Design of passive voltage balancer system for lead acid battery

Bandiyah Sri Aprillia, Desri Kristina Silalahi, Kharisma Bani Adam, Putu Krishna Bhaskara Perteka Yuda
Department of Electrical Engineering, Faculty of Electrical Engineering, Telkom University, Bandung, Indonesia

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ABSTRACT

The use of rechargeable batteries for electrical energy storage requires a voltage balancing system. The voltage balancing system requires monitoring in the use of rechargeable batteries so that they can be utilized properly and can improve the electrical energy storage system. In this research, a monitored lead acid battery voltage balancing system was designed so that the management of the battery voltage balance level and the storage of electrical energy in rechargeable batteries can be stored and used optimally. In this research a series of lead acid battery voltage detection and power dissipation circuits were designed. The power dissipation circuit uses the controlled shunt resistor method which is used when the voltage of the lead acid battery being charged exceeds the maximum voltage. This method is easy to implement and can display the value of the lead acid battery voltage and other parameters, so that it can be monitored by the user. The results obtained show that the average voltage error for batteries 1 and 2 is 0.09% and 0.3% respectively. The power dissipation circuit can dissipate lead acid battery power above the reference voltage VREF=±7 V, with a balanced voltage of 6.8 V at 140 minutes and 160 minutes.

Corresponding Author:

Bandiyah Sri Aprillia
Department of Electrical Engineering, Faculty of Electrical Engineering, Telkom University
Telekomunikasi Street,1, Terusan Buahbatu - Bojongsoang, Sukapura
Dayeuhkolot Districts, Bandung, West Java 40257, Indonesia
Email: bandiyah@telkomuniversity.ac.id

1. INTRODUCTION

One of the media used for electrical energy storage systems is a battery [1]. Batteries that are assembled in large quantities have been used in many electronic systems, such as robotics, renewable energy systems, energy storage in the storage grid, and electric energy-based vehicles [2]. There are two types of batteries, namely: non-rechargeable batteries and rechargeable batteries [3]. One of the rechargeable batteries is a lead acid battery [4]. Lead acid battery is a battery with a lattice made of lead alloy, which has a relatively affordable price and has been widely applied [5]. Lead acid batteries in general have advantages, such as: cheap and easy to manufacture; low cost per watt-hour; self discharge low (lowest among other rechargeable batteries); high specific power (can produce high output current); good performance at both low and high temperatures [6]. Lead acid batteries in general have disadvantages, such as: specific energy low (low ratio between battery weight and energy produced); long charging; must be stored in a charging state to avoid sulfation; limited cycle life (about 500-2000 cycles); for flooded type lead acid batteries need to be filled with water and limited for portable use (due to the electrolyte in the form of liquid; not environmentally friendly [7], [8].

The lead acid battery in series on the charging stack, the charge connected to the anode of the power supply, will charge first. At the time of charging, there are usually 2 points that can be achieved, namely charging the lead acid battery fully in a short time and maintaining battery capacity by increasing the lead acid battery capacity during self-discharge of the lead acid battery with a constant voltage when the lead acid battery is fully charged [9]. In a good technique for charging lead acid batteries, there are generally several stages of charging lead acid batteries. If there is a large imbalance between the total charge between the batteries, it will reduce the total capacity, increase the risk of one battery being overcharged and increase the risk of the other battery undercharging and reduce the performance of using the battery [10]. Thus it is necessary to have a battery voltage balancing system.

Lead acid batteries use lead (Pb) as the negative electrode, lead dioxide (PbO_2) as the positive electrode, sulfuric acid (H_2SO_4) as the electrolyte, and a separator which is used to separate the positive and negative electrodes through a porous membrane to prevent short circuits [11]. The electrodes on a lead acid battery are made of a lead alloy. For the composition of negative electrodes, electrolytes, and positive electrodes when full charge, when discharge, and when full discharge on a lead acid battery. A battery balancing system is needed for certain reasons, namely battery safety from overcharging, battery life, battery charging that is not full, and energy usage from the battery stack [12]. Battery safety from overcharging is needed to prevent the battery from risking battery voltage leakage until the battery burns out. The risk of the battery not being fully charged or called undercharging can be reduced which can reduce the storage capacity of the electric charge. Battery life can be longer, because it prevents overcharging and overdischarging. The use of energy from the battery stack can be used optimally if using a battery balancing system [13]. One of the reasons for using a battery balancing system is battery life.

Many battery charging systems use a battery voltage balancing system, with varying features and prices [14]. If the voltage between the batteries is balanced, then the charge of each battery does not occur overcharging and undercharging and equalizing the electric charge between the batteries arranged in series so that the capacitance between the batteries does not occur imbalance [15]. In general, there are two methods of battery balancing, namely the passive voltage balancer method and the active voltage balancer method [16]. The passive voltage balancer method is a balancing method that dissipates the power of each battery if the charge on the battery is fully charged or the charge on one battery is greater than another battery in a battery series circuit using a dissipation resistor component or a shunt resistor [17], [18]. There are two types of passive voltage balancer circuits, namely: fixed shunt resistor circuits and controlled shunt resistor circuits [19]. While the active voltage balancer method is a battery voltage balancing method that distributes voltage from one battery with a higher voltage to a battery with a lower voltage [17]. The advantages of the passive voltage balancer method are: cost-effective, easy to implement [20], while the drawbacks of the passive voltage balancer method are: less effective in balancing battery voltage [20]. The advantages of the active voltage balancer method, namely: increasing system runtime, being more effective in balancing battery voltage, shorter charging time, less heat generated when balancing battery voltage, while the drawbacks of the passive voltage balancer method are: circuit complexity is more complicated [21].

