid. Although some loads can operate on a non-constant voltage, such as water pumps or fans, etc., other loads such as lighting require a constant voltage, so batteries (in addition to storage) are used to produce a constant voltage for the loads. The batteries also help make the photovoltaic cell operate at its maximum power point(MPP) while supplying the load with the high current when needed without being restricted by the capacity of the PV. A charge controller is used to protect the batteries from (overcharging) and (undercharging). Batteries are also used in emergencies, such as hospitals, when the batteries are always charged with a full charge, they are supplied with a small current whenever their charge is reduced to preserve the plates from damage, taking into account activating them with a high charge from time to time and this method of charging is called (float charge).

Batteries generally consist of two electrodes conducting electricity from two different materials immersed in a solution called electrolyte, where one of the electrodes becomes negative and the other positive. The potential difference between the electrodes depends on the material the electrodes are made of and the electrolyte solution used.[7]

3 Types of rechargeable batteries

a- Lead acid batteries
b- Nickel-cadmium (Ni-ca) batteries
c- Nickel-Metal hydride (Ni MH) batteries
d- Lithium ion batteries
e- Lithium polymer batteries

Today, due to their low cost, ease of manufacture, durability, low self-discharge, and not need maintenance, especially gel type. lead-acid batteries are widely used in photovoltaic systems. We will cover this type of cell in this chapter [3, 4, 7, 8].

4 Lead acid batteries

The anode consists of lead dioxide (pbo2), while the negative electrode consists of sponge lead, and both of them are immersed in a solution of sulfuric acid with water at a ratio of (400-480 g / 1) and a density of (1.24-1.28 kg / 1). The nominal voltage of a single cell of 2 volts drops to 1.8 volts when it loses its full charge and rises to (2.3-2.5) volts when fully charged. The voltage of the 6-cell battery becomes (12, 10.8, (13.8-15) volts, respectively, for each case [7].

4.1 Types of lead-acid batteries

There are many types of lead-acid batteries and they can be classified in several forms and several ways, and for the sake of knowing them clearly, they can be classified first into two main sections, open or closed sealed. Both types are made from plates. These plates are divided into two types, flat and tubular plates. Plates can be thin (as in car batteries) or as thick as in batteries that are used to store the energy generated from photovoltaics. Car batteries use a large number of thin plates to produce a high current to power the car, so they are not suitable for storing energy for a long time, while the plates in storage batteries are thick and have a small number.

Sealed Lead-acid batteries have three types, absorbent glass mat type (AGM), gel type and valve-regulated lead-acid (VRLA).

4.2 Battery parameters and variants

1- The capacity of the battery (Ah)
2- Battery voltage
3- State of charge (SOC) and Depth of discharge (DOD)

4- Battery life cycle
5- Self-discharge
6- Rate of charge or discharge

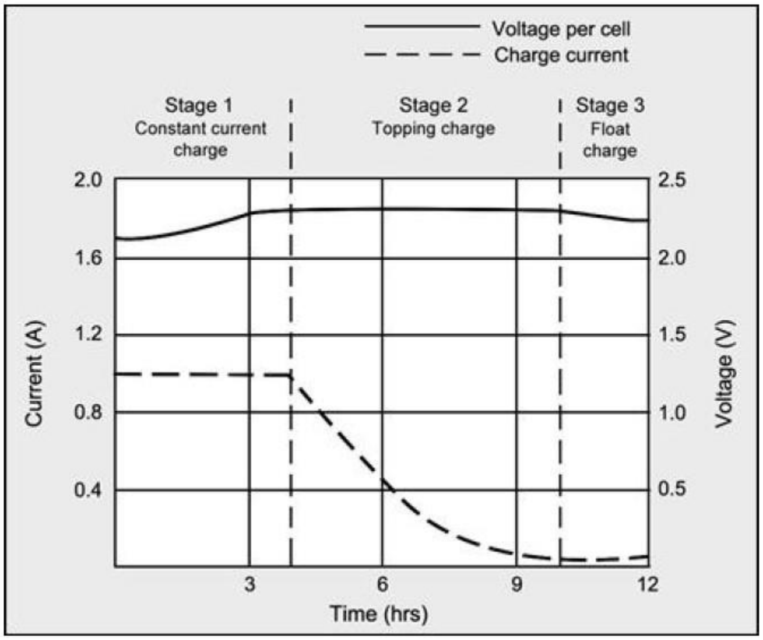

Figure *1* shows three charging stages. The area or first stage represents (constant current charge), the second stage represents (topping charge) and the third stage represents (float charge). The first stage (the constant current charging stage) represents the bulk of the charging of the battery in half the charging time, where approximately 70% of the battery capacity is charged within (5 to 8) hours and the remaining 30% is charged in the second stage at a time of another (7 to 10) hours. The importance of the second stage lies in improving the performance of the battery, without which the battery cannot reach a full charge. After reaching a full charge the third stage maintains this full charge from the self-discharge effect. The charging current decreases when the charge saturation of the battery begins, and the battery reaches full charge when the current reaches only 3% of the total current. When storing, batteries must be fully charged and recharged every 6 months, with a guarantee that the voltage of each cell will not drop below 2.1 volts [7, 8].

