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Microcontroller-Based Lead-Acid Battery Balancing System for Electric Vehicle Applications

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Abstract

In the application of lead-acid batteries for electrical vehicle applications, the 48 Volt of required voltage is connected of four 12 Volt batteries in series configuration. While utilized batteries, the battery stack is repeatedly charged and discharged. Hence, the differences of charge-discharge speed may result in different state-of-charge in the battery cells. If without proper protection, it may cause an excessive discharge which goes to an early damage of the battery. Therefore, lead-acid battery requires to have a battery management system to extend the battery lifetime. Following the LTC3305 balancing scheme, the battery balancing circuit with an auxiliary storage can employ a sequential battery imbalance detection algorithm by comparing the voltage of a battery on stack and the auxiliary storage. The system is in balance if the battery voltage imbalance is less than 12.5 mV/cell. In this paper, we are trying to replace the function of LTC3305 with a NUCLEO F767ZI microcontroller, so the balancing process, the battery voltage, the drawn current to or from the auxiliary battery and the surrounding temperature can be fully monitored. The result is this device was fully created with the highest voltage imbalance between batteries on stack is on 160 mV and the highest voltage imbalance between battery on stack and auxiliary battery is 120 mV which is exceeding the maximum voltage imbalance value. Therefore, this device still needs to be refined in the future to provide the better results.

Keywords: LTC3305, battery balancing system, voltage imbalance, electric vehicle, NUCLEO F767ZI microcontroller.

I. INTRODUCTION

In the electric vehicle application, four 12 Volt battery of Lead-acid batteries are connected in series stack configuration to provides 48 Volt of required voltage [1]. with internal parameter of each battery usually has different initial charge capacities, cell compounds and other external effects.

In addition, while utilized the batteries, the battery on stack is repeatedly charged and discharged. Hence, the differences of charge-discharge speed may result in different state-of-charge in the battery cells and without proper protection, may cause an excessive discharge of lead-acid batteries, and this will cause an early damage of the battery. Therefore, the lead-acid battery requires to have a battery management system to extend battery life [1], [2].

The LTC3305 is an integrated circuit developed by Linear Technology Corporation which specifically designed to be used as the controller for balancing four or more 12 Volt lead-acid batteries connected in series configuration [3].

The objective of this paper is to make the microcontroller-based lead-acid battery management system, with replacing the function of LTC3305 with a microcontroller so the balancing process, the battery voltage, the drawn current to or from the auxiliary battery and the surrounding temperature can be fully monitored

II. BATTERY BALANCING SYSTEM

A. Battery Balancing Method

Method for battery balancing system are classifieds into 2 types, a passive, and an active balancing method. A passive battery balancing method use resistor as a load to balance the cell energy of a battery pack by discharging the excess energy or by consuming the higher energy cell than others. Although this passive battery balancing method is easy to implement, its energy transmission efficiency is usually low due to energy losses generated by heat dissipation from the resistors [4].

On the other hand, an active battery balancing method transfers energy from higher cell energy to lower cell energy using a power electronic interface, which the efficiency will be jump high. Although this active method balancer has higher efficiency than a passive method of battery balancer, its control algorithm may be complex, and its production cost is expensive because each cell should be connected with an additional power electronics interface [4].

B. LTC3305 Balancing Method

The LTC3305 balances four or more 12 Volt lead-acid battery in series configuration. Its use an auxiliary battery or an alternative storage cell to transfer charge to and from individual batteries within a series-connected stack. The balancing process of this method utilized 10 gates or switches to transfer the energy [1], [3]. The detail of its arrangement is shown on Figure 1.

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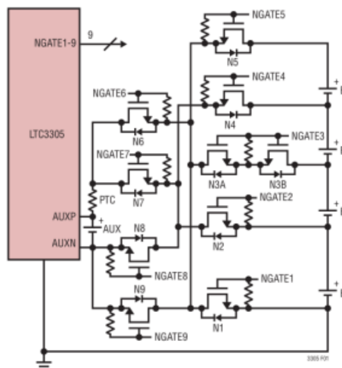

Figure 1. LTC3305 Configuration

The LTC3305 has two operation mode, timer mode and continuous mode. The timer mode operation balancing process begin with the connected of the bottom switch of the battery 1 on the stack to auxiliary battery. For the current state that N9 and N1 switch should turned on. After 35ms internal timer passed up, the voltage comparation sensor starts to compare the voltage between the battery 1 and the auxiliary battery and depend on the voltage differentiation values to the termination voltage [1], [3], [5-9].

If the voltage differentiation is less than chosen termination voltage, the battery will be deemed and after that the bottom switch are turned off [1], [3], [5-9]. The Top and Bottom switch arrangement is given on Table 1.

TABLE 1.
TOP AND BOTTOM SWITCHES ARRANGEMENT FOR FOUR BATTERIES

Battery to be Balanced	**Top Switch**	**Bottom Switch**
Battery 1	NGATE7, NGATE2	NGATE9, NGATE1
Battery 2	NGATE6, NGATE3	NGATE8, NGATE2
Battery 3	NGATE7, NGATE4	NGATE9, NGATE3
Battery 4	NGATE6, NGATE5	NGATE8, NGATE4

If the voltage differentiation is greater than chosen termination voltage, the top switched for the current state N7 and N2 are switch ON allowing the voltage of the battery 1 and auxiliary battery to be connected in parallel which mean the balancing process is begin. And after 35ms settled internal timer passed up, the voltage comparation sensor starts to measure the voltage differentiation and compare it to the termination voltage [1], [3].