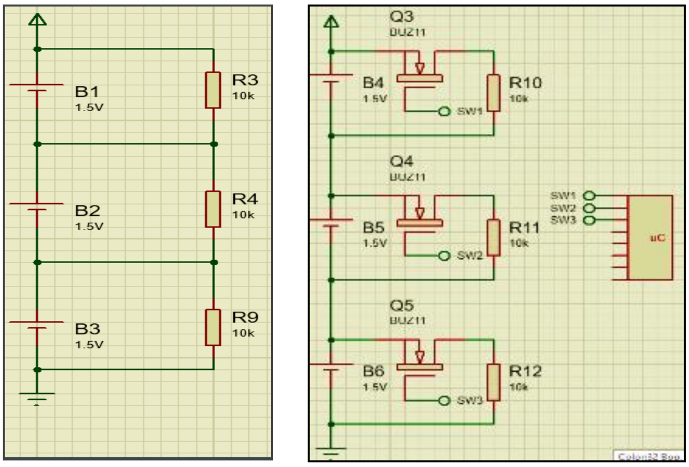
In this research, the method used for battery balancing is the passive voltage balancer method, the type of controlled shunting resistor circuit. In this research, design and manufacture of a lead acid battery voltage balancing system that can be monitored using a voltage divider circuit to detect the voltage of each battery. In the lead acid battery voltage balancing system, it will use a direct current (DC) voltage input with the output load being a DC load. After designing the device with a voltage balancer system, it is hoped that the tool can balance the voltage between lead acid batteries where the charging voltage and several other parameters can be monitored. In this research, the balancer system was designed with a balance voltage of 6.8 V.

2. METHOD

2.1. Passsive battery balancing system

In this research, the method used for battery balancing is the passive voltage balancer method with the type of controlled shunting resistor circuit. The difference between a fixed shunt resistor circuit and a controlled shunt resistor circuit can be seen in Figure 1. In a controlled shunt resistor circuit, the battery stack with the dissipation resistor is not connected continuously. In a controlled shunt resistor circuit, between the battery stack and the dissipation resistor there is a switch (usually a relay or transistor) which is controlled by the controller to set when the battery stack is connected or not connected to the dissipation resistor. There are 2 modes in the controlled shunt resistor circuit, namely: continuous mode and detection mode [22]. In continuous mode, all switches are controlled by the same on/off signal [23]. In detection mode, when an unbalanced state between the batteries in the battery stack is detected, the controller will select which switch to connect to the battery.

Based on the Figure 1(a), the battery stack is connected to a dissipation resistor when the battery is neither fully charged nor fully charged. Furthermore, in Figure 1(b), if the battery capacity is fully charged, then the excess input voltage will automatically be dissipated in the dissipation resistor whose resistance has been adjusted. The power dissipation on the dissipation resistor will last until the capacity of all batteries is balancing. This circuit can only be used on battery types that are tolerant of overcharge conditions, such as lead acid and nickel based battery types. The advantages of a fixed shunt resistor circuit, namely: cheap, easy to implement, do not require a large place, and easy to control [2]. While the disadvantages of the fixed shunt resistor circuit are: less effective (due to power dissipation on the dissipation resistor) [2].



(a) (b)

Figure 1. Types of circuits; (a) fixed shunt resistor circuit and (b) controlled shunt resistor circuit

2.2. Battery voltage balancer system (BVBS)

In the design of the tool there is a method used in the lead acid battery voltage balancing system is a passive voltage balancer using a controlled shunting resistor [24]. In this method, a shunt resistor component or a dissipation resistor is used for power dissipation when the battery is fully charged. Batteries when fully charged will not experience overcharge and batteries that are not fully charged can continue to be charged until the electrical charge between the batteries is almost equal [25]. Voltage sensors are used to detect which batteries need charging so that under voltage does not occur [26]. The block diagram of the working principle of the tool, it can be seen in Figure 2.