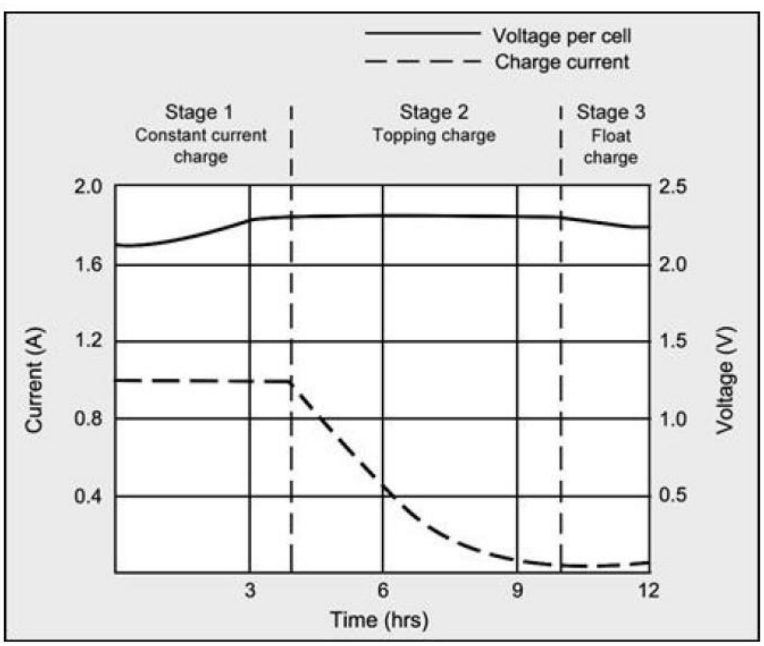

Figure 1: Charging stages of the lead-acid battery [7]

5 Methodology of the proposed bidirectional buck-boost convertor

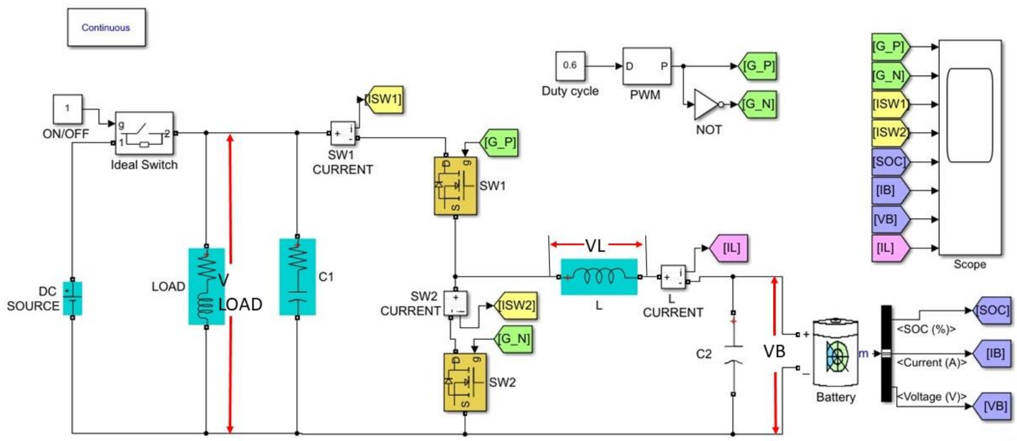

Figure 2 shows a Bidirectional buck-boost convertor. it can be understood how it works by transferring power from the DC source to the load and the battery when the Ideal Switch is on (this means that the DC source has sufficient voltage and is connected to the circuit). When the SW1 is (on) at a time t =0.6T (T=Ton+Toff), the SW2 is (off), (this means that the SW1 is 60% (on) and 40% (off), SW2 is 60% (off) and 40% (on) from the total time (T). The current in the inductor does not change suddenly but depends on the time constant (τ = L / R), where the current increases gradually in the inductor until the SW1 becomes (off). As for the voltage across the inductor, it is (VLOAD – VB), the voltage across the SW1 is zero because it is a short circuit, while the voltage across the SW2 is the source voltage because it is an open circuit and becomes (VLOAD). The inductor at this stage stores energy in the form of a magnetic field that depends on the value of the inductor (L) and the change in current. In the second stage, when the SW1 (off) and the SW2 (on), the inductor returns the stored energy to the circuit, and since the current is not reflected in the inductor, the polarity of the inductor is reversed and the voltage across it becomes negative and its value is (-VB). The output current remains constant because the capacitor is stored and discharges the charge according to its value, and the output voltage approaches a constant value whenever the capacitive value (C2) is large. The values of inductor and capacitor can be calculated from the following equations [1, 9].