The battery 1 will stay connected to the auxiliary battery until the voltage differentiation is on termination voltage range or TBAT timeout occurs. After the differentiation voltage achieve the termination voltage values or TBAT timeout occurs, the top and bottom switch are tuned off and an internal timer are settled to 40ms and after passed up, the process will be going to the next battery and for the current state it will be going to battery 2 [1], [3].

The balancing process of each battery is same. So, it will just follow the first rule of this method. The detail flow process of LTC3305 Timer mode operation is shown on Figure 2 below.

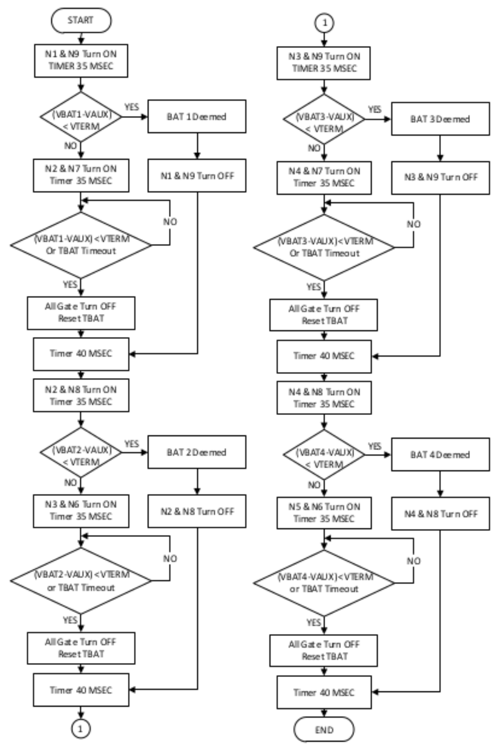

Figure 2. LTC3305 Timer Mode Operation Chart

The Continuous operation mode has a similarity to the timer mode, the different is the balancing process of continuous mode is always continuing even if the battery voltage on the stack is balanced, its mean. The balancing process will be shut off only when the MODE pin pulled to low, so the timer mode operation is selected [1], [3].

In the continuous mode operation, balancing process is not terminated by comparative sensor but terminated by TBAT time out. Its mean that the auxiliary battery is always connected to the battery until TBAT time out occurs, the voltage in connected battery can change before it going to the next battery. The voltage balancing result of this mode may be different to the programmed voltage termination. On the worst, the auxiliary battery voltage is much smaller than the battery on stack and the individual battery on stack voltage may be up to twice the selected termination voltage when it balanced [1], [3].

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Although the concept of balancing has only a little bit different, it has a big differentiation on the actual balancing process, the balancing process on continuous mode used longer time than timer mode because it also balanced the balanced battery [3]. The detail of Continuous mode operation flow process is shown on Figure 3 below

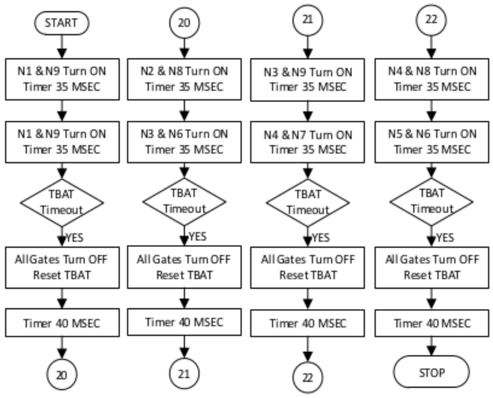

Figure 3. LTC3305 Continuous Mode Operation Chart

The LTC3305 voltage termination (VTERM), is the voltage differentiation between the auxiliary battery and the connected battery on stack which is considered to be balanced. Termination voltage is settled using TERM1 and TERM2 pins on the integrated board [3]. The pins configuration shown in Table 2 below.

TABLE 2.
LTC3305 TERMINATION VOLTAGE

TERM 1	TERM 2	V TERMINATE
0	0	±12.5mV
0	1	±50mV
1	0	±25mV
1	1	±100mV

The battery considered to be balanced if the voltage differentiation is on termination voltage range. For example, when the termination pin, TERM1 is 0 or switched OFF and the TERM2 is 1 or switched ON, the voltage differentiation should be ±50mV to be considered as balanced [1], [3].

Other than mentioned before, LTC3305 also has some feature including under-voltage (UV) & over-voltage (OV) fault threshold. It is also equipped with several indicators that allow users to monitor which battery is being balanced. The detail of this LTC3305 conjugation method please refer to its datasheet [1], [3].

C. Implemented Concept

The concept that has been implemented in this project is based on LTC3305 balancing method which balance four or more lead-acid batteries configured in series configuration. This system employs an auxiliary battery to transfer excess charge from or to each connected battery in the stack. MOSFET also used to connect the battery on stack to auxiliary battery in parallel mode so there is no limit of current flowing to or from the auxiliary battery [1], [3]. The MOSFET switch arrangement can be seen at Figure 4.

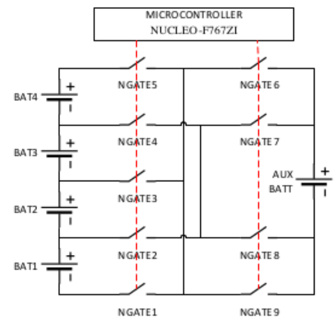

Figure 4. Cell Balancing Diagram with Parallelization Cell to Auxiliary Battery

The model of arranged switch consists of 9 gates as its switch and each gate has important function to ensuring the charge are able to move freely to or from auxiliary battery to each battery on stack. The gate driven by Microcontroller NUCLEO-F767ZI with target controller STM32F767ZI from STMicroelectronics NV to ensure the switching gate are switched on right time, right duty cycle and right frequency.