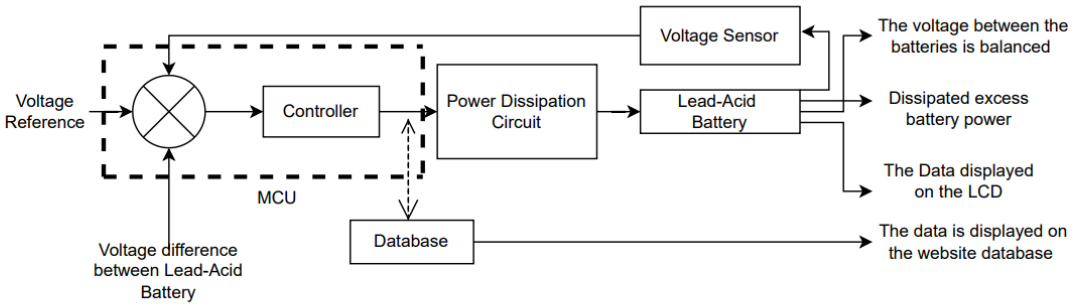


Figure 2. Battery voltage balancer design block diagram

As can be seen in Figure 2, the actuator used is a power dissipation circuit. The plant used is a lead acid battery and the sensor used is a voltage sensor. The database is used to receive or send data between controllers. The input used is the reference voltage and the voltage difference between the lead acid batteries that have been programmed by the user. In the BVBS, the sensor will detect the plant voltage, namely the lead acid battery. The detection data of each voltage sensor will be sent to the database. The voltage sensor detection data will be compared with the reference value. The results of the comparison of these values will later turn on or turn off the lead acid battery power dissipation process. The resulting output is dissipated excess battery power, the voltage between the batteries is balanced according to the reference voltage, the data on the website database and the data is displayed on the liquid crystal display (LCD), so that it can be monitored by the user.

2.3. Programming algorithm for battery voltage balancer system

The design of system programming algorithms uses flow diagrams. The system programming algorithm flow diagram can be seen in Figure 3. Based on Figure 3, the system starts from the input charging voltage (V_{CHG}). In stage 1, the microcontroller unit (MCU) displays the parameters via the LCD. Next, the MCU is connected to the database, then detects the original lead acid (V_A) battery voltage (V_A MCU_1 is voltage B_1 and V_A MCU_2 is voltage B_2). The MCU sends V_A to the database, then retrieves the voltage detected by another MCU (V_L) from the database (V_L MCU_1 is voltage B_2 and V_L MCU_2 is voltage B_1 from the database). Both MCU's display V_A and V_L via LCD. Checks whether V_A>V_{REF} or V_A>V_{RANGE}, where V_{REF} is the upper limit reference voltage V_A and V_{RANGE} is the maximum difference between V_A and V_L. If yes, then the power dissipation circuit is on. If the argument is not, then return to stage 1. The charging system uses an input voltage above ±13.6-13.8 V, because the control voltage value of 1 battery cell is ±2.3-2.35 V [27]. For control current values of ±0.675 A or smaller [28]. V_{REF} is ±7 V, to prevent over voltage on the battery.

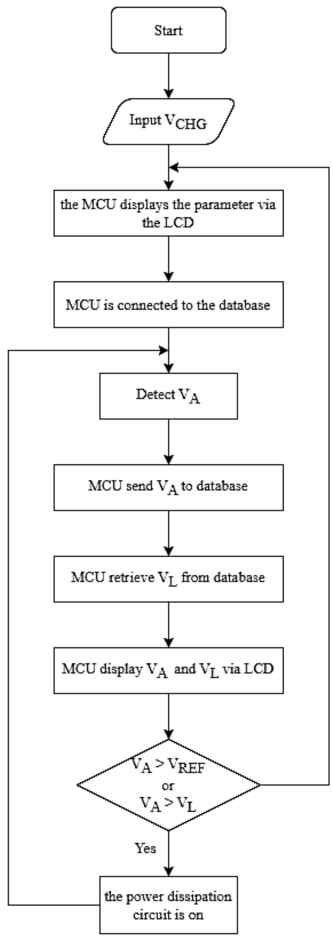


Figure 3. Second flow diagram of system programming algorithm

2.4. Wiring system of battery voltage balancer system

In the charging system, the input voltage is above ±13.6-13.8 V, because the control voltage value of 1 cell battery is ±2.3-2.35 V [29]. For the value of the control current is ±0.675 A or less [30]. V_{REF} worth ±7 V, to prevent battery overvoltage. The wiring system between devices can use 3 systems. The first wiring system can be seen in Figure 4.

In Figure 4, the MCU uses an external battery power supply. While in Figure 4, the MCU uses a USB power supply. The mark (→) indicates the connection between devices using a cable and the mark (---›) indicates the connection between devices wirelessly. The MCU must not use a USB power supply and an external battery or a USB power supply and a voltage source at the same time, so that the MCU does not get excessive input voltage.