$$D = \frac{V_B}{V_{LOAD}} \tag{1}$$

$$\mathrm{L} = \frac{\mathrm{V_B \times (1-D)}}{\mathrm{fs \times \Delta IL}} = \frac{\mathrm{V_B \times (V_{LOAD} - V_B)}}{\mathrm{fs \times \Delta IL \times V_B}} \tag{2}$$

$$\Delta \mathrm{IL} = \frac{(\mathrm{V_{LOAD(max.)}} - V_B) \times \mathrm{D}}{\mathrm{fs \times L}} = \mathrm{I_{L(max.)}} - \mathrm{I_{L(min.)}} \tag{3}$$

To estimate the value of an inductor ripple ΔIL, it is selected between (0.2 to 0.4) of the output current [10]

$$\Delta \mathrm{IL} = (0.2 \text{ to } 0.4) \times I_{LOAD(max.)} \tag{4}$$

$$\mathrm{C_{2(min.)}} = \frac{\Delta \mathrm{IL}}{8 \times \mathrm{fs} \times \Delta \mathrm{V_B}} \tag{5}$$

Where:- V_B = Battery voltage, D=duty cycle, V_{LOAD}=input voltage, L=inductor, I_{in}=input current ΔIL=estimated inductor ripple current, I_B=output Battery current, fs=switching frequency, $V_{LOAD(min)}$=minimum input voltage, $I_{L(max.)}$=maximum inductor current, $I_{L(min.)}$=minimum inductor current, $C_{2(min.)}$=minimum output capacitor, ΔV_O=desired output ripple voltage.

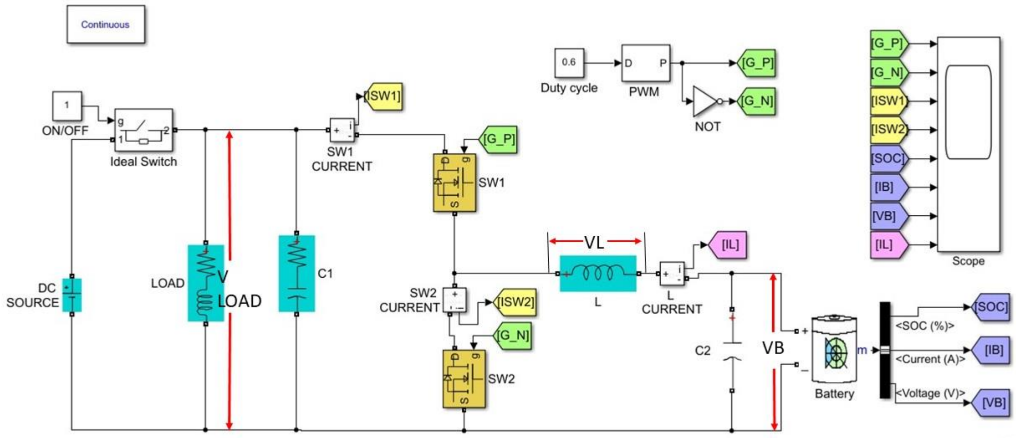

Figure 2: Bidirectional buck-boost converter circuit diagram.

When the ideal switch becomes off, the power is transferred from the battery to the load. When the duty cycle (D=Ton), the SW2 becomes on and SW1 off. Where (T = Ton + Toff). When the SW2 is (on) and because it is an electronic switch, it becomes a short circuit and the voltage across it becomes zero. The inductor will be connected directly to the Battery for a period of (0.4T). The current in the inductor does not change momentarily but depends on the (time constant: τ = L / R). The current continues to increase through Inductance during a period (0.4T). A magnetic field in the coil is formed in the form of stored energy proportional to the value of inductance and the change in current. In this case, the SW1 is off (open circuit). In the second stage (Toff = 0.6T), the SW1 is on and SW2 is off. When the SW1 is on (closed circuit), the coil will become connected in series with the SW1, at this moment the coil signal will be inverted because the current remains in the same direction where the coil energy will be discharged into the Capacitor and the load over the period of 0.6T and the inductor voltage will be VL = -(VB-VLOAD). The output voltage (load voltage) will be the sum of the input voltage and the inductance voltage, so this circuit is a step-up converter [1, 9]

The following equations show how to find the inductor and capacitor of a boost converter.

