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SIMULATION AND IMPLEMENTATION OF A FUZZY CONTROLLED CHARGER FOR NI-CD BATTERIES

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Abstract
In this paper, a general-purpose fuzzy controlled charger for a set of Ni-Cd batteries is investigated, Simulated and experimentally tested. The fuzzy controller applied to a BUCK converter as a battery charging system and during the charge process, battery temperature and voltage variations are used as controller input variables and charge current as output .Battery voltage and temperature is kept safe and stable during the charge process. Experimental results also confirmed by computer simulation and show control potentialities.

Keywords: Fuzzy controller, Simulation, Ni-Cd battery, charger, Temperature, SMR

1. Introduction

The circuitry of the batteries charger in a portable product is an important part of any power supply design. The complexity (and cost) of the charging system is primarily dependent on the type of the battery and the charging time [5]. It is important to note that fast charging can only be done safely if the Battery temperature is within (10-40) °C and 25°C is typically considered optimal for charging [8]. Classical control algorithms such as PID, PI etc. are difficult to implement in this event, due to non-linear current-time relationships of rechargeable batteries [1,2].There are a number of methods for charging the batteries. Charging with constant current, Charging with a semi-constant current, Charging with constant voltage, Multistage charging according to the Ampere - Hour rule and two stage charging cycle which simplifies the Multistage charging method [2].In this method where the charging cycle at first with a constant current and next with constant voltage [1]. Most high-performance charging systems employ at least two detection schemes to terminate fast charging. These are voltage and temperature variations [1,2,4]. The temperature of batteries starts increasing very rapidly when full charge is reached but voltage increased at a slower rate [2]. In this charging system we use these parameters to control charge current and have an optimized time and voltage charge.

DC-dc converters which generally use to battery charging systems are an intriguing subject from the control point of view due to their intrinsic non-linearity [12]. In this paper a BUCK DC-DC converter is used as battery charger and experimentally implemented. A PWM reference signal is provided by Fuzzy controller to control output current of BUCK converter.

The Fuzzy Logic Control (FLC) neither requires a precise mathematical modeling of the system nor complex computations [15]. This control technique relies on the human capability to understand systems' behavior, and is based on qualitative control rules. Thus, control design is simple, since it is only based on linguistic rules. This approach lies on the basic physical properties of the systems and it is potentially able to extend control capability even to those operating conditions where linear control techniques fail. The FLC approach is general, in the sense that almost the same control rules can be applied to several charging systems; however, some scale factors must be tuned according to charger topology and parameters.

In our proposal, the fuzzy controller requires only sensing temperature and the output voltage and current, and its implementation is relatively simple. Fuzzy control program is stored in memory of microcontroller (80C196KB).The proposed control technique was tested on a BUCK converter in order to verify the theoretical forecasts. Simulated results confirm validity of experimental results.

2. Simulation Steps

MATLAB simulation toolbox is strong graphical software for analyzing of control systems. In the next sections simulation steps of the charging system are discussed. The system contains three important blocks, fuzzy controller, BUCK converter and the battery .The basic scheme of a general-purpose fuzzy controlled battery charger is shown in Figure. 1.

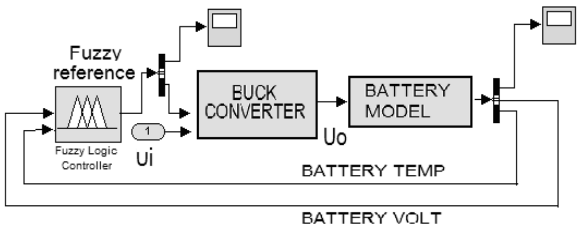


Figure 1: Basic block diagram of charging system

The converter is represented by the above given box from which we only extract the terminals corresponding to input voltage Ui, output voltage Uo, battery voltage V and battery temperature signal T .From these measurements, the fuzzy controller provides a signal proportional to the converter duty-cycle, which is then applied to a standard PWM modulator.