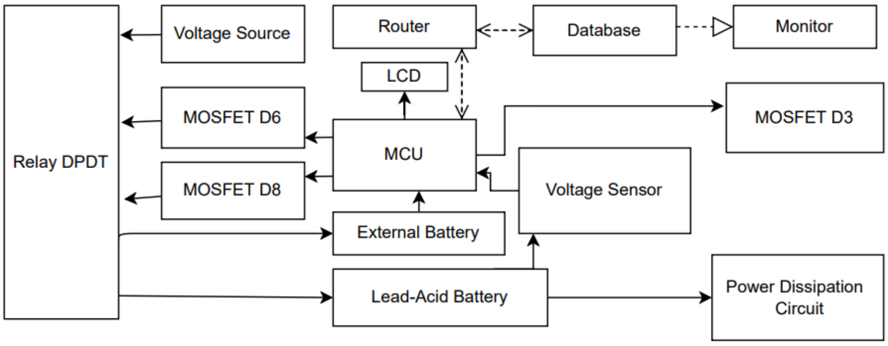
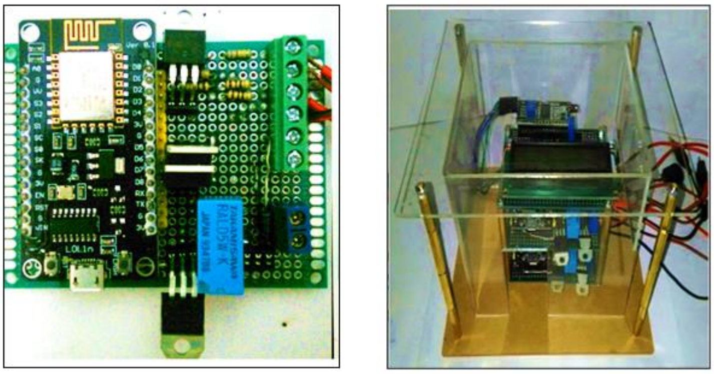


Figure 4. Wiring system

2.5. Hardware design of battery voltage balancer system

Hardware design includes voltage detection circuit, power dissipation circuit, switching circuit for MCU power supply and lead acid battery, display circuit, and circuit packaging. In frame 1 there is a series of displays with a 16x2 LCD connected to the I2C module and a trimmer to adjust the brightness of the LCD backlight. The I2C module also has a trimmer to adjust the text contrast on the LCD. In frame 2 there is a voltage detection circuit with an external resistor to increase the range of detection values, because the MCU already has an internal voltage divider circuit. In frame 3 there is a power dissipation circuit with a MOSFET as a dissipation switch and a resistor for the lead acid battery power dissipation. The MCU_1 and MCU_2 power dissipation circuits use resistors with a nominal value of 100 Ω with a power rating of 0.5 W which are arranged in series-parallel for each of the power dissipation circuits in MCU 1 and MCU 2. In frame 4 there is a switching circuit for the MCU power supply and lead acid battery with MOSFET as the MCU digital pin switch, DPDT relay as a switch from the power supply to the lead acid battery or from the power supply to the MCU, a 7-12 V voltage regulator for the MCU and a 15 V voltage regulator.

Figure 5(a) is a printed circuit board (PCB) circuit and circuit packaging in Figure 5(b). In Figure 5(a) there is a circuit according to the schematic consisting of a voltage detection circuit, power distribution as well as an MCU power supply switching circuit and a lead acid battery assembled on one PCB, namely PCB-1. In Figure 5(b) is a series packaging using acrylic material with a thickness of 2 mm. The circuit pack contains two circuits, namely circuit 1 and circuit 2 packaging. Circuit 1 packaging uses PCB-1 circuit and display circuit. In the display circuit there is a separate PCB of the voltage detection circuit, the power dissipation circuit, and the switching circuit for the MCU power supply and lead acid battery.



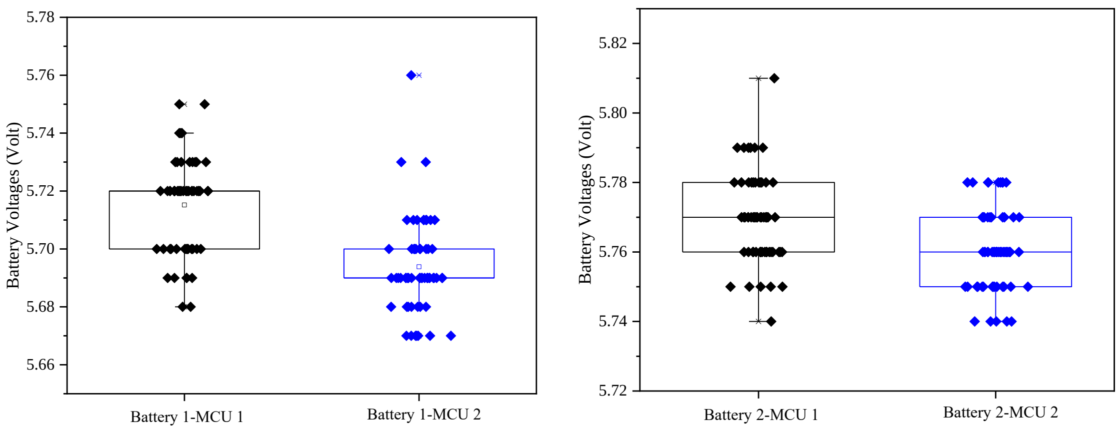
(a) (b)

Figure 5. Hardware design of BVBS; (a) PCB circuit and (b) circuit packaging

3. RESULTS AND DISCUSSION

Before balancing the voltage between the two lead acid batteries, a voltage detection test is carried out for both batteries. This test was conducted to determine the detection capability of the voltage sensor. In this test using an external resistor connected to the MCU. Tests were carried out on MCU_1 and MCU_2. Figure 6 show the boxcharts of measuring battery voltages for battery 1 and battery 2 using MCU_1 and MCU_2.