The way of parallelization is the same scheme as LTC3305 which shown on Table 1. top and bottom switches arrangement for four batteries stack

III. DESIGN AND IMPLEMENTATION

A. Proposed Balancing Method

The proposed balancing method is by replacing the LTC3305 with a NUCLEO F767ZI as its main microcontroller. The basic concept and working principle of this work is shown at Figure 5 below.

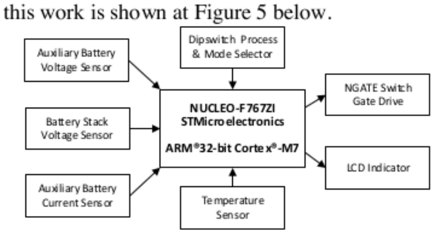

Figure 5. Proposed Concept Diagram

The proposed design which has been used on this work has 8 blocks, the auxiliary battery voltage sensor, battery stack voltage sensor, auxiliary battery current sensor, dipswitch for process and mode selector, temperature sensor, NGATE switch to control MOSFET gate, LCD indicator and NUCLEO F767ZI as main microcontroller.

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B. Working Principle of Each Block

The lead-acid battery balancer system work by accessing many of block operation, each block has different functionality and made separately to prevent mall function of its component.

1) Battery Stack Resistive Voltage Sensor

Battery stack resistive voltage sensor is used to measure each battery voltage using resistive voltage sensor. The sensor generated variable voltage at 0 – 3.3 Volt DC and then the analog voltage data read by analog input on NUCLEO F767ZI before converted it to actual voltage value inside the microcontroller. The circuit is show on Figure 6.

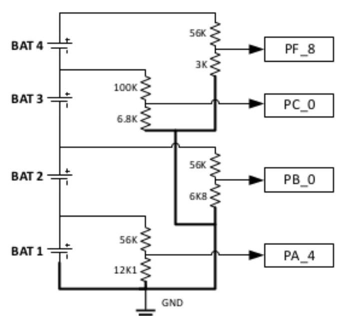

Figure 6. Battery Stack Resistive Voltage Sensor Diagram

The measuring system of this device is accumulating the voltage from the battery voltage below measured battery. So, to measure each battery follow the measure way as Table 3.

TABLE 3.
BATTERY VOLTAGE MEASUREMENT WAY

Measured Battery	Measuring Data			
Battery 1	ADC Value			
Battery 2	Battery 1 Voltage	ADC Value		
Battery 3	Battery 1 Voltage	Battery 2 Voltage	ADC Value	
Battery 4	Battery 1 Voltage	Battery 2 Voltage	Battery 3 Voltage	ADC Value

The NUCLEO F767ZI analog read range is from 0 volt to 3.3 Volt DC, which mean the resistor selection must follow the rule that the output of the resistive voltage sensor on maximum value do not exceed 3.3 volt. If the value exceeds this rule, the NUCLEO F767ZI is able to resist from being explode, but the output digital read by analog pin is same at 3.3 volt.

2) Auxiliary Battery Isolated Voltage Sensor

Auxiliary battery isolated voltage sensor is independent device used to measure the auxiliary battery voltage using resistive voltage sensor system. The resistive voltage sensor also using voltage divider system and then generated analog data 0 – 5 Volt DC before converted it to some value in microcontroller.

Arduino Nano used analog to digital converter on 10 bit's data in order to get more precisely at 0 ~ 1024 data. The data stored on decimal value and then translated it to 10-bit of output. The detail circuit is shown on Figure 7 below.

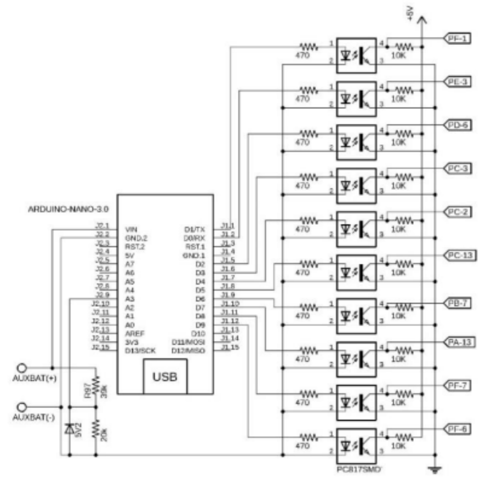

Figure 7. Auxiliary Battery Resistive Voltage Sensor Diagram

To isolate the sensor from the main microcontroller, the optocouplers is used in this system. The 10 pieces of this optocoupler has its own unique function and data value inside it, which shown on Table 4

TABLE 4.
OPTOCOUPLER OUTPUT VALUE

No	Output Pin	NUCLEO Pin	Value	Decimal Value
1	D0	PE_3	2^0	1
2	D1	PF_1	2^1	2
3	D2	PD_6	2^2	4
4	D3	PC_3	2^3	8
5	D4	PC_2	2^4	16
6	D5	PC_13	2^5	32
7	D6	PB_7	2^6	64
8	D7	PA_13	2^7	128
9	D8	PF_7	2^8	256
10	D9	PF_6	2^9	512

Analog data read by analog pin in Arduino Nano directly converted to digital value using binary value [5]. Further explanation is described on Table 5.

