Fuzzy, ANFIS and ICA Trained Neural Network Modeling of Ni-Cd Batteries Using Experimental Data

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Abstract: Nowadays, because of the many applications of batteries, modeling of this energy sources and accurate estimation of their behavior at different conditions is very important. In the traditional linear mathematical based models of batteries, nonlinear behavior of them and the variation of battery voltage during charge and discharge states are neglected. But various nonlinear physical, chemical and electrochemical factors should be considered to achieve accurate battery model. However, this is very difficult or even impossible to calculate that factors. Therefore, in this paper, in order to provide more accurate model and correct estimation of battery voltage during charge states, three nonlinear modeling methods named Fuzzy Logic, Adaptive Neuro Fuzzy Inference System (ANFIS) and Imperialist Competitive Algorithm (ICA) trained Neural Network are proposed for Ni-Cd battery modeling. The main advantage of the proposed models is that they can predict battery output voltage with no knowledge of numerous factors. In order to collect the required data for training of proposed models and to compare models by actual data, experimental data obtained from tests on a 7Ah, size F, Ni-Cd battery at different charge current. Simulation results are compared with the measured battery data at different charge current. The simulations show good agreements with measured data. Also the proposed models can use for other battery types.

Keywords: Ni-Cd Battery, Modeling, Fuzzy, ANFIS, ICA trained Neural Network.

I. INTRODUCTION

Nowadays, batteries as a clean, low size and portable energy source are very attractive for researchers and industrialists. Accordingly, accurate design and correct use of the batteries can have a significant role in improving the performance of them. Hence, modeling of battery and accurate estimation of its behavior at different conditions now play an important role in the design and use of batteries. Various linear models for batteries have been proposed which most of them are based on mathematical equations [1-5]. Though, due to the physical, chemical and electrochemical interactions that occur in batteries, comprehensive studies needed to model them. On the other hand, according to the nonlinear relations between the different parameters in the battery, accurate modeling of batteries performance is very difficult, time consuming or even impossible. Therefore, in this paper, three nonlinear modeling methods have been proposed to model a Nickel Cadmium (Ni-Cd) battery as a case study. Ni-Cd is a rechargeable battery which converts chemical energy to electrical energy upon discharging and converts electrical energy back to chemical energy upon charging. Because of the structural materials they use, Ni-Cd is exceptionally robust, and exempt from risk of sudden failure. Also Ni-Cd batteries have several advantages over other battery chemistries in use today such as: ability to take a fast charge (about 15 minutes), wide temperature range (Up to 70°C) and flat discharge characteristic and etc [6]. In this paper, the modeling of Ni-Cd battery by artificial intelligent methods has been proposed. In the first step, fuzzy logic modeling methodology has been proposed. Fuzzy logic is an effective tool for the approximation of uncertain and complex nonlinear dynamic systems that are otherwise difficult to model, on the basis of measured input-output data [7-10]. At the second step, Adaptive Neuro Fuzzy Inference System (ANFIS) for modeling of Ni-Cd battery using experimental data has been proposed. ANFIS is a kind of neural network that is based on Takagi–Sugeno fuzzy inference system [11-13] which integrates both neural networks and fuzzy logic principles. Contrast to fuzzy systems which require to expert system, the ANFIS approach learns the rules and membership functions from data. In fact, ANFIS is an adaptive network. In the third step, Neural Network (NN) is used to model Ni-Cd battery. The neural network is well established tools used with success in many problems. Parameters and structure of network impresses its performance, so determination of network structure and parameters are very important to find the best model. Currently, many evolutionary algorithms
have been proposed in this regard [14-16]. To introduce a new top model, in this paper a Multilayer Perceptron (MLP) neural network was trained using Imperialist Competitive Algorithm (ICA) has been presented to model Ni-Cd battery. ICA is a computational method that is used to solve different types of optimization problems [17]. ICA is used for optimizing the weights of multilayer perceptron. In comparison with other this evolutionary optimization strategy has shown great performance in both convergence rate and better global optima achievement [20]. More details about this algorithm are presented in the section 4-3. Finally, to compare the proposed models with actual results a 7Ah, size F, Ni-Cd battery has been tested. The results show that simulations values are very close to the actual values. Inputs of the proposed models are battery current (I_{bat}) and battery state of charge for fuzzy model while battery current (I_{bat}), no load voltage and time (t) of charge are inputs of both ANFIS and ICA NN model, also for all of models battery voltage (V_{bat}) is selected as the output. Generally, since the nonlinear electrochemical characteristics and dependency on charging current are also available in other types of batteries, like Nickel-Hydrogen [19], Lithium-Ion [20] and Lead-Acid [21] batteries, the proposed models can also be used for all of this battery types.

This paper is organized as follows: in section 2, the Ni-Cd battery has been introduced. In section 3, the experimental setup described briefly. In section 4, artificial intelligence techniques which have been used in this paper, are presented separately. In section 5, the simulations results which have been performed in MATLAB software and measurement results are compared. Finally, the conclusions are presented in section 6.