$$\mathrm{V_{LOAD}} = \frac{1}{1-\mathrm{D}}\mathrm{V_B} \tag{6}$$

$$\mathrm{L} = \frac{\mathrm{V_B}\times\mathrm{D}}{\mathrm{fs}\times\Delta\mathrm{IL}} = \frac{\mathrm{V_B}\times(1-\mathrm{D})\times\mathrm{D}}{\mathrm{fs}\times\Delta\mathrm{IL}} = \frac{\mathrm{V_B}\times(V_{LOAD}-\mathrm{V_B})}{\mathrm{fs}\times\Delta\mathrm{IL}\times V_{LOAD}} \tag{7}$$

$$\Delta\mathrm{IL} = \frac{\mathrm{V_{B(min)}}\times\mathrm{D}}{\mathrm{fs}\times\mathrm{L}} = \mathrm{I_{B(max.)}} - \mathrm{I_{B(min.)}} = \mathrm{I_{L(max.)}} - \mathrm{I_{L(min.)}} \tag{8}$$

In order to estimate the value of an inductor ripple ΔIL, it is selected between (0.2 to 0.4) of the output current[11].

$$\Delta\mathrm{IL} = (0.2 \text{ to } 0.4)\times I_{LOAD(max.)}\times\frac{V_{LOAD}}{V_B} \tag{9}$$

$$C_{O(min.)} = \frac{I_{LOAD(max.)}\times D}{fs\times\Delta V_{LOAD}} \tag{10}$$

Where:- $\mathrm{V_{LOAD}}$ = output voltage , D=duty cycle , $\mathrm{V_B}$=battery voltage, L=inductor, $\mathrm{I_B}$=battery current ΔIL=estimated inductor ripple current , $\mathrm{I_{LOAD}}$=output current, fs=switching frequency $\mathrm{V_{B(min)}}$=minimum battery voltage, $\mathrm{I_{B(max.)}}$=maximum battery current $\mathrm{I_{B(min.)}}$=minimum battery current, $\mathrm{I_{L(max.)}}$=maximum inductor current, $\mathrm{I_{L(min.)}}$=minimum inductor current, $C_{1(min.)}$=minimum output capacitor, ΔV_O=desired output ripple voltage