TABLE 5.
BINARY VALUE OF OPTOCOUPLER

No	ADC	2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9
1	100			■			■	■			
2	600				■	■		■			■
3	800						■			■	■

4	1000				■		■	■	■	■	■

Based on table above when the data analog data read by Arduino Nano is 100 so, the bits should be ON is 22, 25 and 26, others than this bit should turn off.

3) Auxiliary Battery Current Sensor

Auxiliary battery current sensor is used to measure drew current to or from auxiliary battery to battery on stack. This system used except for monitoring the current also used for protection from over current draw during switching process, when the overcurrent happened the switching process should open and the process stop, after that generated error indicator to be lit. An auxiliary battery current sensor is a device based on ACS758 from Allegro Microsystems the schematic is shown on Figure 8.

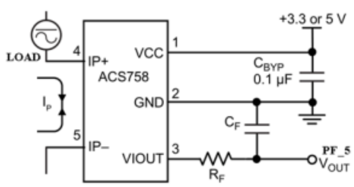

Figure 8. Auxiliary Battery Current Sensor Diagram

The used sensor type is ACS758LCB-050B-PFF-T which able to sense a current flowing through it in bidirectional way, with sensing sensitivity 40mV per ampere with maximum sensing is 50A [10].

4) Temperature Sensor

LM35 based temperature sensor is an integrated circuit device to measure temperature on surrounding area of the sensor. The LM35 series are precision integrated circuit temperature sensor devices with an analog voltage output linearly proportional to the Centigrade temperature, its low-cost temperature sensor due to wafer lever trimming and able to sense on minimum −55°C to maximum 150°C [11]. The schematic detail shown on Figure 9.

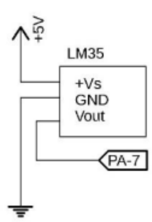

Figure 9. LM 35 Temperature Sensor Diagram

The output is an analog voltage from -550 mV to 1500 mV maximum, even the output voltage is very low, the microcontroller is still able to take an accurate data from the sensor. The sensor sensitivity is about 0+10.0 mV/°C with further explanation on Table 6.

TABLE 6.
LM35 TEMPERATURE VS VOLTAGE

Temperature (°C)	Voltage Output (mV)
150	1500
25	250
-55	-550
30	300
100	1000

5) Dipswitch Process Selector

Dipswitch process selector is a device used to select operational mode of this battery balancer system. The schematic shown Figure 10.

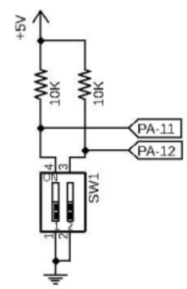

Figure 10. Figure 10. Dipswitch Process Selector Diagram

Each position of the dipswitch ON or OFF has a value inside it. The detail is shown on Table 7.

TABLE 7.
DIPSWITCH PROCESS SELECTOR POLE POSITION ARRANGEMENT

POLE 1	POLE 2	REMARKS
OFF	OFF	Timer Mode
ON	OFF	Continuous Mode
OFF	ON	Batch Test Mode
ON	ON	Individual Test Mode

6) Dipswitch Test Pin Selector

Dipswitch test pin selector work only when the control system entering the batch test mode or individual test mode only. The circuit design is shown on Figure 11.

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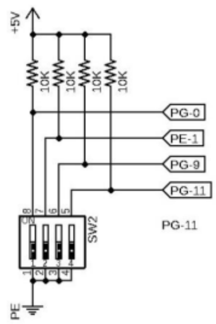

Figure 11. Dipswitch Test Pin Selector Diagram

Batch test mode is mode designed to check the energy transfer unit device performance with actual balancing process of each battery on the battery stack. The pin arrangement is shown on Table 8 below.

TABLE 8.
BATCH TEST MODE POLE ARRANGEMENT

Pole	NUCLEO Pin	Function	Activated Gate
1	PG_0	Battery 1 Gate Batch Test	Gate 7, Gate 2, Gate 9, Gate 1
2	PE_1	Battery 2 Gate Batch Test	Gate 6, Gate 3, Gate 8, Gate 2
3	PG_9	Battery 3 Gate Batch Test	Gate 7, Gate 4, Gate 9, Gate 3
4	PG_11	Battery 4 Gate Batch Test	Gate 6, Gate 5, Gate 8, Gate 4

Individual test mode designed to activate one by one of PWM gate on energy transfer unit, this mode programmed using bit function which each pole has unique value on it, for further explanation please refer on Table 9.

TABLE 9.
INDIVIDUAL TEST MODE POLE ARRANGEMENT

Pole	NUCLEO Pin	Value	Decimal Value
1	PG_0	2^0	1
2	PE_1	2^1	2
3	PG_9	2^2	4
4	PG_11	2^3	8

To activate PWM pin not only requires single pole to be activated but also possible to require three poles, for further explanation please refer to Table 10.

TABLE 10.
INDIVIDUAL TEST MODE GATE SWITCH

NGATE Switch to be Activate	Activated Pole	NUCLEO Pin
1	1	PG_0
2	2	PE_1
3	2, 1	PE_1, PG_0
4	3	PG_9
5	3, 1	PG_9, PG_0
6	3, 2	PG_9, PE_1
7	3, 2, 1	PG_9, PE_1, PG_0
8	4	PG_11
9	4, 1	PG_11, PG_0

The concept of this data reading is similar to auxiliary battery isolated voltage sensor which also read the data based on bit function. When the pole switch has been selected the NUCLEO pin will always generated PWM until the pole switched OFF or going to other NGATE switch.

