POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

A Microcontroller Based Fuzzy Logic Controller Development for the Float Current Analysis of Batteries

TESI MAGISTRALE IN ENERGY ENGINEERING – INGEGNERIA ENERGETICA

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Academic Year: 2022-2023

1. Introduction

The study aimed to improve an electronic test equipment, so-called Floater, for the investigation of the ageing process of lithium-ion batteries by developing and implementing a new control algorithm to measure the float currents of various lithium-ion battery types and to shorten the duration of the tests. The project was conducted at the ISEA Institute of RWTH Aachen University. The study had two primary objectives, namely, to eliminate the manual efforts required to tune the proportional-integral-derivative (PID) controller gains and minimize test durations. A new intelligent self-tuning controller was developed to replace the previous conventional PID controller, and an automatic setpoint designation feature (namely auto-setpoint feature) was introduced being optional on the operator's preference.

The study's first phase involved developing an intelligent self-tuning controller. A fuzzy logic based proportional-integral (PI) controller was determined to be more appropriate for the control task. The next phase was to conduct experimental tests with the new controller implemented on the Floater's microcontroller. The results indicate that the proposed algorithm significantly reduces the duration of the tests using auto-setpoint feature to phase out the manual assigning of the voltage setpoint. The new algorithm also eliminates the need for manual tuning of the controller gains, making the process more efficient and cost-effective. The exclusion of the manual tuning not only did not compromise the voltage control performance of the Floater, but also improved the float current analysis results by reducing the fluctuations in charging current readings.

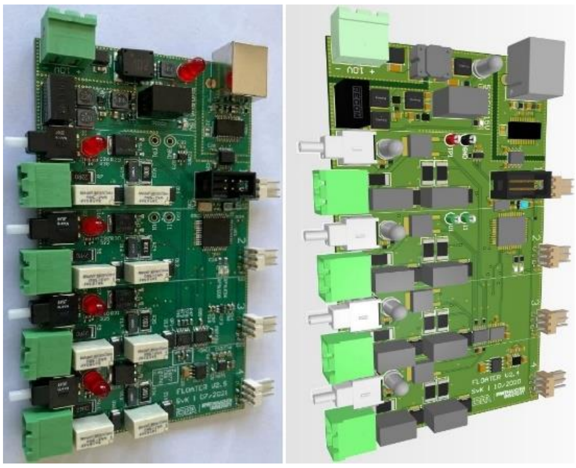

Figure 1: Manufactured and 3D model of Floater test device [1]

2. Methodology

This section describes the design process of a control algorithm for the Floater, the float current analysis test equipment. Figure 1 shows the manufactured and the 3D model of the Floater test device. The Floater test device is used to regulate the charging current of the battery cell to minimize voltage deviation from the setpoint voltage.

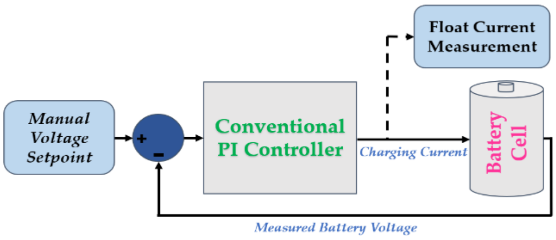

Figure 2: Floater's previous controller configuration: PI controller

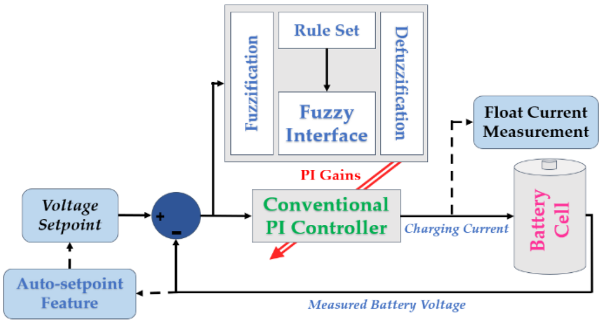

Figure 3: Floater's new controller configuration: Fuzzy+PI controller

The first objective was to replace the previous conventional PI controller with an intelligent self-tuning Fuzzy+PI controller to address the difficulty in tuning and optimizing the PI controller gains required for each battery type. Figure 2 and Figure 3 show the previous conventional and the new fuzzy logic-based PI controller configurations, respectively.