A. Battery simulation

There are many types of batteries used today for the storage and conversion of energy. All batteries can be defined as devices to convert energy. Ni-Cd batteries usually convert the energy by chemical reactions. High current batteries have thin sintered plates as electrodes. They are wound compactly in a roll and insulated conductive from each other by a porous separator .This structure is embedded in a cylindrical, solid steel casing and closed with a safety vent. The compact, rolled construction of the electrodes leads to a small internal impedance and the high-rated charge and discharge conditions. During charge and discharge, some chemical reactions take place on the positive nickel and the negative cadmium electrode. A typical nickel-cadmium cell consists of positive electrodes made from nickel-hydroxide (NiO(OH)) and negative electrodes made from cadmium (Cd) and immersed in an alkaline potassium hydroxide (KOH) electrolyte solution[8]. When a nickel-cadmium cell is discharged, the nickel hydroxide changes form (Ni(OH)2) and the cadmium becomes cadmium hydroxide (Cd(OH)2). The concentration of the electrolyte does not change during the reaction so the freezing point stays very low. Following are the electrochemical reactions for the flooded nickel-cadmium cell.At the positive plate or electrode:

$$2NiO(OH)+2H_2O+2e^- \Leftrightarrow 2Ni(OH)_2+2OH^-$$

At the negative plate or electrode:

$$Cd+2OH^- \Leftrightarrow Cd(OH)_2+2e^-$$

Overall nickel cadmium cell reaction:

$$Cd+2NiO(OH)+2H_2O \Leftrightarrow Cd(OH)_2+2Ni(OH)_2$$

Notice these reactions are reversible and that the elements and charge are balanced on both sides of the equations. The discharge reactions occur from left to right, while the charge reactions are reversed. Charging with high current can leads to overcharging of the cells. This is because of the limited current reception of the cells. The generated oxygen diffuses to the negative cadmium electrode and recombines. This reaction is exothermic, so that at the end of the charging process the temperature of the cell rises. The voltage of a cell rises only slightly during the process of charging. But just before reaching the full charge point, the voltage rises higher and then falls, because the temperature decreases the internal resistance. Battery characteristics play a dominant role in the Electrical Power System performance. Therefore, an accurate battery model, in simulation of power systems is required. The ideal equivalent model of the Ni-Cd battery consists of a simple voltage source [6], as shown in figure 2(a).This model does not reflect the physical characteristics of the battery since it's nonlinear behavior and internal parameters are ignored. The battery voltage in this model simply calculated as:

$$V_{bat}(t)=E_0 \tag{1}$$

A linear model is also suggested for Ni-Cd battery (Fig. 2(b)) that includes an internal resistance [6]. In this model the voltage source E_0 and internal resistance R are fixed and don't change with charge/discharge rates. The battery voltage is defined as:

$$V_{bat}(t)=R.I_{bat}+E_0 \tag{2}$$

The third circuit used to model the battery reactions is the Thevenin model. The model contains the electrical values of no-load voltage (E_0), internal resistance (R2) and a parallel R1, C circuit that incorporates the impact of over voltage conditions [6], as shown in figure 2(c). The battery voltage can be computed as:

$$V_{bat}(t)=R_2.I_{bat}+R_1.I_{bat}(1-e^{\frac{-t}{R1C}})+E_0 \tag{3}$$

Parameters: R_1 , R_2 , C and E_0 are computed using measurement characteristics. These parameters are fixed and don't change with charge current. Therefore, this model is not accurate for other charge currents. Figure 2(a, b and c) shows the above mentioned models.

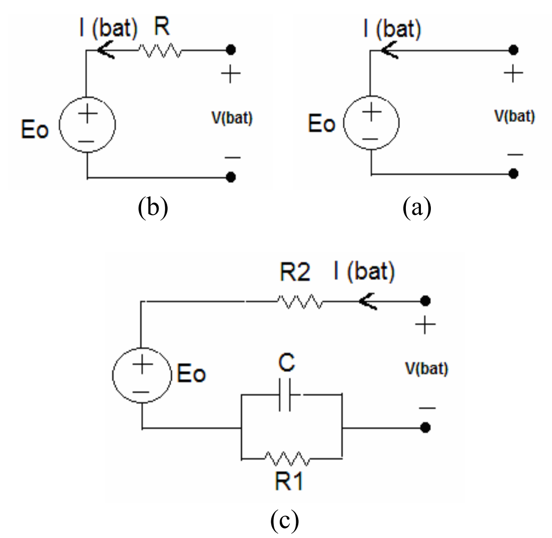


Figure 2: battery models

In this paper a dynamic model with variable parameters is investigated for Ni-Cd batteries [6]. The parameters variation depends on battery charge. This model is showed in Figure.3 The model components are designed according to the step response of battery voltage [6]. The dynamic model contains a series RC circuit in series with a parallel RC network and a constant voltage E_0, as shown in Figure.3 Therefore, battery voltage can be computed as:

$$V_b(t) = \Delta V_P(t) + R_1(t).I_{bat}(t) + V_{C1}(t) \qquad (4)$$

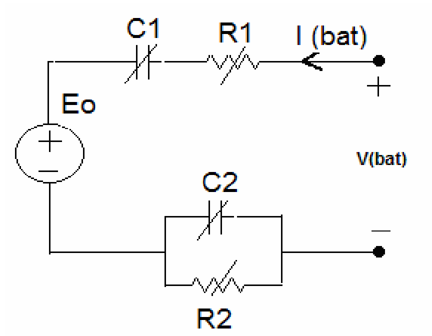


Figure 3: Dynamic model for Ni-Cd battery

In this model battery Parameters are extracted from measured characteristics [6].

$$\begin{aligned} R_1 &= R_{1O} + K_{R1}(I_{bat} - I_O) \qquad (5) \\ C_1 &= C_{1O} + K_{C1}(I_{bat} - I_O) \\ C_2 &= C_{2O} + K_{C2}(I_{bat} - I_O) \\ R_2 &= K_{R11}.I_{bat}^2 + K_{R12}.I_{bat} + K_{R13} \end{aligned}$$

Measurements show that R_1, C_1 and C_2 are linear functions of charge current, while R_2 changes nonlinearly with the rate of charge. I_{bat} Is charge current and I_0 is the biasing current level for computing parameters. R_{1O}, C_{1O} and C_{2O} are the values of R_1, C_1 and C_2 at I_0 respectively. Constants of K_{R1}, K_{C1} and K_{C2} are obtained from measurements at two charge rates (2C and C) while K_{R11}, K_{R12} and K_{R13} are computed from measured characteristics at three different charge rates (3C, 2C and C) [6].

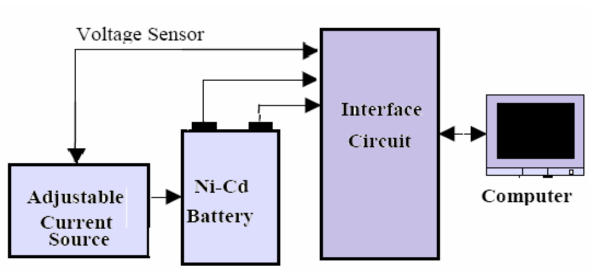


Figure 4: Measurement of battery parameters

Constant parameters of battery model for a 10 AH Ni-Cd battery obtained from measurement and presented in table 1.

Table 1: battery model parameters

Battery model parameter	Parameter value
C_{10}	178 (F)
C_{20}	345 (F)
R_{10}	0.058 (Ω)
K_{R11}	0.004 (Ω/A^2)
K_{R12}	-0.065 (Ω/A)
K_{R13}	0.23 (Ω)
K_{R1}	-0.015 (Ω/A)
K_{C1}	1265 (F/A)
K_{C2}	8.55 (F/A)

Figure.5 shows the nonlinear model diagram in SIMULINK. Parameters of modeled battery change according to charge current.

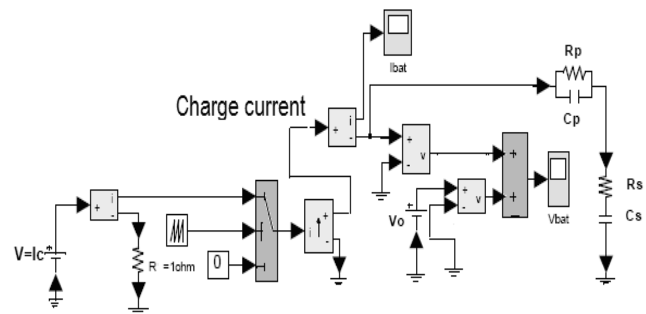


Figure 5: Battery nonlinear model diagram in Simulink.

B. BUCK converter simulation

In this section a BUCK dc-dc converter model is investigated. Figure 6 shows the simple circuit of this converter [11, 12].