7) NUCLEO F767ZI Microcontroller

To maintain and control all connected equipment, the NUCLEO F767ZI is selected. NUCLEO F767ZI is high speed and high-performance microcontroller from STMicroelectronics which its core is based on ARM® chipset on 32-bit Cortex®-M7 running up to 216 MHz, this device is a family of STM32 144 board which provides a flexible and an affordable way for users to try out new programming concepts and build a prototype with the STM32 microcontroller [12].

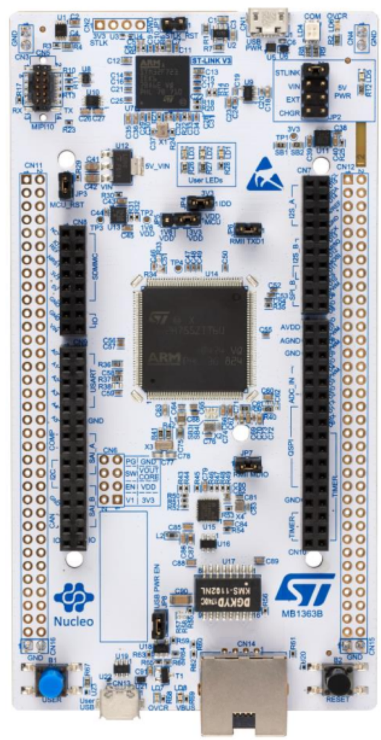

Figure 12. NUCLEO F767ZI

8) Control Power Supply Unit

Control power supply unit is simple device used to regulate the battery voltage on 12 VDC to 5 VDC and directly connect the output to the power supply +5V on

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the NUCLEO board. This device is used to power all device which using 5VDC as its power supply [13].

This device consists of two 100 micro-Farads of capacitor as filter to stabilize the output and single voltage regulator IC 7805 from Texas Instrument. The circuit of this device is shown on Figure 13.

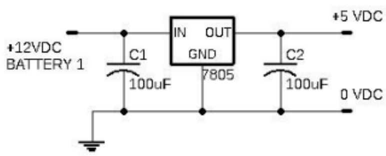

Figure 13. DC 5Volt Power Supply Diagram

9) LCD Monitor

LCD Monitor is main device for displaying current status of the battery balancer system. It is displayed voltages of batterie stack, auxiliary battery voltage, auxiliary battery current, surround temperature and which battery being balance [13]. This device only consists of LCD 2004 and its supporting circuit. Its circuit is shown on Figure 14.

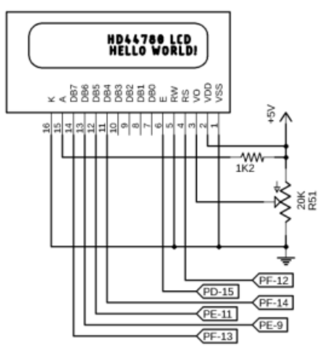

Figure 14. LCD 1602 Diagram

10) Energy Transfer Unit

Energy transfer unites is an electronic relay device used to transfer energy to or from battery stack to auxiliary battery when there is the voltage differentiation on it to keep the battery voltage balance.

The detail schematic is shown on Figure 15. The connection using DC-DC converter as isolated power supply to activate the bidirectional switch of MOSFET. Also, the HCPL 3120 optocoupler is used to separate the voltage between the microcontroller and the MOSFET switch.

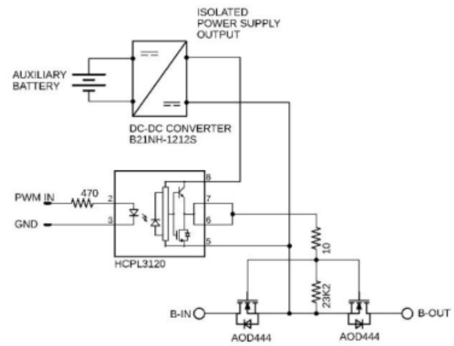

Figure 15. Energy Transfer Unit Sectional Diagram

The schematic on Figure 15 is shown only single energy transfer unit, which mean there are 9 copied schematics to replace the NGATE switch shown on Figure 4 implemented concept.

The PWM pin on NUCLEO F767ZI board to be connected to PWM IN is designed as shown Table 11 below.

TABLE 11.
PWM PIN FOR ENERGY TRANSFER UNIT

NGATE No	**PWM Pin**
NGATE 1	PA_5
NGATE 2	PB_6
NGATE 3	PC_7
NGATE 4	PB_10
NGATE 5	PB_4
NGATE 6	PA_3
NGATE 7	PD_13
NGATE 8	PE_14
NGATE 9	PE_13

C. Battery Balancer Working System

The lead-acid battery balancing system utilized four mode, two mode is based on LTC 3305 and another two mode is an additional mode for easier way to check and troubleshooting the circuit. For further explanation refer to Figure 16.

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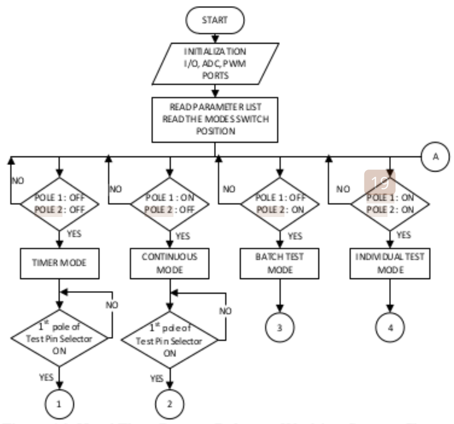

Figure 16. Head Flow Battery Balancer Working System Chart

There are four points where the program loop will begin on the sequencer, Timer Mode Operation, Continuous Mode Operation, Batch Test Mode and the last is Individual Test Mode. Each mode has its own sequence with his unique function. For more detail, please refer to explanation on the next sub chapter.