The battery voltage measurements in Figures 6 use the values of DC voltage maximum (V_A DC_{MAX}) 1 V. Based on Figure 6(a), the value of battery 1 in MCU_1 mode is 5.72 V, the value of battery mode 1-MCU_2 is 5.69 V, the average value of battery 1-MCU_1 around 5.71 V, the average value of battery 1-MCU_2 equal 5.69 V. While the measurement of battery voltage 1 using a multimeter of 6.12 V. Furthermore, based on Figure 6(b), the value of battery 2-MCU_1 mode is 5.77 V, the value of battery 1-MCU_2 mode is 5.76 V, the average value of battery 2-MCU_1 is 5.77 V, the average value of battery 2-MCU_2 is 5.76 V. While the results of the measured voltage of battery 2 using a multimeter of 6.19 V. Based on Figure 6, there is an error in the value of the average voltage measurement of batteries 1 and 2 using MCU_1 against the average voltage measurement value using a multimeter >43% and the error value of measuring the average voltage of batteries 1 and 2 using MCU_2 against the value of measuring the average voltage of batteries 1 and 2 using a multimeter >43%, so the values of direct current voltages maximum (V DC_{max}) need to be changed. After several observations have been made to improve sensor accuracy, the values of V $DC_{max\ 1}$ is 1.072 V for MCU_1, and V $DC_{max\ 2}$ is 1.075 V for MCU_2. The graph of the results of the second voltage measurement on battery 1 and battery 2 using MCU_1 and MCU_2 respectively can be seen in Figure 7.



(a) (b)

Figure 6. Boxchart of battery using MCU_1 and MCU_2; (a) first battery and (b) second battery

Based on Figure 7(a), the value of battery 1-MCU_1 mode=6.11 V, the value of battery 1-MCU_2=6.12 V, the average value of battery 1-MCU_1=6.12 V, the average value of battery 1-MCU_2=6.12 V. While the results of measuring battery voltage 1 using a multimeter, amounted to 6.12 V. Therefore, the average error value of battery 1–MCU_1 and MCU_2 against the value of measuring battery voltage 1 using a multimeter is 0.1% for MCU_1 and 0.1% for MCU_2.

In Figure 7(b), the value of battery 2-MCU_1 mode=6.19 V, the value of battery 2-MCU_2 mode=6.19 V, the average value of battery 2-MCU_1=6.19 V, the average value of battery 2-MCU_2=6.19 V. The result of measuring the voltage on the multimeter also shows a value of 6.19 V for battery 2. The percentage error of the average voltage of batteries 1 and 2 using MCU 1 against the average voltage detection value using a multimeter is 0.09%. Meanwhile, the average error percentage for batteries 1 and 2 using MCU 2 is 0.3%. After calibrating the voltage sensor measurement to the multimeter, the power dissipation circuit is tested. This test is carried out to determine the ability of the power dissipation circuit to dissipate battery power. The test uses the reference value=7.1 V on MCU_1 and MCU_2. The results of the power dissipation circuit capability test are tabulated in Table 1.

Based on Table 1, it can be seen that the dissipation circuit on MCU_1 and MCU_2 can turn on if it is above the reference voltage and not turn on if it is below the reference voltage. After testing the performance of the power dissipation circuit running well, a lead acid battery voltage balancer test was carried out. The test uses V_{ref}=7.1 V on MCU_1 and MCU_2. The test also uses the voltage and electric current of the power supply to the lead acid battery with values of 13.8 V and 0.5 A, respectively. The test results for balancing battery 1 against battery 2 are repeatedly shown in Figures 8 to 10.

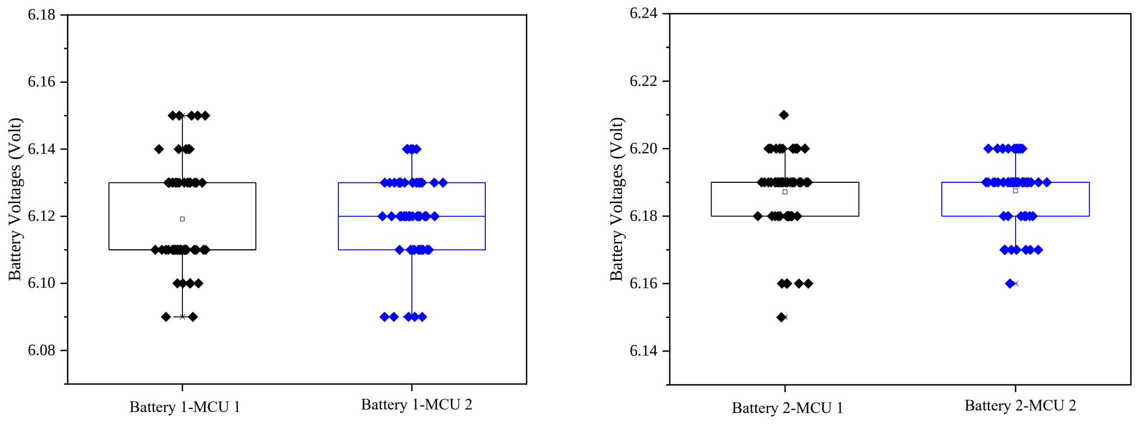


Figure 7. Boxchart of battery using MCU_1 and MCU_2; (a) first battery and (b) second battery

