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Design and Fabrication of An Automatic Temperature Control Lithium-Ion Battery Charger

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ABSTRACT

This study presents the design and construction of an automatic lithium-ion battery charger that monitors the temperature of the lithium-ion battery during charging and sends a signal to the relay to cut off the power supply from the battery terminal if the battery temperature rises above 45°C which is the maximum allowable temperature for charging most lithium-ion batteries. This charger also has an auto-cut-off circuit that cut off the power supply from the battery terminals upon fully charged with LED indicators to indicate when the battery is charging and fully charged. The system comprises a 220/15V AC stepdown transformer, LM317T, ATMEGA 328P microcontroller, LM35, and a 16x2-bit liquid crystal display monitor. In order to ensure optimal performance of the circuit, the battery charger was used in charging the 12volt 14Ah lithium-ion battery, the battery was exposed to various degrees of temperature to simulate a rising battery temperature. Above 45°C the trip signal was triggered and the LCD monitor displayed a message which prompts the user to cool the battery temperature.

1. Introduction

There is no doubt that battery is one of the most important aspects of technologies today which have revolutionized our world [1], almost all technologies in the world today are dependent on batteries either to start them or to operate them continuously. Some of the applications of batteries include; use in powering electric vehicles, use in powering kick-starter for starting the engine, use in storing energy for solar power systems, [2] etc. There are different types of batteries, these various types of batteries have their uniqueness and are also suitable for specific applications. Lithium battery is one of the most commonly used rechargeable batteries because of their long charging cycle, large capacity, lightweight and smaller size [3]. However, these batteries have some drawbacks and one of the major drawbacks is their rapid rise in temperature when charging or discharging [4, 5] amongst others. Research has shown that this rapid rise in temperature can lead to the reduction of battery life, and overheating of the battery and can also cause rupture and explosion of the battery [6].Many practices show that the charging process of the lithium-ion battery may largely affect its life [5]. The general charging control algorithms can be classified into the following categories in accordance with different control objects [7]: timing control, current control, voltage control, and temperature control. A battery can be charged at a constant current until its voltage reaches a pre-determined restrain, thereafter, the pre-defined restrain is kept constant until the current diminishes to a low value. This process is called the constant current constant voltage (CC/CV) charging method [8, 9, 10]. Research has shown that the method satisfactorily fast charges a lithium-ion battery to almost 100% state-of-charge (SOC) [4] however, there is a linear rise in temperature which peaks at about 55ºC. Therefore, it is very necessary to investigate a fast and efficient charging system for lithium-ion batteries with a temperature control unit. Alternatively, some battery charger used in charging lithium-ion batteries requires manual operation. Such a method is prone to oversights like the case of a lithium-ion battery fire outbreak which was reported in Boeing aircraft Dreamliner battery system 2012 as a result of poor monitoring of lithium-ion battery temperature during charging [11]. Therefore, this paper implements automation in addition to the design of a temperature control lithium-ion battery charger. In a bid to ensure efficient charging of lithium-ion batteries, researchers have come up with different types of automatic battery chargers, most of these battery chargers are user-friendly and can cut off the power supply from the battery terminal when it is fully charged so as to prevent overcharging of the battery. [12] proposed an automatic battery charger that is capable of charging the battery efficiently at sustained power optimization. It was a simple design and could charge the battery more efficiently and prevent overcharging of the battery. But the charger could not regulate the battery temperature during charging and could not prevent self-discharge of the battery when the battery is in the standby state. Thus, this battery charger is not suitable for lithium-ion batteries and may also affect the lifespan of the battery. Also, [5] proposed a smart fast battery charger based on the ATMEGA128 microcontroller and LTC4100 battery charging controller. The system could charge the battery more effectively than the conventional battery charger and more accurate in preventing overcharging of the battery through the use of a timer module, however, the battery charger required an operator to set the timer in accordance with the mAh of the battery, which made it less independent than the automatic battery charger. In addition, a model of an automatic battery charger for 12-volt batteries was developed [13]. The design device consisted of LM338 IC, L298 motor driver, PCB unit, and PIC18F452 microcontroller among others. The system was designed to prevent overcharging of the battery, however, it does not make room for thermal management of the battery which is paramount in preserving battery life. Hence it is not suitable for lithium-ion batteries which have high thermal runaway. Similarly, [4] implemented a MATLAB model of the lithium-ion battery that studies the effect of battery model parameters such as charging technique, voltage, current and temperature and how they are related to one another. The simulated model used a well-defined charging technique for lithium-ion batteries and highlighted the importance of a temperature management system. Thus, the aim of this paper is to design and construct a 12V automatic temperature-controlled lithium-ion battery charger that is based on an ATMEGA328P microcontroller and LM35 temperature sensor to charge the battery and cut off power to the battery when its temperature exceeds 45°C and when it is fully charged.