To enabling the modes, users must change the pole position of dipswitch process selector following the data on Table 12.

TABLE 12.
DIPSWITCH PROCESS SELECTOR POLE POSITION

POLE 1	POLE 2	REMARKS
OFF	OFF	Timer Mode
ON	OFF	Continuous Mode
OFF	ON	Batch Test Mode
ON	ON	Individual Test Mode

1) Timer Mode Operation

Timer mode operation is a mode based on LTC3305 which the balancing process is depending on sensor and timeout value. The balancing method of timer mode operation is same as shown on Figure 2 above, which the balancing process will run continuously from the battery 1 till battery 4 on stack repeatedly [3].

The balancing process of this method for example battery 1 will be end if the sensor of battery voltage determined that the voltage differentiation is on accepted range or the time out value has been achieved, after that the balancing process will go to the next battery, for current condition it should be go to battery 2, and the process repeatedly until the voltage of battery on stack and auxiliary battery has been balanced.

2) Continuous Mode Operation

Continuous mode operation is a mode based on LTC3305 which the balancing method is depend on timeout setting value. The balancing process is same as shown on Figure 3 above which shown to us the balancing process will run continuously from the battery 1 till battery 4 on stack repeatedly [3].

The balancing process of this method for example battery 1, will be end if the time out value has been achieved, after that the balancing process will go to the next battery, for current condition it should be go to battery 2, and the process repeatedly until the voltage of the battery on stack and auxiliary battery has been balanced

3) Batch Test Mode

Batch test mode is menu for driving the battery balancer system with connecting the top and bottom switch of auxiliary battery to a single battery on stack continuously while the switch is switched ON. This mode used to test the balancing process of the single battery on stack one by one to determine they are on perfect condition or on bad condition, this mode created because while the system working on continuous mode operation or timer mode operation it's difficult to check which circuit need to be maintain, because its switch is switched ON just for a while, while batch test mode is always running balancing process on single battery on stack during the switch toggle switched ON. The detail is shown on Figure 17.

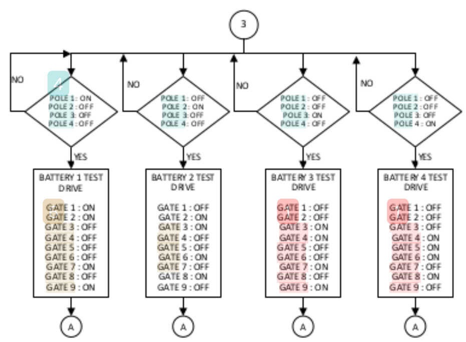

Figure 17. Batch test mode operation chart

4) Individual Test Mode

Individual test mode is menu for driving the battery balancer system one from nine energy transfer unit continuously during the switch sis switched ON. This mode used to test the balancing process on single energy transfer unit one by one to determine they are working well or not. This system is different from batch test mode, because batch test mode driving 4 energy transfer unit on the same time for balancing a single battery test, while individual test mode is only driving single energy transfer unit on a time. The detail of this mode is shown o Figure 18 below.

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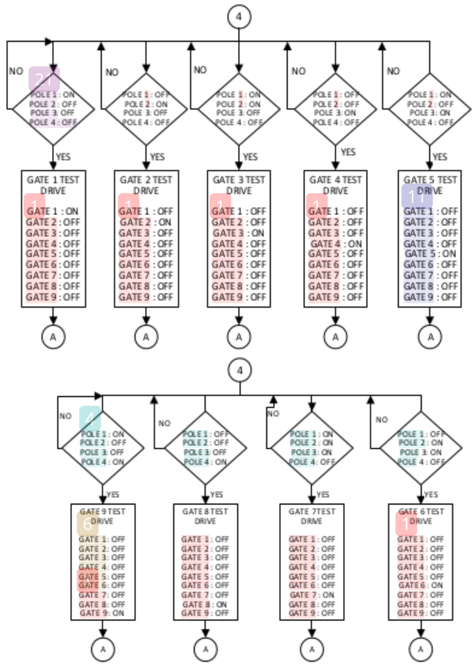

Figure 18. Individual test mode operation chart

IV. Experimental Result and Analysis

A. General Result

The general result of this experimental is all the connected block component are all working well. Which the connected block is consists of Battery stack resistive voltage sensor, Auxiliary battery isolated voltage sensor, Auxiliary battery current sensor, Temperature sensor, Dipswitch process selector, Dipswitch test pin selector, NUCLEO F767Zi microcontroller, control power supply circuit, LCD Monitor, and energy transfer unit.

B. Individual Test Mode Operation Result

Individual test mode is a mode specifically designed for testing and conforming each of the energy transfer unit block are working well before attaching it to the full connected system. When the abnormality detected, the energy transfer unit should be repair or replaced it with spare energy transfer unit.

The internal microcontroller parameter to drive the energy transfer unit is divided into 3 data, which the parameter is shown on Table 13 below.

TABLE 13.
INDIVIDUAL TEST MODE PARAMETER LIST

DATA	VALUES
Frequency of PWM	10 KHz
Duty cycle of PWM	80 %
Battery voltage (RMS)	12.9 Volt

The experiment held twice, the first is while the energy transfer unit on the positive side of the battery and the second time is while the energy transfer unit placed on negative side of the battery. Detail about the first experiment circuit configuration is shown on Figure 19 below.