Table 1. Power dissipation circuit test results

No	MCU voltage 1 (V)	MCU voltage 2 (V)	First dissipation circuit (V)	Second 1 dissipation circuit (V)
1	0.965	0.86	OFF	OFF
2	1.955	1.86	OFF	OFF
3	2.905	2.81	OFF	OFF
4	3.845	3.82	OFF	OFF
5	4.8	4.82	OFF	OFF
6	5.74	5.85	OFF	OFF
7	6.69	6.82	ON	ON
8	7.65	7.8	ON	ON
9	8.6	8.81	ON	ON
10	9.55	9.76	ON	ON
11	10.49	10.73	ON	ON
12	11.47	11.81	ON	ON
13	12.35	12.7	ON	ON

According to Figures 8 to 10, the detection voltage of the two batteries is balanced at 6.8 V during the battery voltage balancing test within 140 minutes and 160 minutes. In addition, the power dissipation resistor circuit does not heat up to the touch of a finger. So, it can be concluded that the battery balancing circuit is functioning properly.

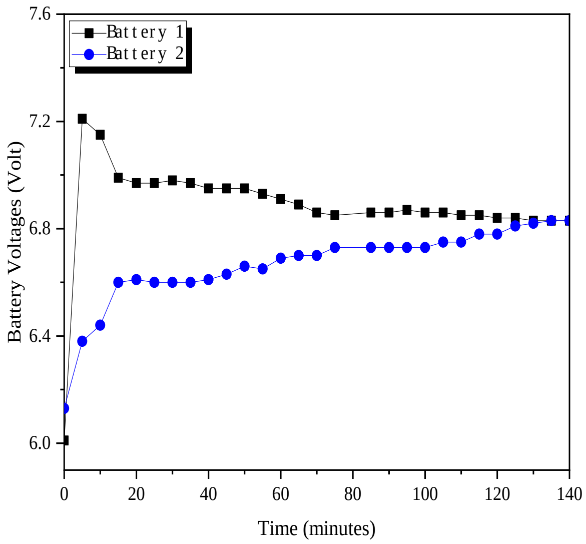


Figure 8. First test results battery voltage balancing 1 and 2

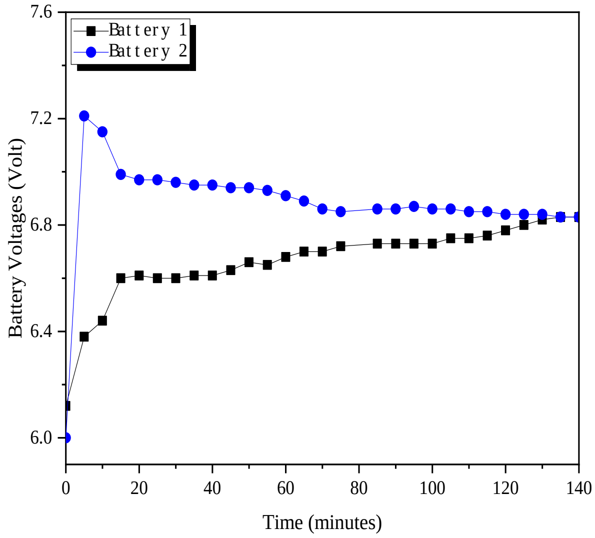


Figure 9. Second test results battery voltage balancing 1 and 2

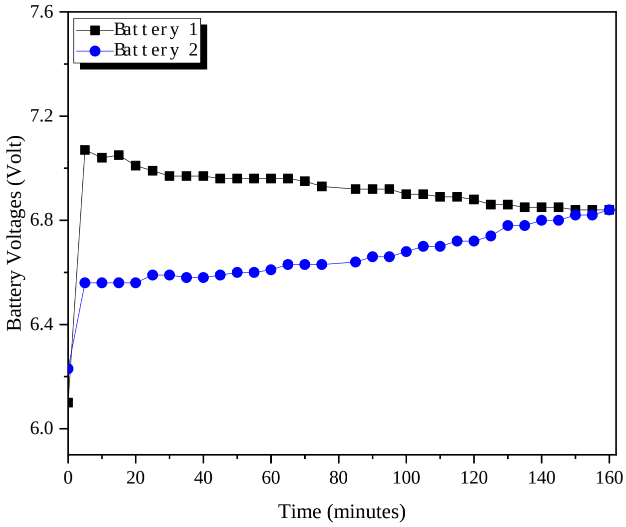


Figure 10. Third test results battery voltage balancing 1 and 2

4. CONCLUSION

The voltage balancing system for 2 lead acid batteries can be monitored with a large balance voltage at 6.8 V at a time of 140 minutes for MCU 1 and 160 minutes for MCU 2. System power supply can be via a USB power supply with a voltage of 5 V with a current of 1 A or a power supply 300 mAh capacity external battery. The system can detect battery voltage using a voltage detection circuit with MCU 1 voltage detection errors for battery voltage detection values 1 and 2. The average error percentage of batteries 1 and 2 using MCU 1 against the average voltage detection value using a multimeter is 0.09%. Meanwhile, the average error percentage for batteries 1 and 2 using MCU 2 is 0.3%. The system can send, receive or display 2 lead acid battery voltage data between MCUs using a wifi module arranged in series through a series of displays and databases, so that it can be monitored by the user. The system can dissipate excess lead acid battery power using a dissipation circuit, if the detected voltage exceeds the reference voltage.

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REFERENCES

[1] P. Breeze, "Power System Energy Storage Technologies," *Power Generation Technologies*, pp. 219-249, 2019, doi: 10.1016/b978-0-08-102631-1.00010-9.

[2] S. Ci, N. Lin, and D. Wu, "Reconfigurable Battery Techniques and Systems: A Survey," *IEEE Access*, vol. 4, pp. 1175-1189 2016, doi: 10.1109/ACCESS.2016.2545338.

[3] E. M. Erickson *et al.*, "Review—Development of Advanced Rechargeable Batteries: A Continuous Challenge in the Choice of Suitable Electrolyte Solutions," *Journal of The Electrochemical Society*, vol. 162, no. 14, 2015, doi: 10.1149/2.0051514jes.

[4] Y. Liang *et al.*, "A review of rechargeable batteries for portable electronic devices," *InfoMat*, vol. 1, no. 1. pp. 6–32, 2019, doi: 10.1002/inf2.12000.