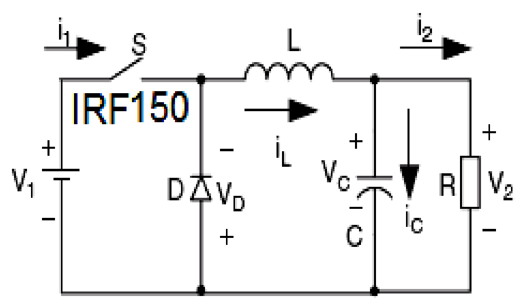


Figure 6: Basic circuit of BUCK converter

Figure.7 shows the exact simulated model for the BUCK converter which is given in figure 6. The parameters in figure 7 are extracted from experimental data and presented in table (2)

3. Simulation of Fuzzy Controller

The use of fuzzy logic and fuzzy systems for control has promised the development of powerful control strategies. These expectations can be explained by the linguistic representation of the control actions and the flexible nonlinearities that can be constructed with such systems. On the other hand, some limitations to the analysis of these control systems arise from the complex mathematical description of the nonlinearities. To explain the different part of fuzzy controller, a preliminary understand of Fuzzy controller structure is necessary. Following sections of paper provide details of designed fuzzy controller.

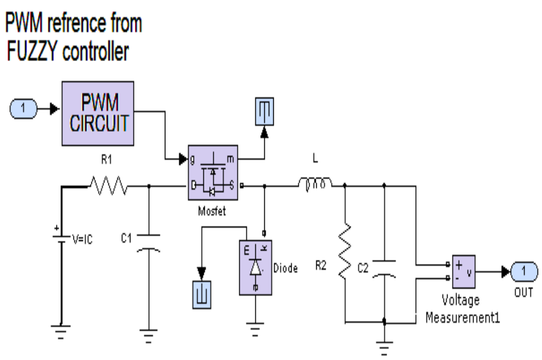


Figure 7: Simulated model for BUCK converter

Table 2: parameters of buck converter model

BUCK model parameter	Parameter value
L	5 mH
R1	0.75 Ω
R2	115 Ω
C1	3150 uf
C2	3480 uf

A. Basics of fuzzy control

Fuzzy Logic Control is one of the most successful applications of Fuzzy Set Theory, introduced by L.A. Zadeh in 1965. Its major features are the use of linguistic variables rather than numerical variables. Linguistic variables, defined as variables whose values are sentences in a natural language, may be represented by fuzzy sets [15]. The general structure of a fuzzy logic control is represented in Figure 1 and comprises four principal components [14, 15].

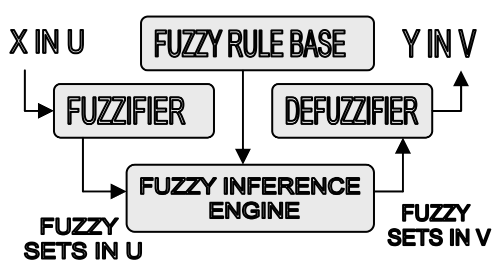


Figure.8: Basic configuration of Fuzzy controller

A Fuzzifier, which converts input data into suitable linguistic values; a fuzzy rule base, which consists of a database with the necessary linguistic definitions and the control rule set; a fuzzy inference engine which simulating a human decision process, that infers the fuzzy control action from the knowledge of the control rules and finally linguistic variable definitions; a Defuzzifier, which yields a nonfuzzy control action from an inferred fuzzy control action[14].The first step in the fuzzy controller definition is to select input and output variables. Block diagram of the fuzzy controller structure show that we have two input variable (battery temperature and output voltage) While the only output variable is charge current as an external signal to switch duty-cycle. Fuzzy controller is simulated in fuzzy toolbox of MATLAB software. Figure.9 shows simulated fuzzy controller.