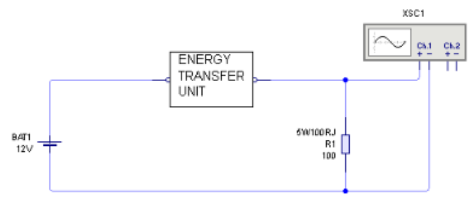

Figure 19. Single energy transfer unit on battery positive side test configuration

On the energy transfer unit, when the PWM charged with specification on Table 13 above, the result is shown on Figure 20 below.

Figure 20. Single energy transfer unit on battery positive side test result

As shown on Figure 20 above, the result of positive side test of energy transfer unit is look good, the wave frequency and duty cycle are almost the same as expected regarding the base parameter which shown on Table above.

The second time of experiment circuit configuration is shown on Figure 21 below, which the energy transfer unit placed on negative side of the battery.

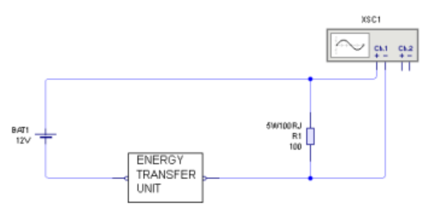

Figure 21. Single energy transfer unit on battery negative side test configuration

On the energy transfer unit, when the PWM charged with specification on Table 13 above, the result is shown on Figure 22.

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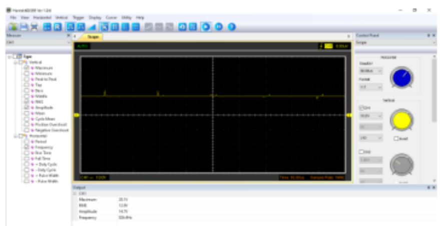

Figure 22. Single energy transfer unit on battery negative side test result

As shown on Figure 22 above, the result is good although the wave form is not formed but while there is no PWM to the energy transfer unit there is no voltage on the resistor side.

Beyond these two experiments when the energy transfer unit placed on positive or negative side of the battery the resistor temperature is arisen and that prove that the current flow though this circuit is good.

C. Batch Test Mode Operation Result

Batch test mode is a mode specifically designed for testing and conforming one block of the energy transfer unit which consist of 4 energy transfer unit are working well or not. This operational test can be done after passing the individual test.

The circuit diagram used to test this four-energy transfer unit is shown on Figure 23 below test with 120 Ohm 5W resistor as load (B circuit test).

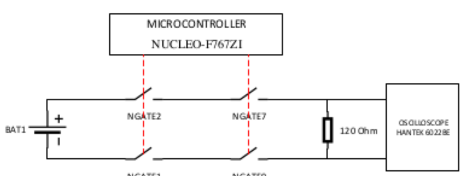

Figure 23. Batch test energy transfer unit configuration

Also, on the first test while driving PWM on circuit the result on the load area is shown on Figure 24 below.

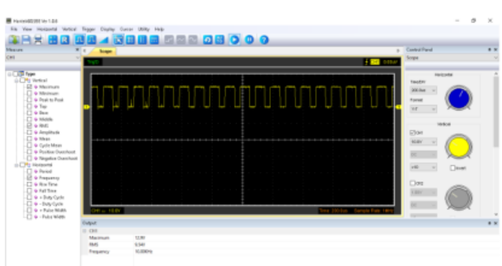

Figure 24. Batch energy transfer unit test result

Based on the result on the Figure 24 above, the result of this batch test mode is good. Beyond these experiment the resistor temperature is also arisen along with the time.

D. Timer Mode and Continuous Mode Testing Parameter

Full arranged energy transfer unit general parameter has two important point, pulse width modulation signal from microcontroller to drive energy transfer unit and the time spent for the battery balancing process will be held.

The programmed parameter for pulse width modulation generated by microcontroller to activate the energy transfer unit is shown on Table 14 below.

TABLE 14.
PWM MICROCONTROLLER SPECIFICATION

Gate No.	BMS Program		Measured by Oscilloscope	
	Freq.	Duty cycle	Freq.	Duty cycle
1	100 Hz	80 %	100 Hz	80 %
2	100 Hz	80 %	100 Hz	80 %
3	100 Hz	80 %	100 Hz	80 %
4	100 Hz	80 %	100 Hz	80 %
5	100 Hz	80 %	100 Hz	80 %
6	100 Hz	80 %	100 Hz	80 %
7	100 Hz	80 %	100 Hz	80 %
8	100 Hz	80 %	100 Hz	80 %
9	100 Hz	80 %	100 Hz	80 %

The microcontroller used on this system is NUCLEO F767ZI with 216 MHz maximum CPU frequency for high-speed data reading and processing.

The internal parameter setting of the switching time or how long the battery balancing process will be held on single battery on stack through auxiliary battery is shown on Table 15 below.

TABLE 15.
INTERNAL MICROCONTROLLER PARAMETER

No	Setting Name	Value
1	TBAT Timeout	5000 milliseconds
2	Down Switch to Top Switch Buffer time	35 milliseconds
3	Next Battery Time Gap	40 milliseconds

TBAT timeout is the time value for how long the balancing process held for one battery on stack. Down switch to top switch buffer time is a time gap before driving the top switch of configured energy transfer unit after driving the down switch of the configured energy transfer unit.

The voltage measurement result of each battery which shown on the chart are taken after the battery 4 balancing process is completed or while battery on its steady condition not while the balancing process is on progress.