6 Fuzzy logic control as a controller

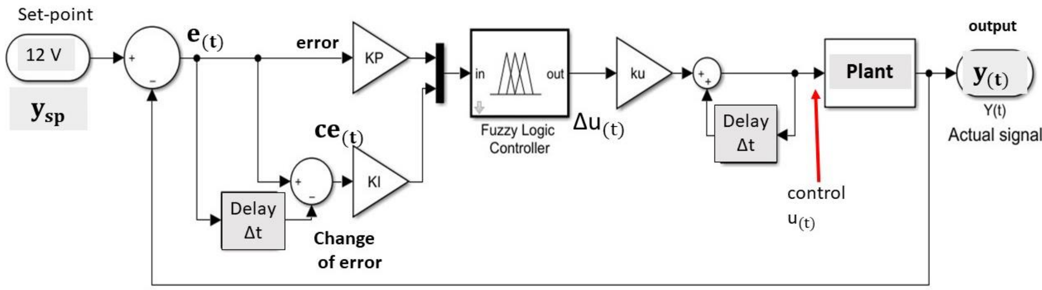

Figure 3: A block diagram of a PI fuzzy control system

In order to achieve the charging stages of a lead-acid battery shown in

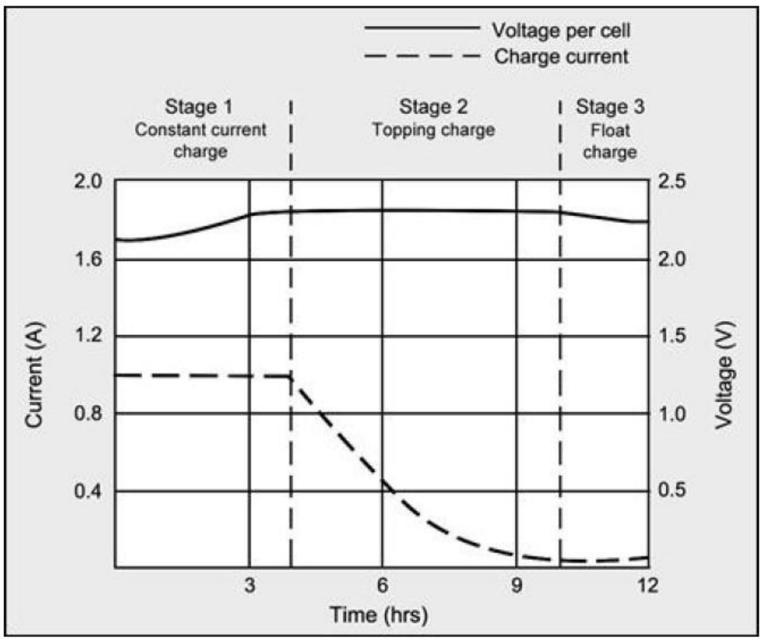

Figure *1*, it requires controlling the amount of the duty cycle so that the current is stabilized first (bulk charge approximately from 10 to 30% of the battery capacity) until the state of charge (SOC) reaches 80%. Then the voltage is installed (topping charge) at the limits (from 2.30 to 2.45 volts per cell). After the battery is fully charged, either the battery is disconnected from the source or it continues charging at a voltage of approximately 2.25 volts/cell (float charge) to protect the battery from damage [7]. To achieve all of these Conditions require one of the control methods, and we will use in this paper the Fuzzy Logic Control (FLC) to control the battery charge. The reason for choosing this type of control system is that it does not need any information about the system and does not require that the system be linear or non-linear [12].

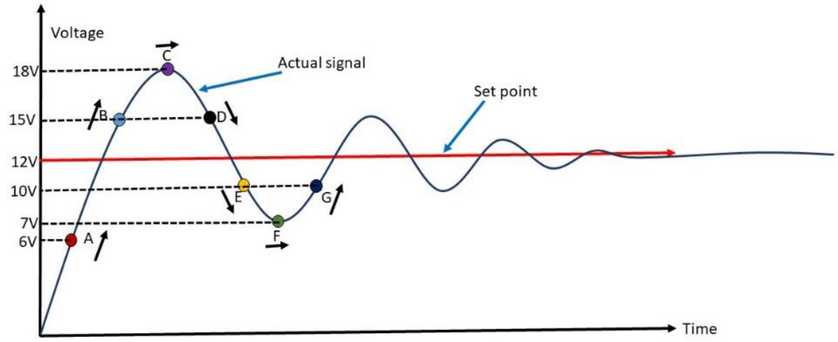

Figure 4: set point and actual signal for the system.

The Fuzzy control circuit shown in Figure 3 is based mainly on comparing the error e(t) with the change of error when comparing the actual signal coming out of the system with the desired reference signal. To understand how the circuit works, the signals are analyzed in Figure 4. In point A, the (12-6=6) volt error is positive because the reference signal is greater than the actual signal, while in point B the error is (15-12=-3) volt. Thus, the value of the remaining points can be calculated in the same way by subtracting the value of the actual signal from the reference signal. In this way, the value of the error can be determined, but the direction of its movement can only be known by comparing the current error with the previous error with a new parameter called the change of error ce(t). For example, when moving from point A to point B, the magnitude of the change of error will be (-3-6= - 9). So we will have the following cases. The points that fall above the reference signal all have the error amount negative, while for all the points below the reference signal the error magnitude is positive. The amount of change in error is below and above the reference signal, either negative or positive, depending on the movement of the point. For example, points A, B, and G are negative while points D and E are positive. And C, F is zero because slop is zero.

$$e_{(t)} = y_{sp} - y_{(t)} \quad (11)$$

$$ce_{(t)} = e_{(t)} - e_{(t-1)} \quad (12)$$

Where: - $e_{(t)}$=the error, y_{sp}= set-point or reference point or desired value, $y_{(t)}$=actual output value.
$ce_{(t)}$=the change of error, $e_{(t-1)}$= the previous error.
Case (1):- If $e_{(t)}$ is negative $y_{sp} - y_{(t)} < 0$, then $y_{sp} < y_{(t)}$.
case (2):- If $e_{(t)}$ is positive $y_{sp} - y_{(t)} > 0$, then $y_{sp} > y_{(t)}$. For both cases $ce_{(t)}$ it can have a positive or negative value
$ce_{(t)} = e_{(t)} - e_{(t-1)} = y_{sp} - y_{(t)} -[y_{sp} - y_{(t-1)}]$. y_{sp} is constant because it is the reference voltage.
$ce_{(t)} = -(y_{(t)} - y_{(t-1)})$. Now if $ce_{(t)}$ is negative $-(y_{(t)} - y_{(t-1)}) <0$, then $y_{(t-1)} < y_{(t)}$. if $ce_{(t)}$ is positive $-(y_{(t)} - y_{(t-1)}) >0$, then $y_{(t-1)} > y_{(t)}$.