The Floater's brain is an Atmel ATmega324P microcontroller model which is relatively simple to configure [2]. However, its processing capability must be carefully considered since it lacks performance compared to higher bit microcontrollers [3]. The Fuzzy+PI controller was preferred because it does not require a model of the system under control, which is advantageous for systems where obtaining a dynamic model is difficult or computationally expensive.

The Fuzzy+PI controller takes the error and error change as inputs and outputs the k_P and k_I gains. The design process involved choosing the membership functions for the inputs and outputs, defining the rule set, and selecting the defuzzification method. The weighted average defuzzification method was chosen based on the requirement to keep the computational load as low as possible [4]. Overall, the intelligent self-tuning Fuzzy+PI controller proved to be an effective control system choice for regulating the charging current in the Floater test device.

One critical aspect of designing a fuzzy control system is defining the rule set that governs the system's behavior. Since the system has two outputs, namely k_P and k_I gains, a fuzzy rule set in the form of two different charts were developed. Each chart was structured as a 5 by 3 linguistic matrix, reflecting the five membership functions of the first input, the error, and the three membership functions of the second input, the error change. The resulting fuzzy logic rule set charts for the electronic test equipment is presented in Table 1 and Table 2.

k_P		Error				
		NB[1]	NS	ZO	PS	PB
Error Change	N[2]	Z[3]	S	S	M	L
	Z	Z	S	S	M	L
	P	Z	S	S	M	B

Table 1: The rule set chart for k_P output

k_I		Error				
		NB	NS	ZO	PS	PB
Error Change	N	Z	Z	S	S	M
	Z	Z	S	S	M	L
	P	S	S	M	L	B

Table 2: The rule set chart for k_I output

Figure 4 and Figure 5 displays the fuzzy control surfaces for the k_P and k_I outputs, respectively, depicting their variation in response to changes in the input variables based on the rule set charts for the respective output. These graphs provide a

[1] **NB**: negative big / **NS**: negative small / **ZO**: zero / **PS**: positive small / **PB**: positive big

[2] **N**: negative / **Z**: zero / **P**: positive

[3] **Z**: zero / **S**: small / **M**: medium / **L**: large / **B**: big

visual representation of the control system's response to different input combinations, aiding in the understanding and optimization of the system's behavior.