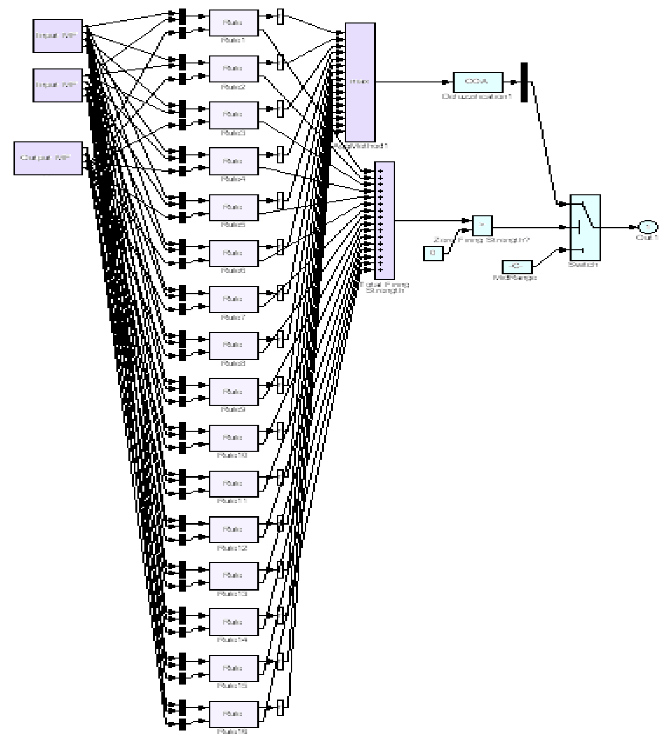
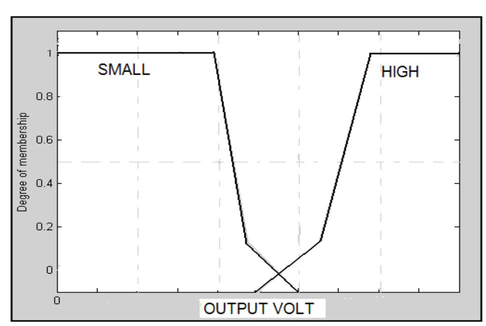


Figure.9: Block diagram of fuzzy controller

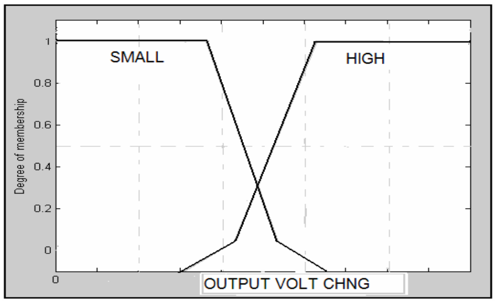
B. Membership functions

Fuzzy sets must be defined for each input and output variable. As shown in Figure 10, four fuzzy Subsets *(ZERO, SMALL, MEDUM, HIGH)* have been chosen for charge current while only two fuzzy subsets *(SMALL, HIGH)*, have been selected for the Battery temperature and voltage changes in order to smooth the control action. As shown in Figure 10, triangular and trapezoidal shapes have been adopted for the membership functions.

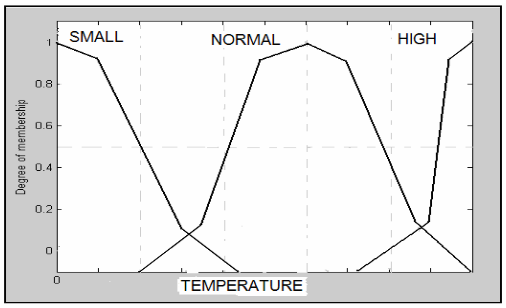
The value of each input and output variable is normalized in [-1, 1] by using suitable scale factors.



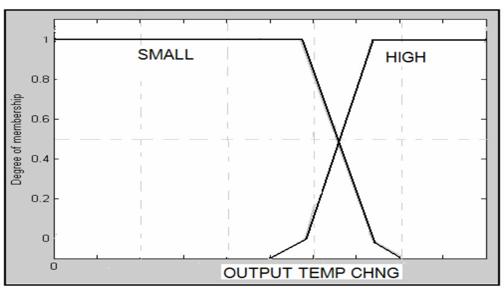
a- Battery voltage – U (V)



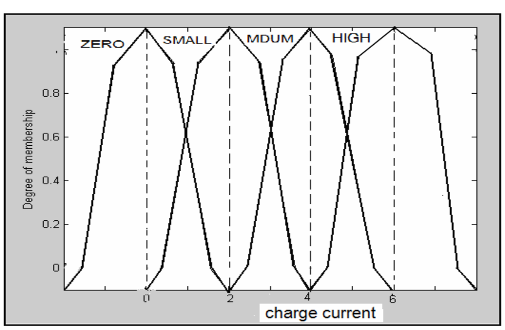
b- Battery voltage change- (dU/dt)



c- Battery temperature -T(C *)



d- Battery temperature changes- (dT/dt)



e- Battery current changes

Figure.10: Membership functions for .I, .U,.T

C. Derivation of control rules

Fuzzy control rules are obtained from the analysis of the system behavior. In their formulation it must be considered that using different control laws depending on the operating conditions can greatly improve the battery charger performances. The improved performances are the dynamic response and robustness. For instance, when the battery temperature is far from the set point (ambient temperature), the corrective action which is expected to reduce the duty cycle in order to have the dynamic response as fast as possible or when the battery voltage increases to high values, the output current would alter in order to perform the safe and smooth charge action and to prevent large overshoots. The selected control rules are described hereafter.