II. Ni-Cd Battery

Nickel Cadmium (Ni-Cd) battery is a rechargeable battery which nowadays, commonly used in many applications such as: portable phones, TVs, tape players, shavers, memory back-up, security system, toys and power tools [6]. They also are used in aviation, rail and mass transit, satellites, backup power for telecoms and etc [22-23]. This battery uses nickel oxide in cathode, a cadmium compound in anode, and potassium hydroxide solution in electrolyte. The overall cell reaction is:

\[ 2\text{NiOOH} + \text{Cd} + 2\text{H}_2\text{O} = 2\text{Ni(OH)}_2 + \text{Cd(OH)}_2 \] (1)

When it is charged or discharged, basically it won’t consume electrolyte, but the electrode can absorb or release water. Ni-Cd cells have a nominal cell potential of 1.2 volts (V) and during charging, the battery temperature typically stays low (around 0°C), but around the battery full charge the temperature will rise to 45–50°C [6].

III. The Experimental Setup

To collect the required data for training the neural network and ANFIS system and compare the proposed models with actual values, an experimental setup is used, as shown in Figure 1. This system includes an adjustable current source, a personal computer, an interface circuit and a 7AH Ni-Cd battery manufactured by SANYO.

![Figure 1](image-url) The experimental setup used to measure battery characteristics.

The interface circuit sample battery voltage during charging time and stores data in the personal computer. For different charge current, the battery output voltage is measured at different times with a time step of 500 seconds during one hour.
IV. ARTIFICIAL INTELLIGENCE BASED BATTERY MODELING

In this section, three artificial intelligence based battery modeling includes Fuzzy Logic, Adaptive Neuro Fuzzy Inference System and Imperialist Competitive Algorithm trained Neural Network are presented.

IV.1 Fuzzy Logic based Modeling

The theory of fuzzy sets was pioneered in 1965 by Lotfi A. Zadeh [24]. Fuzzy systems can serve different purposes, such as modeling, data analysis, prediction or control. A fuzzy system employing fuzzy if-then rules can model the qualitative aspects of human knowledge and reasoning processes without employing precise quantitative analysis. In this paper, Mamdani Fuzzy system has been used to model a Ni-Cd battery. The idea behind using a Mamdani rule base to model crisp system behavior is that the rules for many systems can be easily described by humans in terms of fuzzy variables.

Inputs of the proposed fuzzy model are battery current ($I_{bat}$) and state of charge ($SOC$) while battery voltage ($V_{bat}$) is selected as the output. As a function of battery current and time ($t$) $SOC$ is expressed as follows:

$$SOC = SOC_0 - \frac{1}{C_N} \int_0^t \delta(I) I_{bat} dt$$

where $SOC_0$ is the nominal $SOC$, $C_N$ is the nominal or rated capacity, $I_{bat}$ is the battery current, and $\delta(I)$ is the current loss coefficient (typically 0.98–1). The fuzzy variables are expressed by linguistic variables “positive big” or (PB), “positive medium” or (PM), “positive small” or (PS), “zero” or (ZZ), “negative small” or (NS), “negative medium” or (NM), and “negative big” or (NB). The membership functions of SOC have seven fuzzy subsets and the membership functions of $I_{bat}$ have five fuzzy subsets. The fuzzy sets of membership functions for the input variables are as shown in the Fig.2.a and Fig.2.b. Also seven triangle membership functions is considered for output variable ($V_{bat}$). The range of the output variable must be divided up into various membership functions. Figure.2.c shows the output membership functions.

Fuzzy rules are usually expressed in the form: IF variable IS property THEN action which maps an input space to an output space. Table 1 shows the rules have been designed in this paper for Ni-Cd battery modeling.

Table 1: Fuzzy logic rules.

<table>
<thead>
<tr>
<th>SOC</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZZ</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>PB</td>
<td>PB</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PM</td>
<td>PB</td>
</tr>
<tr>
<td>NS</td>
<td>PB</td>
<td>PM</td>
<td>PM</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
<td>PS</td>
</tr>
<tr>
<td>ZZ</td>
<td>PB</td>
<td>PM</td>
<td>PS</td>
<td>ZZ</td>
<td>ZZ</td>
<td>ZZ</td>
<td>ZZ</td>
</tr>
<tr>
<td>PS</td>
<td>PB</td>
<td>PS</td>
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<tr>
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<td>PB</td>
<td>PS</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>NM</td>
<td>PB</td>
</tr>
</tbody>
</table>

IV.2 ANFIS based Modeling

ANFIS can be used in modeling, similar to other artificial intelligence methods such as NNs and Fuzzy Logic. In this paper, the designed ANFIS is utilized as a model for Ni-Cd battery. In the study of ANFIS based modeling of Ni-Cd battery, the model structure is combined of Takagi, Sugeno fuzzy inference system and neural network. There are two input variables in the ANFIS model established in this paper as shown in Figure 3. First one is battery charge current, and the second is charging time where it consists of five generalized bell membership functions on first input (current) and also five generalized bell membership functions on other input (time). Fig.4 shows the ANFIS structure to the system under study (after training).