2. Materials and Methods

The block diagram of the charger is given in Figure 1. The design was done in two stages which are the hardware stage and the software stage. The hardware comprises electronics components that are responsible for the physical operation of the circuit. The software is the machine language programmed into the microcontroller that helps for the smart operation of the charger circuit. The various components needed for the construction of the system has selected these components includes; a 220V to 15V 5A A.C step-down transformer, 1N4007 general purpose diode, 5K and 10K variable resistors, 50 µF 1000V capacitors, PCB connector, LM317T and LM7805 power supply regulators, 0.1nF and 1nF capacitors, 6V and 12V DC voltage regulator, Heat sink, BC5471 (NPN) transistors, resistors 1k, 2k, 550, 470, and 220, LED green and yellow, 9V Zener diode, 1N1418 signal diode, 16MHz crystal oscillator, male and female headers and jumper wires, ATMEGA328p microcontroller, Veroboard and positive and negative alligator peg. The operation of the charging system is discussed as follows;

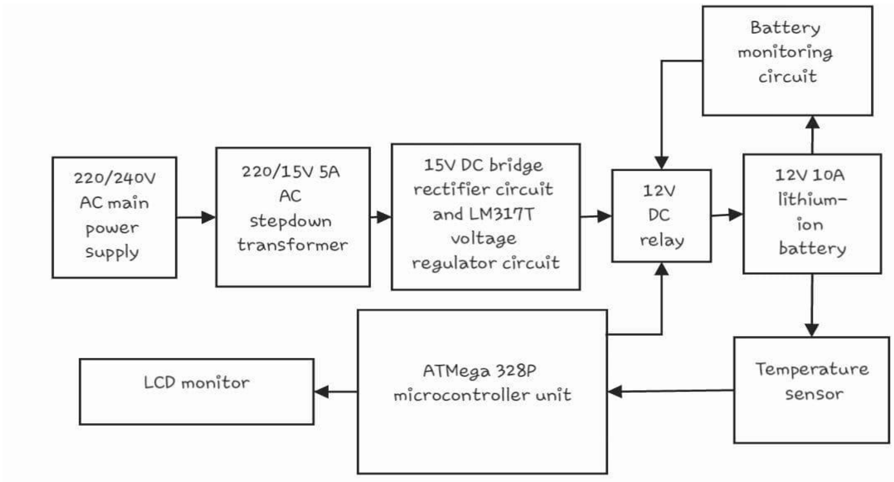

Figure 1 Block diagram of the automatic temperature control lithium-ion battery charger

2.1. Battery Charging system

The battery charging system comprises various components that work together to provide the constant voltage and the constant current that is needed to charge the battery. The battery charging system makes use of a transformer to step down the 220volt A.C power source to 15volt. The step-down voltage is then passed through a rectifier which converts the A.C current into D.C current, a capacitor is used to filter out ripples and the resulting output is then passed through a voltage regulator.

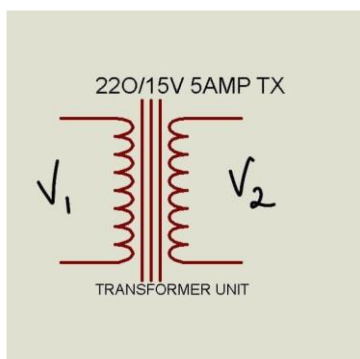

Figure 2. Schematic diagram of a 220/15V stepdown transformer.

2.2. Rectifier and voltage regulator circuit

The voltage regulator was designed to automatically maintain a constant voltage across its output terminal. It may use a simple feed-forward design or may include negative feedback. For the purpose of this design, we have employed a linear voltage regulator. A linear voltage regulator works by automatically adjusting the resistance on a feedback loop accounting for a change in both load and input while keeping the output voltage constant.

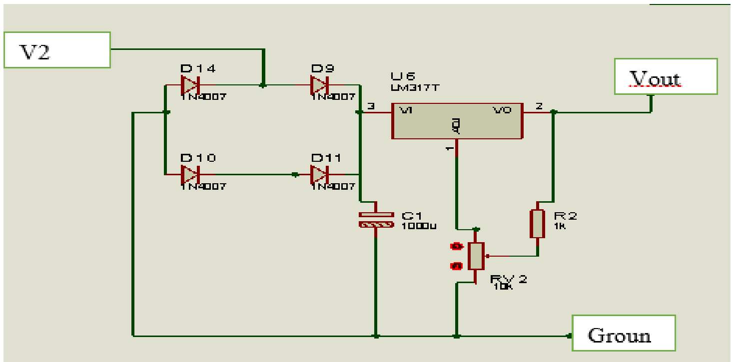

Figure 3. Bridge rectifier and Voltage regulator circuit diagram

The bridge rectifier circuit makes use of four 1N4007 general purpose diode in a bridge configuration as shown in Figure 3. 16.72V from the transformer goes to the bridge rectifier circuit.

$$V_{pk}(\,peak\ secondary\ voltage) = V_{rms} \times \sqrt{2} \tag{2}$$

= 16.72 x $\sqrt{2}$ = 23.65V

At any instant in the bridge rectifier, two diodes in series are conducting, there will be a voltage drop of 0.7V across each diode.