If T is SMALL then I is SMALL
If U is HIGH then I is ZERO
If T is HIGH and dT is HIGH then I is ZERO
If T is NORMAL and dT is SMALL then dU is HIGH then I is HIGH
If T is NORMAL and dT is HIGH then dU is HIGH then I is SMALL
If T is HIGH and dT is SMALL then I is MEDUM
If T is NORMAL and dU is HIGH then I is HIGH
If T is NORMAL and dU is SMALL then I is ZERO

In design of FLC parameters, there are no precise criteria to select gains, fuzzy set characteristics and fuzzy algorithm complexity. Only general guidelines for the design of the FLC can therefore be given. The fuzzy partition (number of terms for each input and output variable) and the membership functions shape may vary depending on the desired granularity of the control action. Obviously, increasing the number of labels of the input variables increases the number of rules needed to perform a proper control action. In general the universe of discourse for each fuzzy variable was normalized in [-1;1]. Scale factors greatly affect the bandwidth and the overall performance of the controller and some heuristic tuning can be used in order to improve charger performances. Note that, rules and membership functions are valid for any charger system. But in this case design of the scale factors should be done according to converter topology which is used as charger and the desired performances.

D. Fuzzy algorithm and software features

There are numbers of ways on how to define fuzzy implications. The fuzzy rules and the inference mechanism; criteria and properties can be found in the literature [14, 15]. The fuzzification process is done through fuzzy singletons, while the Mamdani's Max-Min method is used for inference process. Finally, the Center of Area method was selected for the defuzzification. With these choices the inferred value of the control action in correspondence to the value U and T is:

$$\Delta U = \frac{\sum_{l=1}^{m} \alpha_l W_l}{\sum_{l=1}^{m} W_l} \qquad (6)$$

Where W_l is singleton value of fuzzy output variable using the l[th] rule, and α_l is the degree of Fulfillment of the l[th] rule. Using the Min operator can be expressed as:

$$\alpha_l = Min\{\mu_{Al}(e), \mu_{Bl}(\Delta e)\} \qquad (7)$$

Where, Δe are the input fuzzy variables corresponding to the l^{th} rule

E. Tuning of control rules

Even though the proposed fuzzy control rules are general, some slight modifications can be done depending on desired performances. The rule modification can be accomplished by using the linguistic rules and adjusting some of them in order to optimize the system response in the linguistic phase plane. Control operation was verified by MATLAB simulation.

4. Experimental Results

The overall program is presented in a flowchart in figure 11. The scheme includes two basic sections. In the Software section, fuzzy inference process is performed and output variable is computed. This section also includes fuzzy logic data initializing process. The hardware section which includes several commands related to input and output data transfer from 80C196 Microcontroller.