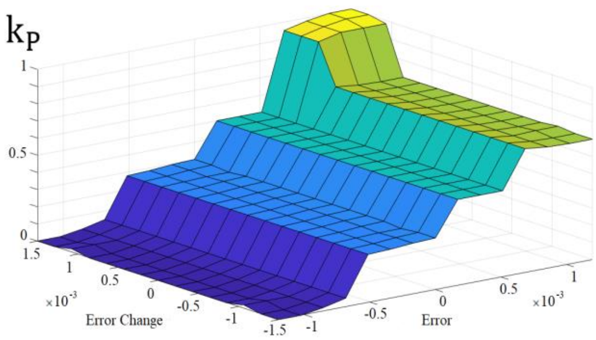

Figure 4: Fuzzy control surface for k_P output

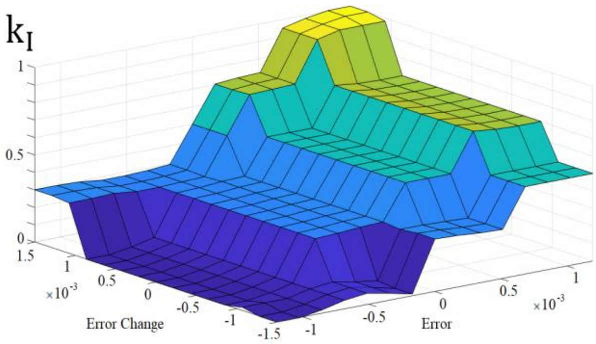

Figure 5: Fuzzy control surface for k_I output

Following the design and development of the fuzzy logic controller, the next crucial step was to convert the algorithm into executable code for the microcontroller using the C++ programming language. This process involved translating the algorithm's rules and membership functions into code, defining the inputs and outputs, performing defuzzification, incorporating denormalization, etc. Once the code was written, it was tested and debugged before being uploaded onto the Floater device using a Raspberry-Pi 3 computer module.

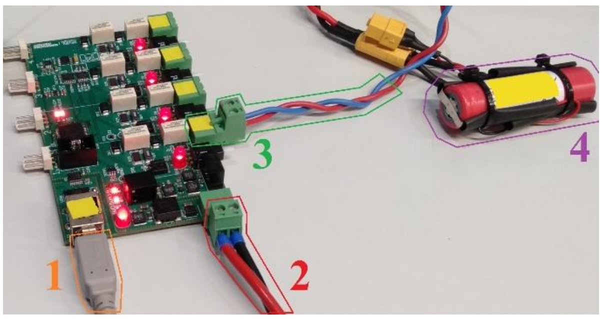

Figure 6: Floater's connections to: (1) Raspberry-Pi 3, (2) power supply, and (3) battery cell, and (4) the cylindrical lithium-ion battery cell itself

The setup for the experimental tests consisted of the Floater device, one or more battery cells, a power supply module, and a Raspberry-Pi 3 computer module. Figure 6 shows the Floater device and its connections to (1) the Raspberry-Pi 3, (2) the power supply, and (3) the battery cell. The experimental tests were performed in the laboratory where the battery cell(s) being contained inside an oven to run the tests under specified ambient temperature, i.e., 25°C. During the experimental tests, the performance of the fuzzy controller algorithm was evaluated. The results of the test were logged, including the charging current (which is called the float current in the steady-state region) and the battery voltage to be subsequently analyzed to determine the effectiveness of the fuzzy controller algorithm in regulating the charging current while keeping the cell voltage constant.

3. Results

The evaluation of the results will be conducted in two areas. The first area is the performance comparison of the Fuzzy+PI controller and the conventional PI controller. The second area is the impact of the auto-setpoint feature on the duration of the experimental tests.

3.1. Fuzzy+PI vs. Conventional PI controller

In this section, the test results of the newly developed self-tuning Fuzzy+PI controller will be compared to those obtained from the previously used conventional PI controller. The voltage readings and the corresponding charging currents obtained from both controllers will be analyzed and compared in terms of their standard deviations. Additionally, the time required for manual tuning of the conventional PI controller will be discussed.

For the sake of comparison, four experimental tests were conducted on two different types of battery cells. The first two tests were performed using the conventional PI controller with manual tuning, where the setpoint was appointed manually by measuring the initial voltages of the battery cells. The setpoint values were chosen to be very close to the measured voltages, with initial errors ranging from 2 to 3 mV. The other two tests were conducted using the Fuzzy+PI controller with the auto-setpoint feature on the same battery cells. All four tests were carried out in a thermal oven to maintain a constant temperature of 25°C throughout the duration of the tests, which were run for 24 hours. The test parameters for all four experimental tests are presented in Table 3.

#	Test Type	Setpoint Setting	Initial Voltage	Setpoint Voltage	Initial Error
1	**Conv. PI LIB type A**	Manual	3.66100 V	3.664 V	**3000 μV**
2	**Conv. PI LIB type B**	Manual	3.64300 V	3.645 V	**2000 μV**
3	**Fuzzy+PI LIB type A**	Auto-setpoint	3.66518 V	3.6652 V	**20 μV**
4	**Fuzzy+PI LIB type B**	Auto-setpoint	3.64658 V	3.6466 V	**20 μV**

* *Tests were conducted under ambient temperature of 25°C*

Table 3: Test parameters for the experimental tests

The figures present the data recordings on charging currents, voltages, and corresponding error values.