Therefore, peak output voltage ($V_{outpeak}$) $= 23.65 - 2\ (0.7)\ =\ 22.25V$

$$V_{dc}(DC\ output\ ) \ = \ \frac{2\ x\ \text{Voutpeak}}{\pi} \tag{3}$$

$V_{dc} = \frac{2\ x\ 22.25}{\pi}$ = 14.165V

The 14.165V DC output voltage from the bridge rectifier goes to the voltage regulator circuit. The voltage regulator used for this design was an LM317T voltage regulator. LM317T is an adjustable voltage regulator that gives a constant DC output voltage across its output.

The output voltage of the LM317T voltage regulator is given by;

$$V_{out} = \ 1.25(1 + \frac{R_{adjust}}{R_2}) \tag{4}$$

$R_{adjust} = R_{V2}$= 10kΩ and R_2= 1kΩ, thus;

$V_{out} = \ 1.25 \quad (\,1 + \frac{10k\Omega}{1k\Omega})$= 13.75V

The circuit also makes use of the LM7805 voltage regulator to give a constant 5V dc power supply to the microcontroller unit and the 5V DC relay.

2.3. Charging monitoring system (Auto cut off circuit)

The battery monitoring circuit tracks the battery voltage and cut off supply when the battery is fully charged. It makes use of a Zener diode, two bipolar transistors, resistors and a relay. A schematic of the circuit is shown in Figure 4. When the battery is fully charged, its voltage exceeds the threshold of the Zener diode causing the Zener diode to conduct in the reverse direction and bias the base of the transistor driving it into saturation. This, in turn, switches on the second transistor and the relay which is connected to the battery in normally closed configuration is energized and the contact is opened which in turn disconnects the battery from the supply.

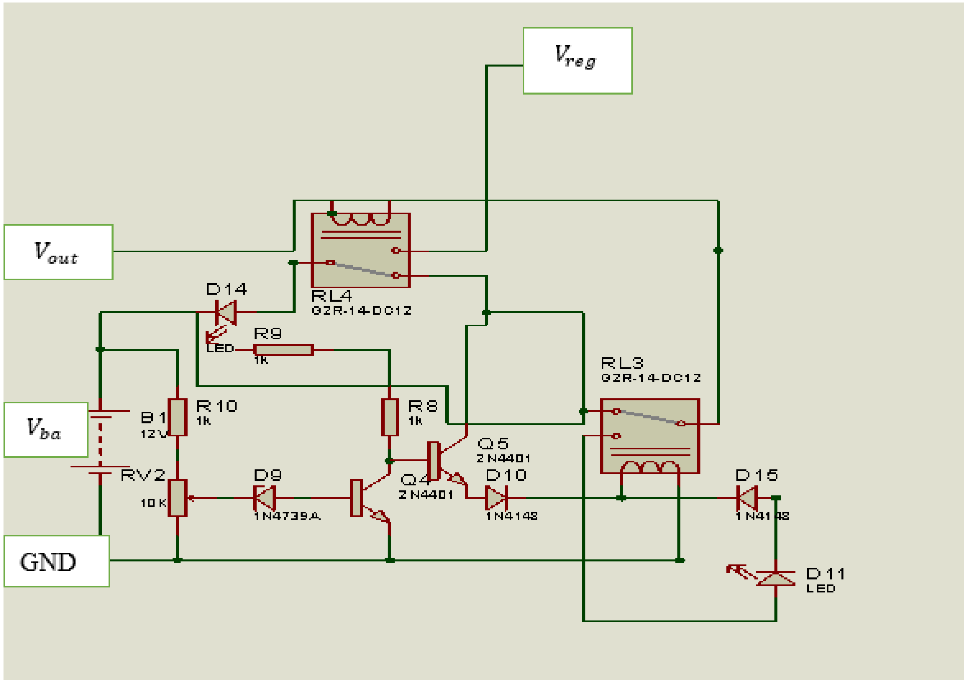

Figure 4 Battery Auto-Cutoff Circuit Diagram

The monitoring circuit makes use of a Zener diode (D9 as shown in Figure 4) to keep track of the voltage level of the battery and then signals the relay RL3 to cut off the 13.75V voltage from the battery. A fully charged 12v battery will measure about 14v across its terminal. However, the design considers a fully charged voltage of 13.5V for the battery. To calculate the values of the resistors R8 and R9 for the transistor biasing, the following calculations will be performed;

The voltage dropped across the charging indicating diode D14 is 13.75 – 0.25 = 13.5V

Thus, the available voltage at the battery terminal (V_{ba}) = 13.5V

The reverse current I_r of a Zener diode is given by the formula.

$$I_r = \frac{Vs - Vz}{R}. \tag{5}$$

Where V_s is the source voltage (Battery full voltage = 13.5V)

V_z is the voltage of Zener diode (9V)

R is the resistance between the source voltage and the Zener diode (R10 + RV2 = 1kΩ + 2KΩ = 3kΩ)

$$Ir = \frac{13.5-9}{3} = 1.5mA.$$

This implies that when the battery is fully charged the reverse current across the diode is 1.5mA. This current flow in the opposite direction across the Zener diode and bias the base of the 2N4401 NPN transistor. The gain β of the transistor 2N4401 transistor is 10, hence the collector current, I_c is βI_b.