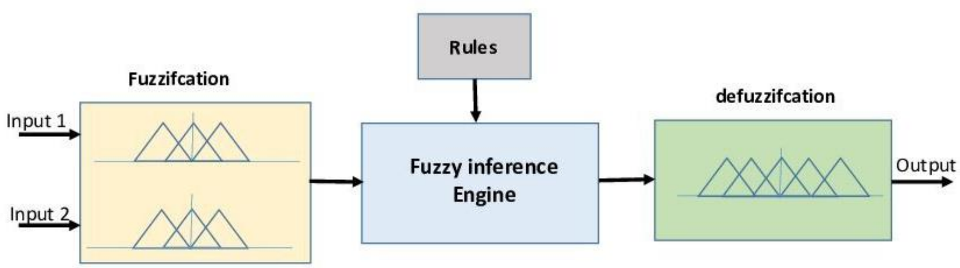

Figure 5: General structure of fuzzy logic control.

After determining the error values and the change in error, they are entered into the Fuzzy circuit shows in

Figure 5 is the block diagram which is converted into linguistic values, and take for example the error values (positive big(PB), positive medium (PM), positive small (PS), zero, negative small (NS), negative medium (NM), and negative big (NB)). In the same way, the values of the change of error and output control u(t) are converted into linguistic values, then they are compared with each other through a rule table specifying the conditions discussed in Figure 4, according to the relationships shown below.

If e(t) positive and ce(t) negative, then u(t) positive

If e(t) negative and ce(t) negative, then u(t) negative

If e(t) negative and ce(t) positive, then u(t) positive

If e(t) positive and ce(t) positive, then u(t) negative

Table 1 shows the relationship between error and change of error, and variables from 1 to 49 represent the linguistic value of the control signal required to correct the actual signal in order for it to apply to the reference signal [12, 13]. Finally the defuzzification by returning the linguistic values to a crisp value.

Table 1: Rule base.

$ce_{(t)}$ / $e_{(t)}$	NB	NM	NS	ZE	PS	PM	PB
NB	1 NB	2 NB	3 NB	4 NB	5 NM	6 NS	7 ZE
NM	8 NB	9 NB	10 NB	11 NM	12 NS	13 ZE	14 PS
NS	15 NB	16 NB	17 NM	18 NS	19 ZE	20 PS	21 PM
ZE	22 NB	23 NM	24 NS	25 ZE	26 PS	27 PM	28 PB
PS	29 NM	30 NS	31 ZE	32 PS	33 PM	34 PB	35 PB
PM	36 NS	37 ZE	38 PS	39 PM	40 PB	41 PB	42 PB
PB	43 ZE	44 PS	45 PM	46 PB	47 PB	48 PB	49 PB

The circuit in Figure 2 is controlled by replacing the Duty Cycle constant with the circuit shown in Figure 6, which is a two-stage charging stage and a discharging stage

6.1 Charging stage

When the state of charge (SOC) is less than 80%, Switches 1 and 2 pass the actual current and reference current shows in Figure 6. As for switches 5 and 3 in Figure 7, they pass the voltage and thus we achieve the first condition for the charge status of the lead-acid batteries shown in

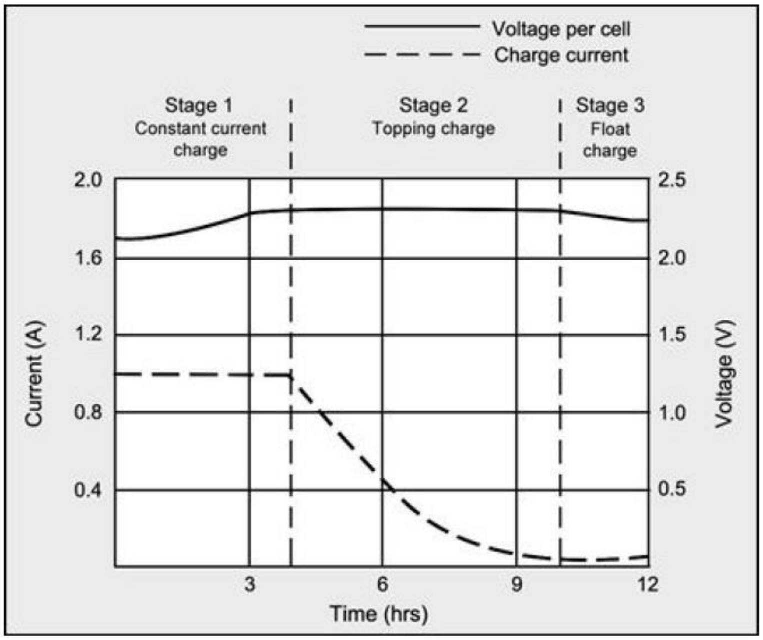

Figure *1*, provided that switch 4 is in case 1, meaning that the source is connected to the circuit. When the charging state reaches 80% or more, the previous state will be reversed and the voltage is connected through switches 1 and 2, while the current is connected through switches 3 and 5. After the charging state reaches 100%, the voltage is reduced to 13.1 volts by switch 6, which is the voltage that prevents self-discharge. Fuzzy Logic Controller 1 and 2 is a double-loop feedback control by controlling the voltage and current when the converter is in the (buck converter) state. The current or voltage is controlled when the output of the first controller becomes a reference for the second controller so that under no circumstances is it allowed for the voltage or current to rise to a greater extent than the nominal battery values.