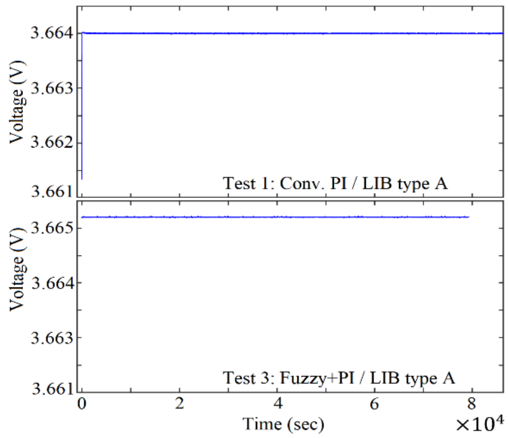

Figure 7: Voltage readings for Test 1 and 3

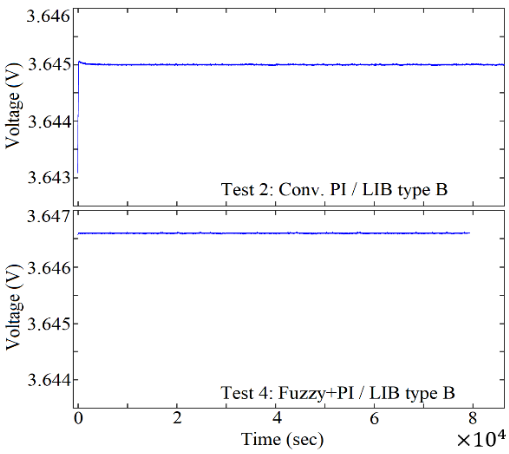

Figure 8: Voltage readings for Test 2 and 4

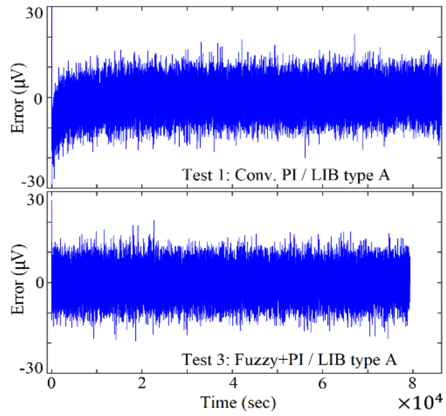

Figure 9: Error values for Test 1 and 3

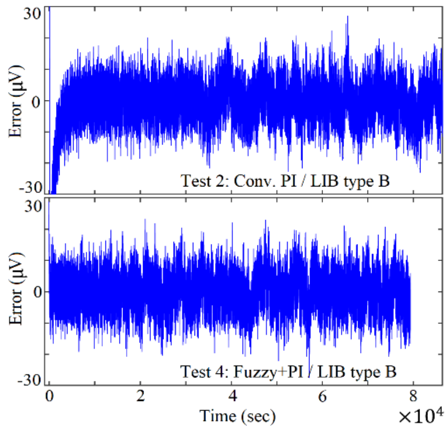

Figure 10: Error values for Test 2 and 4

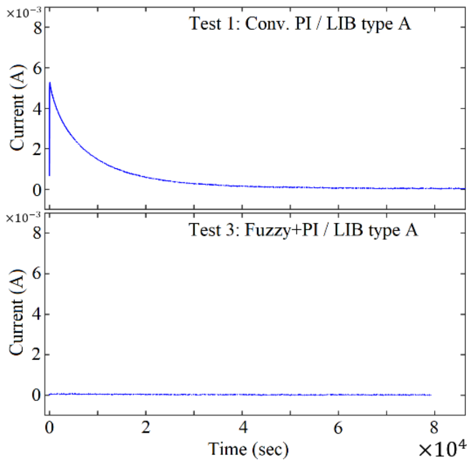

Figure 11: Current readings for Test 1 and 3

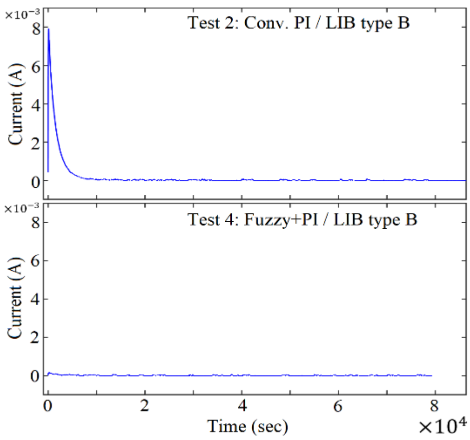

Figure 12: Current readings for Test 2 and 4

One striking observation is the impact of manually appointed setpoints on the charging current. While the initial errors in the range 2 to 3 mV may seem very small, in the upper plots of Figure 11 and Figure 12 (Test 1 and 3), the charging current initially increases to high values then decreases to overcome the transient phase. In contrast, in the lower plots of Figure 11 and Figure 12 (Test 2 and 4), the charging currents are almost within the steady-state region because of the auto-setpoint feature, which maintains a smaller initial error of 20 μV. The impact of the auto-setpoint feature will be elaborated on further.
To compare the performance of the two controllers, the standard deviation in the readings was used as a metric. For voltage readings, the comparison was straightforward by neglecting the first few hours to eliminate the effect of higher initial errors for the conventional PI controller with manual setpoint. For the sake of fair comparisons on the current readings, not only was the data on the first a few hours neglected, but also a high-pass filter was applied to the charging current readings to phase out the effect of the decreasing trend.