However, $I_b = I_r$, thus $I_c = 10 \times 1.5mA = 15mA$

The collector resistor according to the following equation becomes;

$$R_c = \frac{13.5-VcE}{\text{Ic}} = \frac{13.75-0.2}{0.015} = 903.3\Omega. \quad (6)$$

Thus, a resistance of 1kΩ was chosen for resistors R8 and R9. The diodes D15 and D10 prevent backflow of current from the coil to the battery monitoring circuit.

2.4. LM35 sensor

The LM35 is a three-terminal temperature sensor that is capable of measuring from -55 degrees Celsius to +150 degrees Celsius. The voltage output of LM 35 increases by 10mV per degree Celsius rise in temperature.

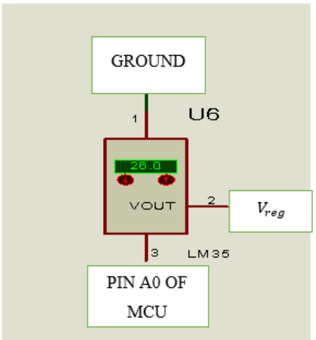

Figure 5. LM35 Temperature Sensor

LM 35 temperature sensor was used for this project because of its characteristics, the sensor is capable of measuring temperature in the range of -55°C to 150°C, and can deliver 10mV per °C. pin 3 of the LM35 sensor is connected to the analogue pin A0 of the ATMEGA 328P temperature sensor. Pin 2 is connected to 5V and pin 1 is connected to the ground.

2.5. ATMEGA328P microcontroller unit and liquid crystal display

The automatic battery charger makes use of the ATMEGA 328P microcontroller for the control of the circuit and also as an interface between the sensors, the battery, the sensor and the user. The microcontroller is programmed either with C and C++ programming language which are in turn interpreted by the microcontroller in bits to enable them to execute a particular function.

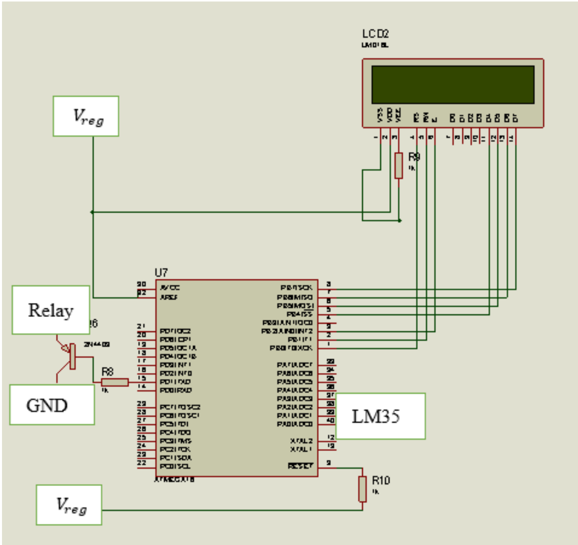

Figure 6. ATMEGA 328P Microcontroller and Liquid Crystal Display

A 5V power supply is fed from an LM7805 voltage regulator to reset pin 2 and Voltage reference pin V_{cc} of the microcontroller. The LM35 temperature sensor is connected to the analogue pin 22 and the temperature is then displayed in a 16×2 bit LCD monitor. The LCD monitor is connected in a 4-bit mode. The transistor Q6 send the signal that switches the relay to cut off power supply from the battery when its base is biased by digital pin 15 of the ATMEGA 328P as a result of battery temperature exceeding 45°C.

2.6. Flow chart algorithm of the system

The flow chart algorithm of the system is shown in Figure 7. It is a closed-loop system that depicts the operation of the automatic temperature control lithium-ion battery charger. The charging technique used is the constant current constant voltage method which is popular for fast and efficiently charging lithium-ion batteries. The algorithm considers four charging stages; pre-charging, fast-charging, compensation charging and trickle charging stage [5]. The algorithm starts with the initialization and constantly check for when the voltage reaches the pre-determined voltage threshold while charging at a constant current. Thereafter, it maintains the charging at the pre-determined restrain till the battery is fully charged. This is determined by the SoC of the battery using the coulomb counting method [14]. The pre-charging stage starts off at a low-constant current and then moves to a higher current fast charging where the temperature management system is implemented. Since research has shown the linear rise in temperature at about 15/60°C per minute, a fairly general constraints would be a rate of no more than 1°C per minute (see Figure 8). Also, a maximum temperature limit of 45°C is added. Beyond the fast charging, stage is the compensation stage which keeps the voltage level hooked at the pre-defined threshold.