[5] C. Singhtaun and N. Viteejongjaroen, "Determining the appropriate setting of lead-acid battery plate coating with sulfuric acid via response surface methodology," *International Journal of Smart Grid and Clean Energy*, vol. 7, no. 2, pp. 109-116, 2018, doi: 10.12720/sgce.7.2.109-116.

[6] G. J. May, A. Davidson, and B. Monahov, "Lead batteries for utility energy storage: A review," *Journal of Energy Storage*, vol. 15, pp. 145-157, 2018, doi: 10.1016/j.est.2017.11.008.

[7] M. Faisal, M. A. Hannan, P. J. Ker, A. Hussain, M. Bin Mansor, and F. Blaabjerg, "Review of energy storage system technologies in microgrid applications: Issues and challenges," *IEEE Access*, vol. 6, pp. 35143-35164, 2018, doi: 10.1109/ACCESS.2018.2841407.

[8] J. Büngeler, E. Cattaneo, B. Riegel, and D. U. Sauer, "Advantages in energy efficiency of flooded lead-acid batteries when using partial state of charge operation," *Journal of Power Sources*, vol. 375, pp. 53-58, 2018, doi: 10.1016/j.jpowsour.2017.11.050.

[9] Narayan R and Venkateswarlu M, "Studies on portable power banks for recharging electronic gadgets," *International Research Journal of Engineering and Technology*, vol. 5, no. 3, pp. 1549-1553, 2018.

[10] O. K. Atusiuba and S. A. Daramola, "A Remedy for Overcharging and Undercharging of Batteries Connected in Series," *International Journal of Innovative Research in Science Engineering and Technology*, vol. 9, no. 11, pp. 10208–10214, 2020, doi: 10.15680/IJIRSET.2020.0911002.

[11] H. C. Wang, X. Cao, W. Liu, and X. Sun, "Research Progress of the Solid State Lithium-Sulfur Batteries," *Frontiers in Energy Research*, vol. 7, pp. 1-20, 2019, doi: 10.3389/fenrg.2019.00112.

[12] Y. Barsukov and J. Qian, *Battery Power Management for Portable Devices*. Norwood, Massachusetts: Artech House, 2013.

[13] D. Thiruvonasundari and K. Deepa, "Evaluation and comparative study of cell balancing methods for lithium-ion batteries used in electric vehicles," *International Journal of Renewable Energy Development*, vol. 10, no. 3, pp. 471-479, 2021, doi: 10.14710/ijred.2021.34484.

[14] M. Uzair, G. Abbas, and S. Hosain, "Characteristics of battery management systems of electric vehicles with consideration of the active and passive cell balancing process," *World Electric Vehicle Journal*, vol. 12, no. 3, pp. 1-38, 2021, doi: 10.3390/wevj12030120.

[15] C. S. Moo, Y. C. Hsieh, and I. S. Tsai, "Charge equalization for series-connected batteries," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 39, no. 2, pp. 704-710, 2003, doi: 10.1109/TAES.2003.1207276.

[16] Z. B. Omariba, L. Zhang, and D. Sun, "Review of Battery Cell Balancing Methodologies for Optimizing Battery Pack Performance in Electric Vehicles," *IEEE Access*, vol. 7, pp. 129335-129352, 2019, doi: 10.1109/ACCESS.2019.2940090.