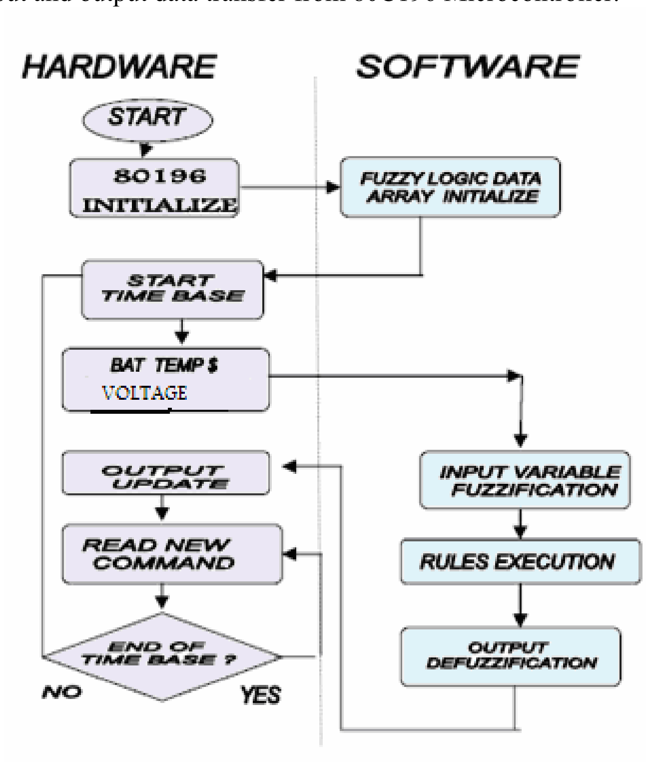


Figure 8: Fuzzy control software flowchart

The above program stored in the memory of the *80C196* microcontroller. The value of charge current as a nonlinear function of the input variables is easily computed via a fuzzy process. In the fuzzy controller block, signals of T and U are fed to analog-to-digital converters as Fuzzy input variables and a PWM signal as output reference. Hardware over current protection is also needed. Control operation was verified by a *BUCK* converter topology which is shown in figures 12 and 13 and is made in electrical laboratory of Islamic Azad University (Marvdasht branch) and experimentally tested. The results are reported and shown in figure.14.

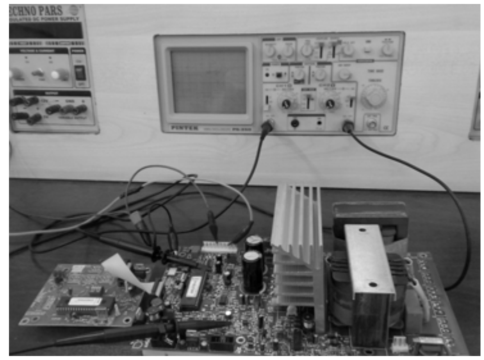


Figure 12: fuzzy controller implementation Marvdasht IAU electronic lab

The results illustrated in graphical forms, are the charge current, temperature and voltage of battery cells during the charge process. As indicated in these graphs there are two dash and solid line graphs in each picture. Dash lines show the practical results and solid lines belong to simulated responses. This fast and safe method is used to charge a set of Ni-Cd batteries and the charge time is 100 min and temperature during charge process doesn't exceed from 40°C which show better potentialities compared with other charge methods.

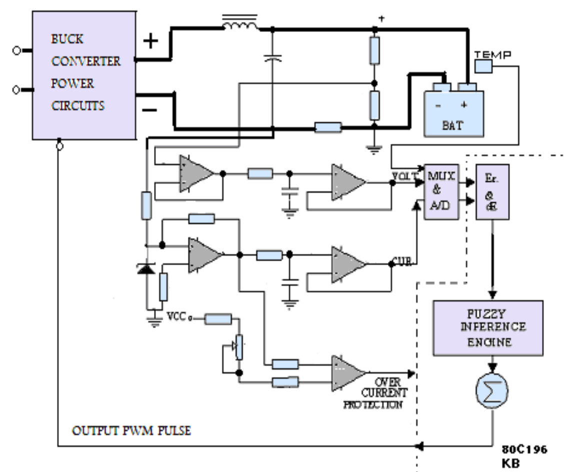
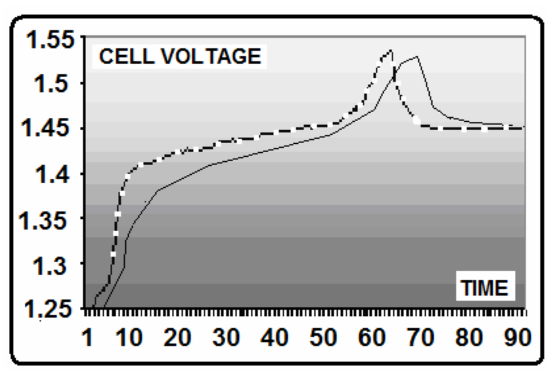
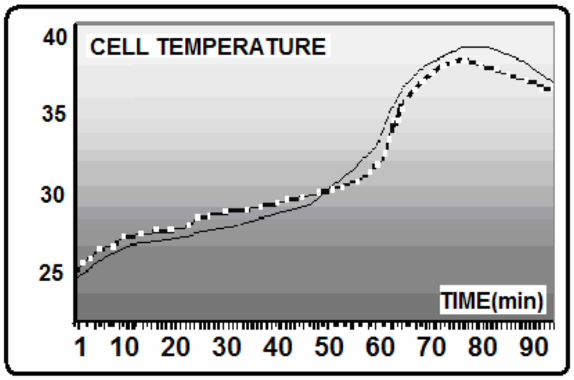