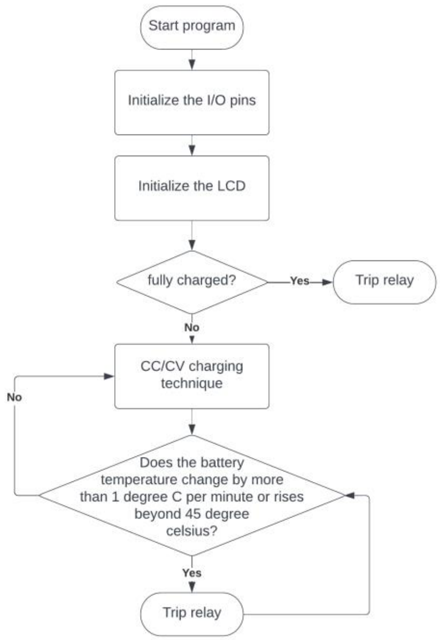

Figure 7. The flow chart of the system

The trickle charging stage is usually added with a time limit and was not implemented in the CC/CV charging technique.

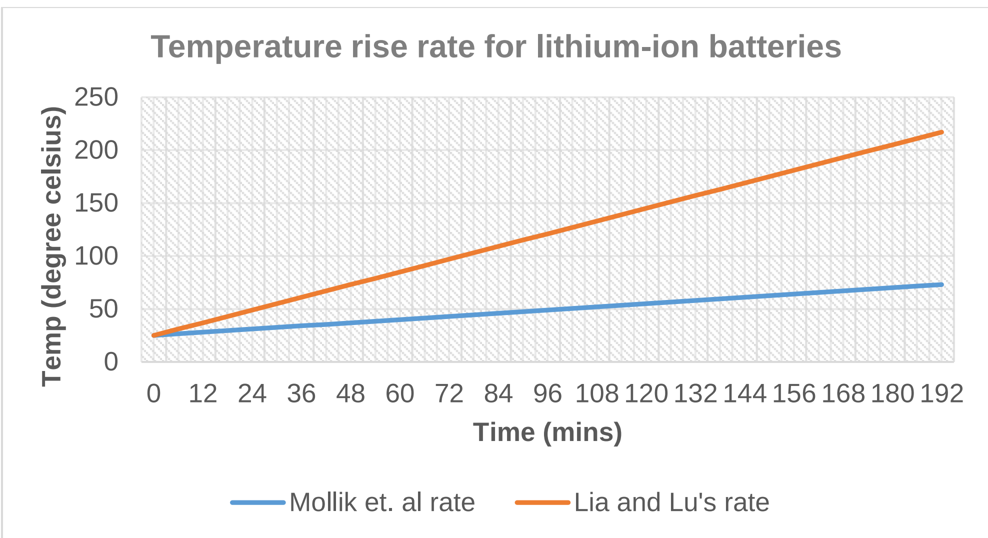

Figure 8. Comparison of temperature rise values for temperature management system