E. Timer Mode Operation Result and Analysis

Timer mode operation is a mode based on LTC3305 which the balancing process is depending on sensor and timeout value. The balancing method of timer mode operation is same as shown on Figure 2 above, which the balancing process will run continuously from the battery 1 till battery 4 on stack repeatedly.

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The data result below shown a voltage measurement chart data of each battery on stack. The experiment has been done twice with the different is only on the initial battery voltage before balancing process.

The full arranged energy transfer unit timer mode operation test 1 result is shown on Figure 25 below.

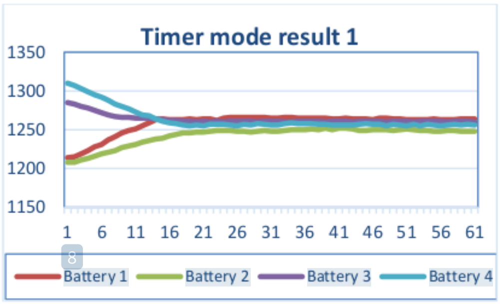

Figure 25. Timer mode test 1 result chart

Based on result charts on figure 25 result 1 above, the biggest voltage differentiation in the last minute of the test is between Battery 1 and battery 2 with the voltage imbalance is 160 mV.

The full arranged energy transfer unit timer mode operation test 2 result is shown on Figure 26 below.

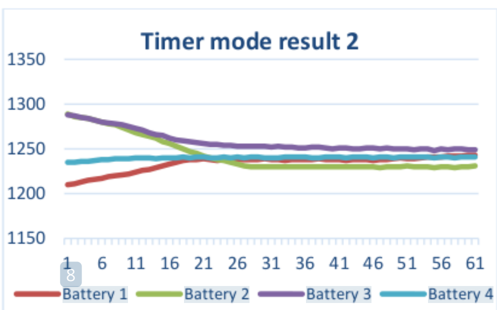

Figure 26. Timer mode test 2 result chart

Based on result charts on figure 25 result 1 above, the chart is more stable than the first-time trial. The biggest voltage differentiation in the last minute of the test is also between Battery 1 and battery 2 with the voltage imbalance is 180 mV.

battery balancing process on this work is not fully working, the battery voltage differentiation is over the voltage imbalance value on 12.5 mV.

Although the longer of time given for the experiment, the value of the battery voltage is unable to achieve the voltage imbalance below 13.5mV.

During the balancing process, the battery balancing process is run well without any overcurrent and over temperature.

F. Continuous Mode Operation Result and Analysis

Continuous mode operation is a mode based on LTC3305 which the balancing method is depend on timeout setting value. The balancing process is same as shown on Figure 3 above which shown to us the balancing process will run continuously from the battery 1 till battery 4 on stack repeatedly.

The data result below shown a voltage measurement chart data of each battery on stack. The experiment has been done twice with the different is only on the initial battery voltage before balancing process.

The full arranged energy transfer unit continuous mode operation test 1 result is shown on Figure 27 below.

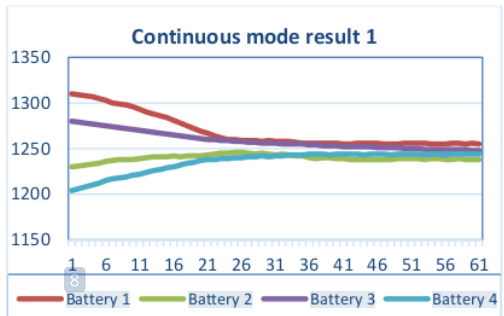

Figure 27. Continuous mode test 1 result chart

Based on result charts on figure 27 result 1 above, the biggest voltage differentiation in the last minute of the test is between Battery 1 and Battery 2 with the voltage imbalance is 170 mV.

The full arranged energy transfer unit continuous mode operation test 2 result is shown on Figure 28 below.

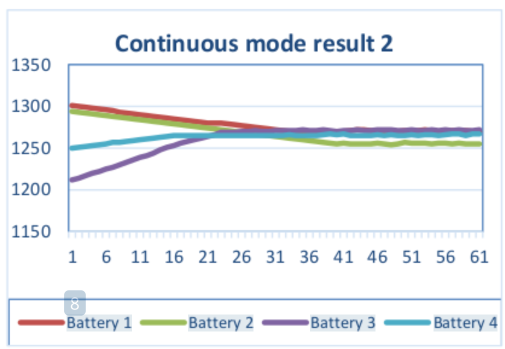

Figure 28. Continuous mode test 2 result chart

Based on result charts on figure 28 result 1 above, the biggest voltage differentiation in the last minute of the test is also between Battery 1 and battery 2 with the voltage imbalance is 170 mV.

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Although the longer of time given for the experiment, the value of the battery voltage is unable to achieve the voltage imbalance below 13.5mV.

During the balancing process, the battery balancing process is run well without any overcurrent and over temperature.

CONCLUSIONS

The prototype of microcontroller-based lead-acid battery balancing system has been made and the actual batteries voltage monitoring with actual auxiliary battery current drawn monitoring have been attached to the system. Also, an additional testing mode for an easier way to check the output on each transfer unit has been added. Lastly, the overcurrent and overheat protection system of this device is successfully built.

Based on the results of our testing analysis, the biggest voltage imbalance for the timer mode is between Battery 1 and Battery 2. And from timer mode and continuous mode, result tests show that the highest voltage imbalance based on its final value is 180 mV, which is higher than the target of voltage imbalance to be below 13.5 mV. Although, timer mode operation balancing process is faster than continuous mode operation one. However, there is no overcurrent and over temperature during the balancing process of timer mode and continuous mode operation along the time.

ACKNOWLEDGMENTS

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