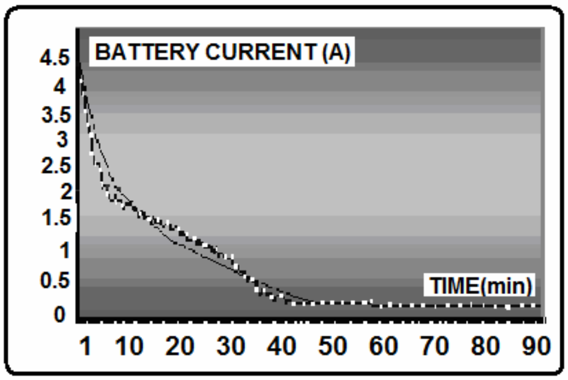
Figure 13: Control circuits of Fuzzy charger



a. Battery cell voltage during the charge process



b. Battery temperature during the charge process



c. Battery charge current during the charge process

Figure 14: charge current, voltage and temperature

5. Conclusion

As a final result, it is shown that fuzzy controller provides a safe and stable charge process with optimized time and acceptable temperature variations. This fast and safe method is used to charge a set of Ni-Cd batteries and the charge time is 100 min and temperature during charge process doesn't exceed from 40°C.This system can be used to charge batteries with different characteristics because of it's independence to state variables and system model. The system has also online over current protection circuit, which prevents the battery from destruction. The simulation results also confirmed experimental responses.

Refrences

[1] D.C.Bandara,Ratcho Ivanov, Stoyan Gishin,"Intelligent Fuzzy Controller for a Lead-Acid Battery Charger",2"d European Symposium on Intelligent Techniques, ESIT99, Crete, Greece**,** pp.80, 1999.

[2] P.D. Ionescu, Mihuelo Mosculu, A. Moscalu" Intelligent charger with fuzzy logic"

[3] Hartmut Surmann "Genetic Optimization of a Fuzzy System for Charging Batteries" IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, VOL **43,** NO *5*, OCTOBER *1996*

[4] A **Fuzzy** Logic Based Rapid Battery Charger for Nickel-Cadmium Batteries," Proceedings of the HiPC 2002 Workshop on **Soft** Computing (WOSCO'O~)B, angalore, India, pp. 9-14.

[5] B. J. R. Hodge, R. Bonnaterrk, and F. Putois, "Fast charging of sealed Nickel-Cadmium batteries: Theory and practice," in Int Symp. Power Sources, 1974.

[6] Mohammad A.S. Masoum Mohammad Sarvi "A Nonlinear Electrical Model for Ni-Cd Batteries"

[7] "Mathematical modeling of nickel-cadmium batteries," ***J. Electrochem.Soc.***, vol. 183, no. 10, pp. 2952-2960, Oct. 1991.

[8] Sealed Type Nickel-Cadmium Batteries-Engineering Handbook, Sanyo Electric Co. Ltd., 1990.

[9] T. R. Crompton, Battery Reference Book. London, U.K.: Butterworth,1990.

[10] Nickel-Cudmium Batreries-Technical Handbook. Panasonic Co. Ltd., 1992.

[11] M. H. Rashid, Power Electronics, 2nd ed., Prentice-Hall, Englewood Cliffs, NJ, 1993.

[12] N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics:Converters, Applications and Design, 2nd ed., John Wiley & Sons, New York, 1995.

[13] R. Erickson, Fundamentals of Power Electronics, Chapman and Hall, New York, 1997.

[14] R. R. Yager, "On a general class of fuzzy connectivities," Fuzzy Sets and Systems, vol. 4, pp. 235-242, 1980.

[15] H. J. Zimmermann, Fuzzy Set Theory and **Its** Applications, 2nd ed. Norwell, MA: Kluwer, 1990.

[16] A. I. Pressman, Switching Power Supply Design, 2nd ed., McGraw-Hill,New York, 1998.

[17] A. M. Trzynadlowski, Introduction to Modern Power Electronics, Wiley Interscience, New York, 1998.