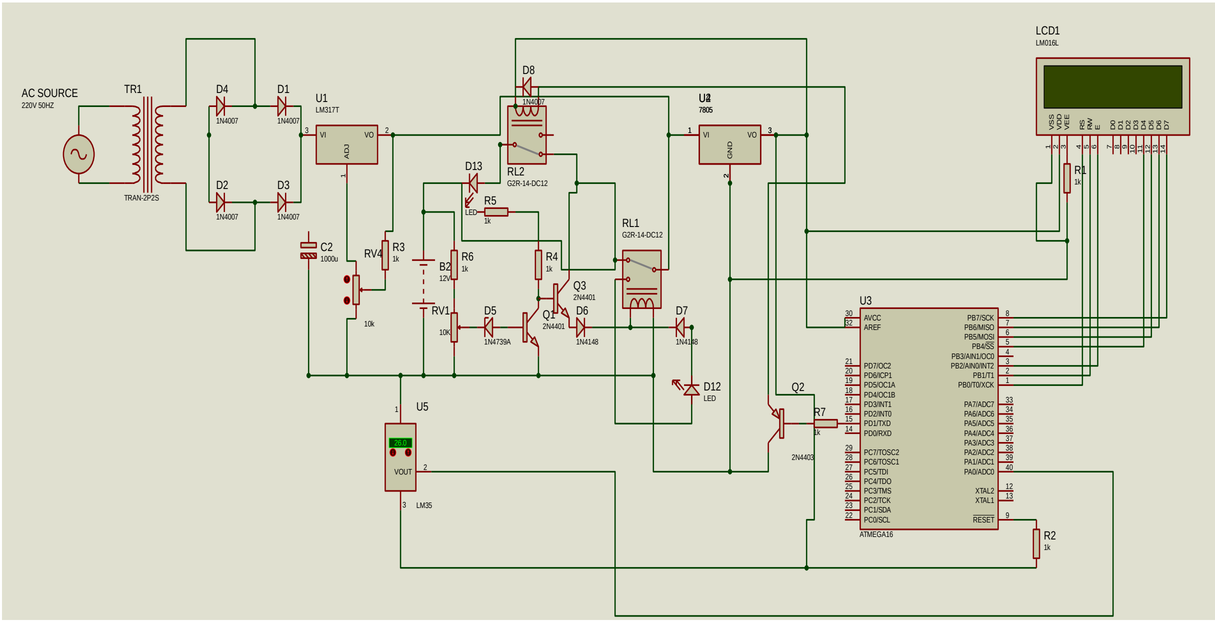

Figure 9. Circuit diagram of the Automatic temperature control lithium-ion battery charger

The next step in the design process is the construction of the system on the acquired Vero board. The procedure taken to reproduce the circuit diagram on the Vero board are as follows;

i. All the components of the system were placed on the Vero board
ii. The components were soldered to the Vero board
iii. All joint, jumper wires, male and female header strip was properly connected
iv. All exposed joints and connections were properly insulated
v. Plastic casing was used to cover up the whole system.
vi. An epoxy gum was used to hold the Vero board and the transformers in place.

3. Results and Discussion

The fabricated automatic temperature control lithium-ion charger is given in Figures 10 and 11.

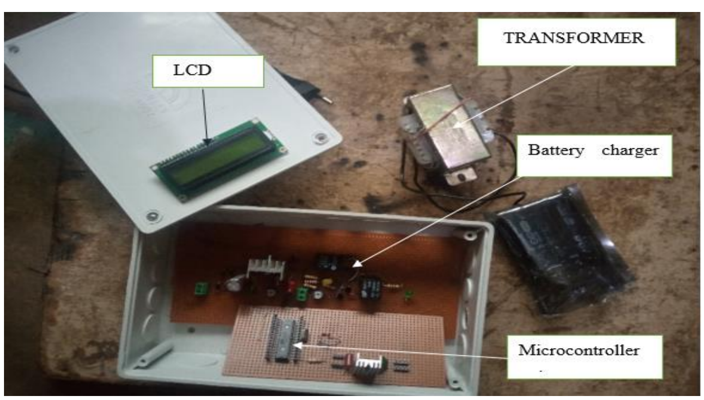

Figure 10. Battery Charger under construction

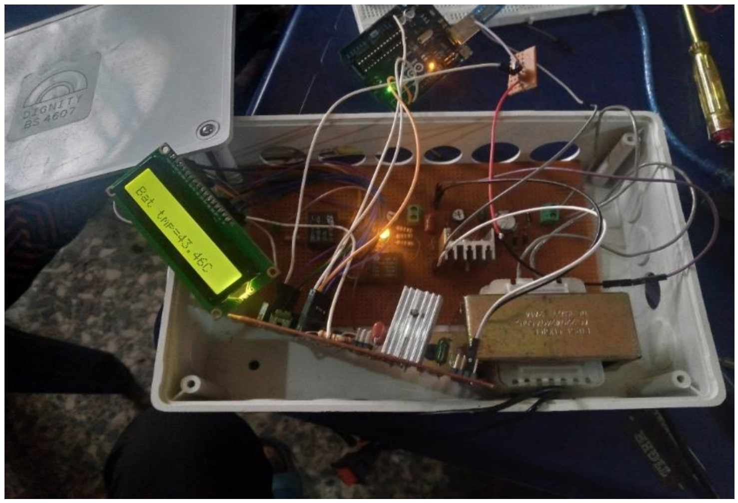

Figure 11. System after Construction

After the implementation, some tests were carried out to determine the performance of the 12V automatic temperature control lithium-ion battery charger. The experimental setup had the charger connected to the 12-volt battery, a digital multimeter to measure the output voltage and current of the charger and a choke resistor of 10 MΩ for the load on the battery. The charger was used to charge a 12V lithium-ion battery at room temperature. The charging time and temperature at different instances of time during charging were recorded. Thereafter, the battery charger was also subjected to charging the battery at higher temperatures than room temperature. When the battery was fully charged the open terminal voltage of the battery was measured with the digital multimeter. Other tests carried out include continuity, open circuit test and short circuit test, these tests were carried out with a digital multimeter.

Different results were obtained after multiple tests were carried out to determine the performance of the battery charging circuit, the majority of the test was carried out with a digital multimeter. The results of the various test are shown in Tables 1—3. The experimental setup tested for the following; when the battery charger would cut off power from the battery terminal, when the battery would be fully charged and when the battery temperature would exceed the maximum charging temperature for the lithium-ion battery. This test was carried out with a digital multimeter and the result is shown in Table 2.