![Figure 3. Structure of the ANFIS](image1)

The hybrid learning algorithm is used in this study. In the algorithm, parameters are epoch size, error tolerance, initial step size, step size decrease rate, and step size increase rate. A number of data are used for testing a different number of data is used for training of data recognition. Figure 4 shows the comparisons of the measured and simulated values for testing of data set.

![Figure 4. Comparisons of the measured and simulated values for testing of data set.](image2)
IV.3 ICA Trained Neural Network based Modeling

As an artificial intelligent technique, neural network is viewed as universal approximation for any nonlinear function. However, finding the optimal value of the weights for each node by tried and error approaches, are very time consuming and uncertain. During the evolution, the architecture of the neural network is reconstructed and then fixed, so optimal value for weights of neural network can find using by an optimization algorithm. In this paper, Imperialist Competitive Algorithm (ICA) algorithm is used for optimization of the weights for each node. ICA has been proposed by Atashpaz-m Gargari and Lucas [9], in 2007 which has inspired from a socio-political phenomenon. Figure.5 shows the flowchart of the ICA. As shown in this figure, the flowchart ICA like other evolutionary algorithms starts by generating an initial population which is known as Countries. A country contains types of: colonies and imperialists which together form empires. The cost function of the optimization problem determines the power of each country. Countries that have more power will be Imperialists and will form Empire. Other countries would be Colonies that are controlled by Imperialists. Three main operators of this algorithm are Assimilation, Competition and Revolution. Imperialistic competition among these empires forms the proposed evolutionary algorithm. During assimilation and revolution, a colony might reach a better position and has the chance to take the control of the entire empire and replace the current imperialist state of the empire. Also during competition the weakest empires collapse and stronger ones will get more potency. At the end only one imperialist will remain when the position of imperialist and its colonies will be the same.

![Flowchart of the ICA](image)

**Figure.5.** The flowchart of the ICA.

In this paper, the number of colonies are assumed to be $N_c = 100$, and the number of initial imperialist are assumed to be $N_p = 10$ also the stopping criteria is defined as reaching to the maximum number of iterations (Max Iteration=1000) and when no more than one imperialist exists in the search space. Figure.6 shows the network output versus real output for test data which correlation value is equal to 0.9874.
In this section, comparisons of simulated results and measured data are presented for three proposed models. At the first step, in order to investigate the accuracy of the proposed models, for two different charge current (I=4 A and I= 6 A) simulation results are compared with measured results as shown in Figure 7. These data are used in training process of ICA neural networks and ANFIS system. As shown in this figure, the simulation results are very close to the measurement results. The results also show that output of the fuzzy system has appropriate coordination with the measured results. The advantage of the fuzzy model compared to two other proposed models, is that fuzzy model not require to large number of accurate measured data and this model is easier to implement.
At the next step simulations done for new set of data (I=3.25 A and I=5.25 A) which did not involved in the training of the neural network and ANFIS modeling. The outputs of proposed models with the measured results are shown in Figure 8. As is clear from this figure, all three models can predict the behavior of battery with very good accuracy.

At the last step of this section, in order to compare the proposed models, the mean values of difference between the measured data and simulated data for different charge current are presented in Table 2 where:

\[ \text{Error} = |\text{Measured} - \text{Simulated}| \]  \hspace{1cm} (3)

Calculations show that ANFIS and ICA trained neural network approximately have equal error and in comparison with fuzzy model are more accurate.

![Comparison of simulated and measured battery voltages at different charge rates](image)

**Table 2.** Mean of errors between measured and simulated data.

<table>
<thead>
<tr>
<th>Battery Current</th>
<th>ANFIS</th>
<th>ICA trained NN</th>
<th>Fuzzy</th>
</tr>
</thead>
<tbody>
<tr>
<td>I=4(A)</td>
<td>0.00023</td>
<td>0.00025</td>
<td>0.00230</td>
</tr>
<tr>
<td>I=6(A)</td>
<td>0.00012</td>
<td>0.00012</td>
<td>0.00189</td>
</tr>
<tr>
<td>I=5.25(A)</td>
<td>0.00142</td>
<td>0.00139</td>
<td>0.00182</td>
</tr>
<tr>
<td>I=3.25(A)</td>
<td>0.00129</td>
<td>0.00153</td>
<td>0.00215</td>
</tr>
</tbody>
</table>

**VI. CONCLUSION**

The subject of this paper was to introduce three models based on artificial intelligence techniques for Ni-Cd batteries and to investigate its accuracy through different measurements. Fuzzy logic, Adaptive Neuro Fuzzy Inference System and Imperialist Competitive Algorithm trained Neural Network was presented in this paper which can predict battery output voltage with no knowledge of numerous nonlinear physical, chemical and electrochemical factors. Comparisons of
computed and measured results show very good agreements and demonstrate the high accuracy of the proposed models for a 7AH Ni-Cd battery. The proposed models can also be used for all of battery types, because the nonlinear behavior is also common in other types of batteries. In comparison of the proposed models with each other, both ANFIS and ICA trained NN models were more accurate than fuzzy model when fuzzy has this advantage that does not require many experimental data.

REFERENCES