6.2 Discharging stage

When the DC power supply is disconnected, the switch 4 state becomes off in Figure 6, where the charge controller 1,2 is disconnected. The FLC discharging control is connected via the converter when it is in the boost converter state. The voltage of the load is fixed to 24 volts through the Fuzzy controller. The rule base table is the same as Table 1. Only the rules are reversed for the fact that the relationship of the input voltage to the output of the (boost converter) is inverse according to Equation No. 6, while in the (buck converter) it is positive according to Equation No. 1.

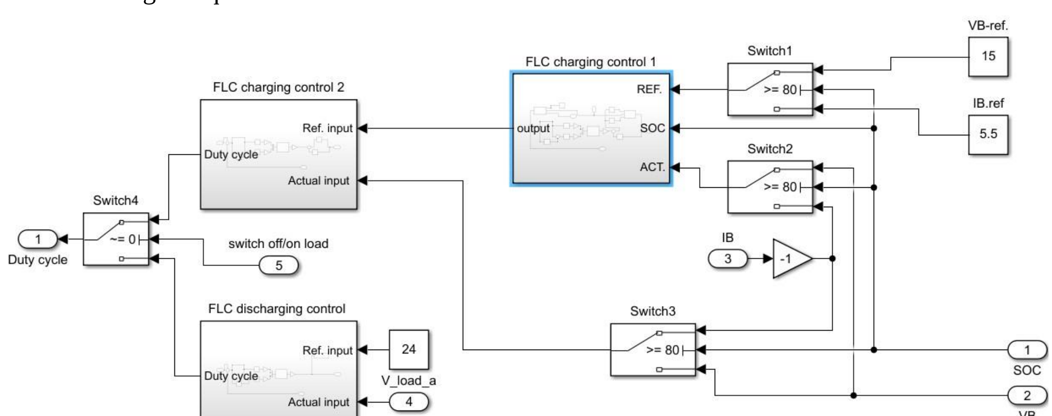

Figure 6: the main controller circuit to control the duty cycle.

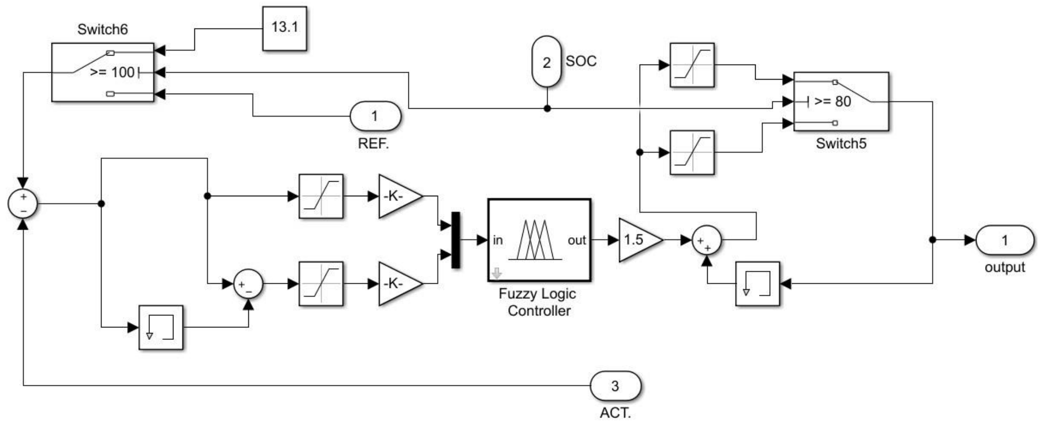

Figure 7: FLC charging controller 1.