Table 1: Results for the circuit output voltage, output current, short circuit test, continuity and open-circuit test.

The output voltage of the charger	**13.75V DC**
The output current of the charger	2.51 amps DC
Open circuit test	No open circuit
Short circuit test	No short Circuit
Continuity Test	The Circuit was continuous.

Table 2: Results for battery open terminal voltage and temperature of the lithium-ion battery when charging at the different instants at room temperature with auto cut-off circuit state.

Period of charging in minutes	**Battery temperature (°C)**	**Battery open terminal voltage**	**Battery Auto cut off circuit State**
0 min	28.30°C	12.30V	Not activated
10min	28.32°C	12.32V	Not activated
30 min	28.29°C	12.45V	Not activated
45 min	29.11°C	12.51V	Not activated
60 min	29.21°C	12.62V	Not activated
1hr & 15 min	30.14°C	12.66V	Not activated
1hr & 30 min	29.18°C	12.78V	Not activated
2hr	29.98°C	13.14V	Not activated
2hr & 15 min	31.22°C	13.17V	Not activated
2hr & 30 min	31.39°C	13.23V	Not activated
3hr & 15 min	32.39°C	13.29V	Not activated
3hr & 30 min	29.94°C	13.33V	Not activated
3hr & 45 min	28.77°C	13.34V	Not activated
4hr & 12 min	28.87°C	13.54V	Activated
4hr & 23 min	28.22°C	13.52V	Activated

Table 3: Results for the temperature of the lithium-ion battery when charging in a high-temperature environment at different times.

Period of Charging	**Battery Temperature**	**Battery Open terminal voltage**	**Battery Auto cut-off**
0 min	32.3°C	12.89V	Not activated
17min	43.48°C	12.95V	Not activated
35min	44.15°C	13.11V	Not activated
47min	42.15°C	13.14V	Not activated
53min	47.13°C	13.17V	Activated
58min	56.16°C	13.21V	Activated

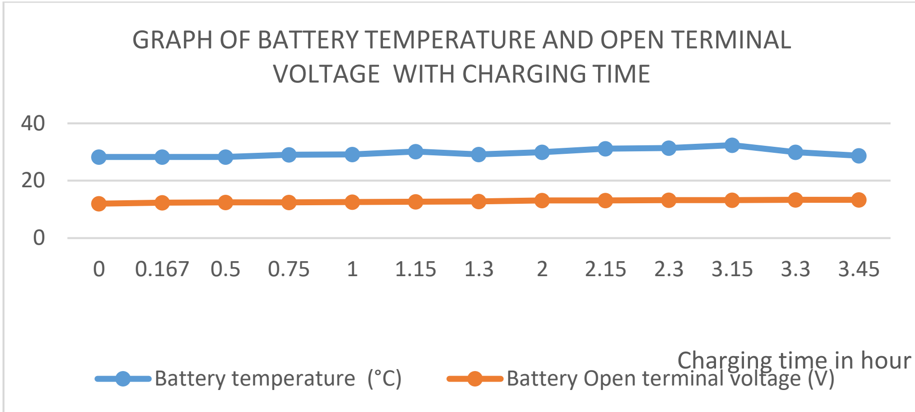

Figure 12. Graph of the battery voltage level and temperature with respect to time

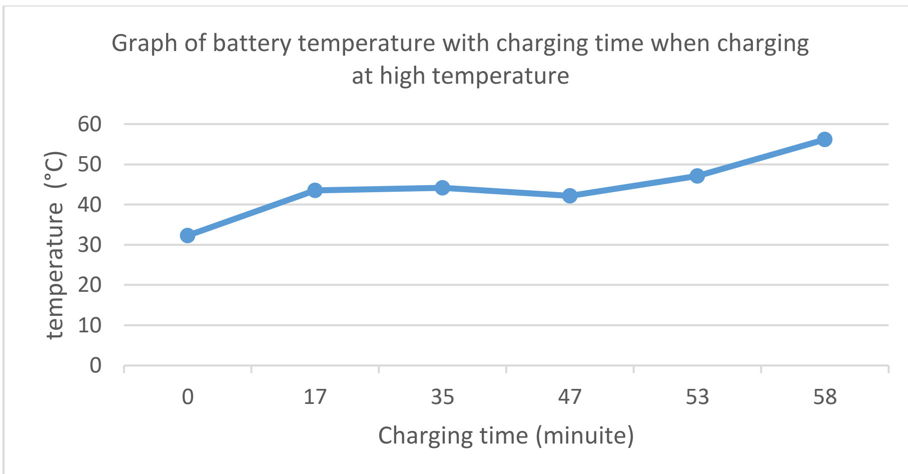

Figure 13. Graph of the temperature of the battery with respect to time.