#	Test Type	Voltage std.	Change	Maximum Error Range	Initial Error
1	**Conv. PI LIB type A**	4.5601 μV	**almost zero (-0.19%)**	40.75 μV	**-13.40%**
3	**Fuzzy+PI LIB type A**	4.5516 μV		35.29 μV	
* *Data in the first approx. 9 hours is neglected.*					
2	**Conv. PI LIB type B**	5.6124 μV	**almost zero (+0.29%)**	50.21 μV	**almost zero (+1.45%)**
4	**Fuzzy+PI LIB type B**	5.6287 μV		50.94 μV	
** *Data in the first approx. 4 hours is neglected.*					

Table 4: Performance comparisons for voltage and corresponding error readings

The results in Table 4 indicate that the voltage control performance of both controllers was almost identical, with a difference of approximately 1% in the standard deviations of the voltage readings and the maximum range of error fluctuations, except for tests conducted on battery type A, where the maximum range of fluctuation was found to have improved by 13.4%. In other words, the voltage control performance of the new Fuzzy+PI controller did not deteriorate compared to that of the previous conventional PI controller.

#	Test Type	Maximum Error Range	Initial Error
1	**Conv. PI LIB type A**	10.2889 μA	**-25.18%**
3	**Fuzzy+PI LIB type A**	7.6981 μA	
* *Data in the first approx. 9 hours is neglected.*			
2	**Conv. PI LIB type B**	15.5213 μA	**-10.83%**
4	**Fuzzy+PI LIB type B**	13.8406 μA	
** *Data in the first approx. 4 hours is neglected.*			