7 Results and discussion

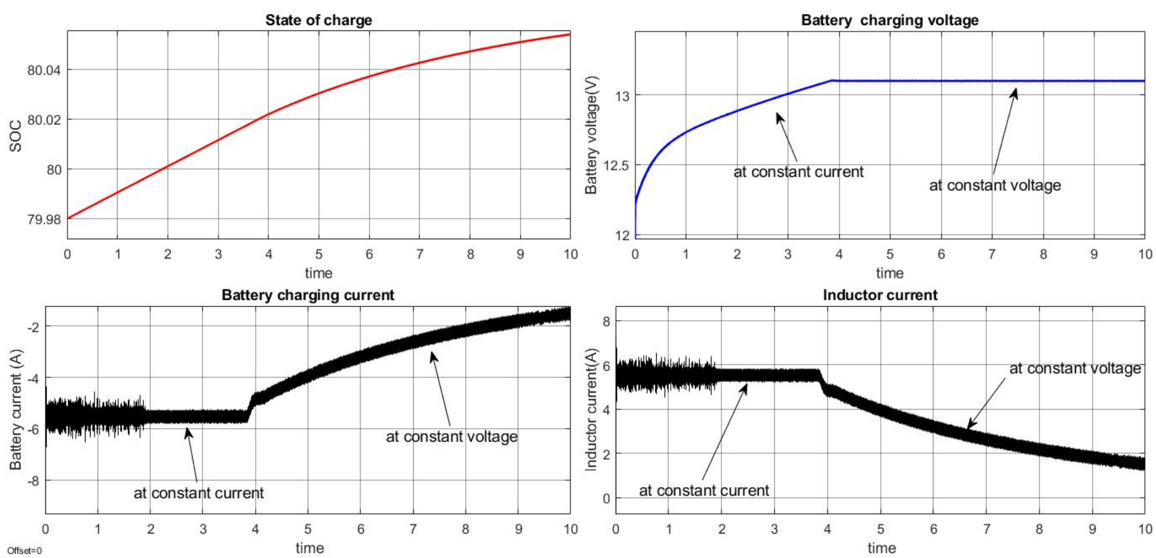

Figure 8: Charging stage results.

The battery used in this experiment has the following specifications (12 volts nominal, 5.5-ampere max. charge/discharge current, 13.08-volt full charging, cycle use 14.4-14.5 volt, standby use 13.1-13.5 volt) as it was adopted from MATLAB. When the charge is less than 80%, the lead-acid batteries are charged with a constant current equal to the charging and discharging current as shown in Figure 8. In order to avoid damage to the positive electrode, battery overheating, gases and water evaporation from the battery, the voltage is fixed at 15 volts after the charging state reaches 80%. Finally, when the battery is fully charged, the voltage is reduced to 13.1 volts, which is slightly higher than the full charge voltage, to ensure the battery remains charged in the standby state

In the case of discharging when the source is cut off from the load, as in Figure 9, the load is supplied with a constant voltage of 24 volts via the boost converter. All of this is achieved through the artificial intelligence of the Fuzzy logic control that was used in this research.[1]

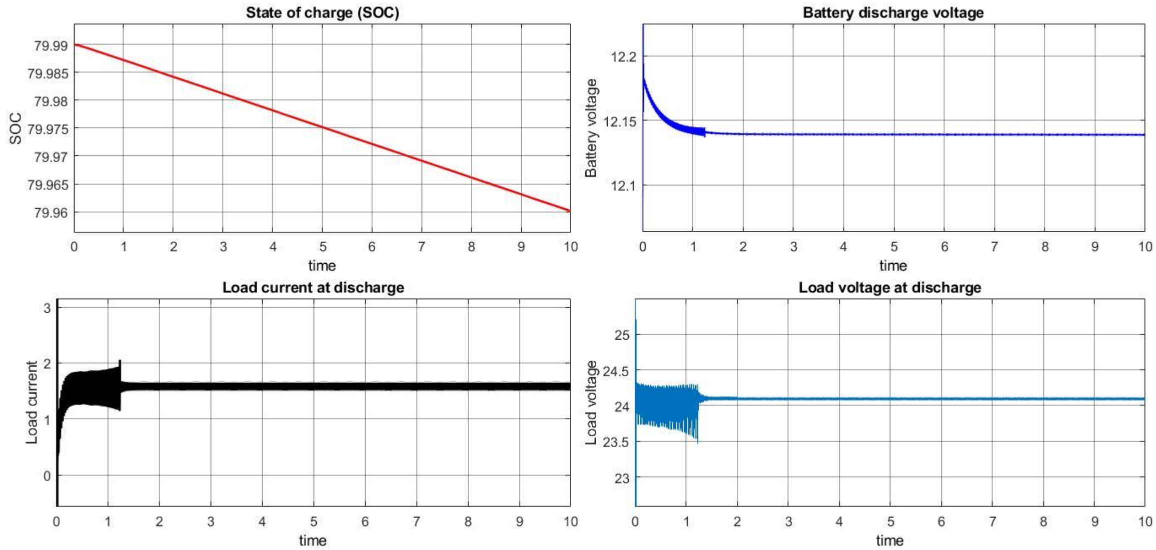

Figure 9: discharging stage results.

8 Conclusion

A new method has been applied in this research to charge lead-acid batteries using artificial intelligence, taking into account the characteristics of batteries represented by the charging current and voltage in order to preserve the battery from damage on the one hand and reduce the charging time on the other hand.

Acknowledgment

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