From Table 2, it was observed that when the battery terminal voltage reaches about 13.54V, the battery auto-cut-off circuit was activated and the green LED which indicates fully charged was turned on and no current supply was flowing to the battery terminal. Similarly, the results in Table 3 shows the response of the automatic temperature-controlled lithium-ion battery charger when temperature of the battery rises. Most of the auto cut-off action was activated when the battery temperature exceeded about 47.13°C. The implemented system automates lithium-ion battery charging with a functional temperature control unit, thereby improving the life cycle of lithium-ion batteries as investigated by [4]. Though a temperature control unit was implemented in [5], it partly automated the charging processes and used a higher temperature rate change which will result in higher rise in temperature beyond the recommended maximum charging temperature. Moreover, the proposed system in this study improves on the lithium-ion charger system designed and fabricated in [12].

4. Conclusion

The study successfully designed and fabricated a 12V automatic temperature control lithium-ion battery charger that will solve the problem of manual operation oversights and rapid rise in temperature during charging. The charger was tested by charging a 12V 14Ah lithium-ion battery. In the two scenarios of test, when the battery was fully charged and when the battery temperature increased more rapidly with time or crossed the threshold, the battery auto cut-off circuit was activated.

5. Acknowledgment

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6. Conflict of Interest

There is no conflict of interest associated with this work.

Reference

[1] S. Kereena, N. Brundha and S. Kumar, "Vehicle Battery Charger Booth using Hybrid Power System," *International Research Journal of Engineering and Technology,* vol. 6, no. 6 june 2019, pp. 380- 384, 2019.

[2] "Uses of Battery," 2022. [Online]. Available: https://byjus.com/physics/uses-of-battery/. [Accessed 17 08 2022].

[3] Electronics-Notes, "Lithium Ion Battery Advantages & Disadvantages," 2022. [Online]. Available: https://www.electronics-notes.com/articles/electronic_components/battery-technology/li-ion-lithium-ion-advantages-disadvantages.php. [Accessed 17 08 2022].

[4] Md.Sazib Molik, MM Rashid, A Hasan, "Temperature effect and battery charging characteristics based on C-Rate," *International Journal of Engineering and Advanced Technology,* vol. 9, no. 3rd October 2019, pp. 159-164, 2019.

[5] J.-g. Lai and X.-q. Lu, "Smart Battery Charging System Based on ATMEGA128 Microcontroller," *International Journal of Information and Computer Science,* vol. 3, pp. 90-93, 2012.

[6] C. C. T. F. M. M. G. R. M. A. S. D. R. M. O. C. M. E. M. L. A. B. M. A.-S. R. B. a. D. G. Melanie. J. Loveridge, "Temperature Considerations for Charging Li-Ion Batteries: Inductive versus Mains Charging Modes for Portable Electronic Devices," *ACS Energy Letters,* vol. 4, no. 5, pp. 1086-1091, 2019.

[7] G. S. y. L. D. l. J. Z. h. a. L. W. Gao Xiao qun, "Parking intelligent charging management system and method for time-sharing charge control". China Patent N102097843A, 2011.

[8] V. a. N. P. W. a. D. S. a. S. S. a. B. R. D. a. S. V. R. Ramadesigan, "Modeling and simulation of lithium-ion batteries from a systems engineering perspective," *Journal of the electrochemical society,* vol. 159, no. 3, p. R31, 2012.

[9] Y. a. K. Y. a. W. Y. a. W. Y. a. K. Y. Inui, "Simulation of temperature distribution in cylindrical and prismatic lithium ion secondary batteries," *Energy Conversion and Management,* vol. 48, no. 7, pp. 2103-2109, 2007.

[10] S. A. a. F. M. M. a. S. J. R. a. A.-H. S. Khateeb, "Design and simulation of a lithium-ion battery with a phase change material thermal management system for an electric scooter," *Journal of Power Sources,* vol. 128, no. 2, pp. 292-307, 2004.

[11] F. Larsson, P. Andersson and B.-E. Mellander, "Lithium-Ion Battery Aspects on Fires in Electrified Vehicles on the Basis of Experimental Abuse Tests," *Battery Safety,* vol. 2, no. 2, pp. 9-22, 2016.

[12] Ovbiagele Umahon; Jerome Dada Keshi, "Design And Implemetation of 12V Automatic Battery Charger," *International Journal of Scientific Engineering and Research,* vol. 6, no. 11th November 2018, pp. 129-131, 2018.

[13] Krishnamurthy, Rashmi Varma, Sonali Tribhuvan, "Automatic Battery Charger," *international journal of advanced research in computer and communication engineering,* vol. 3, no. 5th may 2015, p. 5, 2015.

[14] J. E. A. U. CN Udezue, "12V Portable battery Charging System," *Pacific Journal of Science and Technology,* vol. 17, no. 1st May 2016, pp. 5-11, 2016.

[15] Mohamad Fathi Elias, A.K Arof, K.M Nor, "Design of Smart Charger for sereis lithium ion batteries," *Research gate,* vol. 7, no. 2nd December 2005, pp. 1485-1490, 2005.