[17] M. Daowd, N. Omar, P. Van Den Bossche and J. Van Mierlo, "Passive and active battery balancing comparison based on MATLAB simulation," *2011 IEEE Vehicle Power and Propulsion Conference*, Chicago, IL, USA, 2011, pp. 1-7, doi: 10.1109/VPPC.2011.6043010.

[18] T. Stuart and W. Zhu, "Fast equalization for large lithium ion batteries," *IEEE Aerospace and Electronic Systems Magazine*, vol. 24, no. 7, pp. 27-31, 2009, doi: 10.1109/MAES.2009.5208557.

[19] Hemavathi, "Overview of cell balancing methods for Li-ion battery technology," *Energy Storage*, vol. 3, no. 2, 2021, doi: 10.1002/est2.203.

[20] J. Cao, N. Schofield, and A. Emadi, "Battery balancing methods: A comprehensive review," 2008, pp. 1-6, doi: 10.1109/VPPC.2008.4677669.

[21] S. Wang *et al.*, "Battery system active control strategies," in *Battery System Modeling*, pp. 313-340, 2021, doi: 10.1016/b978-0-323-90472-8.00006-8.

[22] B. Yan, K. Wang, Z. Hu, C. Wu, and X. Zhang, "Shunt Damping Vibration Control Technology: A Review," *Applied Sciences (Switzerland)*, vol. 7, no. 5, pp. 1-31, 2017, doi: 10.3390/app7050494.

[23] R. Pilawa-Podgurski, "The Future of Power Electronics Circuits: New Technologies and Managed Complexity Will Drive the Future," *IEEE Power Electronics Magazine*, vol. 7, no. 2, pp. 41-43, 2020, doi: 10.1109/MPEL.2020.2988078.

[24] N. Samaddar, N. S. Kumar, and R. Jayapragash, "Passive cell balancing of li-ion batteries used for automotive applications," in *Journal of Physics: Conference Series*, 2021, vol. 1716, no. 1, pp. 1-9, doi: 10.1088/1742-6596/1716/1/012005.

[25] E. Banguero, A. Correcher, Á. Pérez-Navarro, F. Morant, and A. Aristizabal, "A review on battery charging and discharging control strategies: Application to renewable energy systems," *Energies*, vol. 11, no. 4. pp. 1-15, 2018, doi: 10.3390/en11041021.

[26] Z. Liu and H. He, "Model-based sensor fault diagnosis of a lithium-ion battery in electric vehicles," *Energies*, vol. 8, no. 7, pp. 1-8, 2015, doi: 10.3390/en8076509.

[27] N. Vangapally *et al.*, "Lead-acid batteries and lead–carbon hybrid systems: A review," *Journal of Power Sources*, vol. 579, 2023, doi: 10.1016/j.jpowsour.2023.233312.

[28] K. R. Bullock, "Carbon reactions and effects on valve-regulated lead-acid (VRLA) battery cycle life in high-rate, partial state-of-charge cycling," *Journal of Power Sources*, vol. 195, no. 14, pp. 4513-4519, 2010, doi: 10.1016/j.jpowsour.2009.10.027.

[29] A. Czerwiński, J. Wróbel, J. Lach, K. Wróbel, and P. Podsadni, "The charging-discharging behavior of the lead-acid cell with electrodes based on carbon matrix," *Journal of Solid State Electrochemistry*, vol. 22, no. 9, pp. 2703–2714, 2018, doi: 10.1007/s10008-018-3981-4.

[30] X. Hao, Y. Sun, Z. Su, and B. Liu, "Health status comparisons of lithium-ion batteries when fusing various features," *International Journal of Performability Engineering*, vol. 15, no. 1, pp. 138-145, 2019, doi: 10.23940/ijpe.19.01.p14.138145.

BIOGRAPHIES OF AUTHORS

Bandiyah Sri Aprillia received her Master degree from Graduate Institute of Applied Science and Technology, National Taiwan University of Science and Technology in 2017. She was a research assistant at Academia Sinica under the supervision of Prof. Li-Chyong Chen and Prof. Kuei-Hsien Chen during her master degree. Her research interests focus on earth-abundant chalcogenide thin-film solar cells. She can be contacted at email: bandiyah@telkomuniversity.ac.id

Desri Kristina Silalahi received Bachelor of Mathematics from University of North Sumatera and Master degree in Mathematic from University of Indonesia. Now, she is lecturer at Bachelor of Electrical Engineering Department, Telkom University, Indonesia. Her research interest focus on statistical, applied mathematics and machine learning. She can be contacted at email: desrikristina@telkomuniversity.ac.id.

Kharisma Bani Adam graduated from the Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, and earned an MS degree from the Institut Teknologi Sepuluh Nopember in 2013. He graduated Doctor of Philosophy from University, Kumamoto, Japan. His research interest focus on power electronics and renewable energy. He can be contacted at email: kharismaadam@telkomuniversity.ac.id.

Putu Krishna Bhaskara Perteka Yuda is an undergraduate alumnus of the Electrical Engineering study program, Telkom University, Bandung, Indonesia. He can be contacted at email: putukrishnayuda@gmail.com.