Table 5: Performance comparisons for charging current readings

In contrast, the analysis of Table 5 indicates a significant difference in the standard deviations of the charging current readings between the two controllers. Specifically, the Fuzzy+PI controller outperformed the conventional PI controller in regulating charging current for battery types A and B, improving the standard deviation by 25.18% and 10.83%, respectively. The results are especially relevant as fluctuations in charging current readings are essential to measure accurately in the experimental tests. Thus, the improvement in charging current regulation by the Fuzzy+PI controller is of considerable importance, as it helps reduce the fluctuations in the readings, leading not only to more precise results in float current analysis, but also to reduce test time durations in order to gain the same amount of required adequate data stream.
Another notable advantage of the new Fuzzy+PI controller over the conventional PI controller is the elimination of the manual effort required to tune the controller gains for each battery cell being tested. Tuning the controller gains manually is a time-consuming process and can be highly tedious, as it often involves a trial-and-error approach. Typically, the tuning process for a battery cell requires at least three trials, each lasting between 4 to 8 hours. The new Fuzzy+PI controller eliminates the need for such a tuning step, resulting in significant savings in time, effort, and costs.

3.2. Auto-Setpoint Feature

This section aims to analyze the impact of the auto-setpoint feature and its advantages in the float current analysis tests on lithium-ion battery cells. The importance of setting an accurate initial error, even at the scale of a few millivolts, cannot be overemphasized, as it has a significant impact on the duration of the test. Manual voltage measurement using a multimeter to define the voltage setpoint on each battery cell is a tedious procedure and the tests can take a large amount of time to overcome the transient phase and reach the steady-state region, given the typical measurement range of a multimeter on voltage reading in the scale of microvolts.

The auto-setpoint feature enables the Floater to set the voltage setpoint automatically, which can lead to a far smaller initial error (in the range of microvolt instead of millivolt). As shown in the lower plots of Figure 11 and Figure 12 (Test 2 and Test 4), the charging currents could reach the steady-state region much sooner, even in a couple of minutes. Consequently, the auto-setpoint feature can greatly reduce the duration of the test, and more useful data can be obtained in a shorter time period, resulting in a considerable cost, time, and effort savings. To assess the effect of the auto-setpoint feature compared to the manual setpoint mode, the duration required for the charging current to decrease below certain values could be considered as the criterion. Table 6 displays these time periods for when the charging current for the first time drops below 1000 μA, 500 μA, 100 μA, and 50 μA for all four tests.

#	Test Type	Initial Error	*Required time to once drop below*			
			1000 μA	500 μA	100 μA	50 μA
1	**Conv. PI LIB type A**	3000 μV	3h:55m	6h:12m	12h:32m	**16h:14m**
3	**Conv. PI LIB type A**	2000 μV	0 sec	0 sec	0 sec	**0 sec**
2	**Fuzzy+PI LIB type B**	20 μV	0h:54m	1h:14m	2h:0m	**2h:40m**
4	**Fuzzy+PI LIB type B**	20 μV	0 sec	0 sec	0 sec	**0 sec**

Table 6: Comparison of time periods for charging currents to drop below certain values

The impact of the auto-setpoint feature is evident from the table, which demonstrates that the Fuzzy+PI controller immediately drops below the specified current values for all criteria, owing to the very low initial error values. In contrast, the experiments conducted with the conventional PI controller show that despite the initial errors being infinitesimal in the range of 2 to 3 mV, it takes several hours for charging currents to decrease below the specified criteria.

4. Conclusion

The introduction of the new Fuzzy+PI controller resulted in several significant enhancements to the system. These enhancements can be described in three main categories as follows:

I. The new Fuzzy+PI controller offered a significant improvement to the system through the elimination of the tedious, time-consuming tuning process required for each battery cell type. This feature can save up to several days that would have been spent performing trial-and-error tests.

II. The new Fuzzy+PI controller provides enhanced performance by reducing fluctuations in charging current values without compromising voltage control. This feature not only saves time but also increases accuracy in acquiring useful data for the float current analysis.

III. The auto-setpoint feature of the new controller has been designed to reduce test durations by allowing the battery cell to pass through the transient phase in a matter of seconds. This feature is optional, as it will only activate if the voltage setpoint is at its default value of zero, and will remain inactive if the operator assigns a specific setpoint.

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