Design of a load detection circuit using magnetic field–based transistor switch for charge controllers

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***Abstract*— This is a design of a load detection circuit using magnetic field – based transistor switch for charge controllers. Charge controllers are mostly used in harvesting energy from renewable sources. It works together with solar panels and the likes to collect and store energy to a battery. It is responsible for the operation of the battery, whether it will charge to store energy or it will discharge to make use of the energy stored. The battery is charged when there is enough energy being produced and it is discharged when the energy is insufficient to supply the power being demanded. This charge controller has two innovative main features. The first one is for the battery charging. Multiple batteries are employed so that more energy will be stored. Conventional charge controllers use only one battery, but once this battery is full the excess energy being harvested is thrown away. To prevent this, another battery will be charged to save and store the excess energy the other one cannot accumulate. The second one is focused in the battery discharging. The load detection circuit aims to guarantee that the energy stored in the battery is being used efficiently. Typical charge controllers let the battery supply the whole system even if no load is connected. This load detection circuit will detect if a load is connected to the system before letting the battery discharge. The battery will be disconnected from the system when there is no load so that the energy will be saved for more practical use. It will allow the battery to discharge for normal operation only when a load is connected to the system.**

Keywords—charge controller; multiple batteries; switching; hall effect; load detector

I. INTRODUCTION

A potential crisis arises whenever the demand becomes greater than the supply. Energy shortage is considered as one of the world's greatest crises today because of the continuous growth in demand and the deterioration of the traditional resources that is fossil fuel. Majority of the population all over the world do not really think energy shortage is a big issue until they see the price of their electric bill go up or when they experience blackouts but this crisis will soon take its full effect in no time. That is why taking advantage of different renewable energies like solar, wind and hydro are logical solution. There are many kinds of renewable energy harvesting systems that we can utilize to generate energy like solar panels, windmill and hydro turbines which can provide power that is sustainable.

Most of these renewable energy harvesting systems has one thing in common and it is the use of charge controller in managing the generated energy. The charge controller basically determines what to do with the harvested energy, whether to store it into a battery or to use the energy to supply a connected load. In a research paper by Matin, M.A., Rahaman, A., Sarker, A. and Uddin, R. (2015), they stated that the success of a renewable energy harvesting system depends on several parameters. Power conversion and energy storage are two of the most important specification to take note if you aim to have an efficient and effective design. Storage, not generation, is the challenge for renewable energy. The generation of energy from these resources is not the main issue regarding its utilization but the real challenge is in the storage.

A device to store and conserve more energy was designed. It would allow the user to maximize the energy production of the renewable energy harvesters while conserving it at the same time. With this, the energy supply in the area where it is installed can meet or exceed the demand. This will make the energy cost much cheaper.

Furthermore, this is primarily for rural areas that are not reached by the main electric grid. The communities that are living without electricity will now have their chance to experience how comfortable life is with electricity. They will know how to use TVs, radios, electric fans and other appliances that they have never used. It seems like a very small thing, but it will surely have a huge impact in their lives.

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II. BACKGROUND

According to an article written by Andorka, F. (2012) charge controllers first surfaced in the early 1980s that came with just one to two stage designs that were not really efficient and complex. The issue with the early charge controller is on how they affect the battery health because their on/off charging style rapidly damages the batteries from either excessive heat or undercharging. Weinhardt, R. (1983) in his design for a photovoltaic battery charge controller used a relay which is connected in series with voltage divider bias resistors. Discrete voltage comparison was used to connect and disconnect the solar panel and the battery through the relay. The solar panel is just directly connected to the battery which makes it inefficient and shortens the lifespan of the battery.

Yeon, S. (1998) patented a battery charge controller having an adjustable termination current. With the use of a gain controller, the initial and second charging current can be set to control the charging phase of the battery. DC – DC converters are already being used to manipulate the voltage and current values for charging batteries.

Stand-alone wind turbine system was patented by Liuchen, C. (2006) which features a power conversion and a control unit. He included a dump load to dissipate excess power that is not required for the load and the battery charging. The dump load turns the excess energy into heat to prevent damage in the battery.

The latest innovations in charge controllers are focused solely on power conversion but the energy storage is not given much attention. The conventional way of energy storage is still on the usage of a single battery and turning the harvester off when the battery is full. Even the basic connections of the circuits were not really modified. It still has a scheme having the harvesters connected to the converters where the converters are interconnected to the battery and the load then gets its supply from the battery. With this kind of connection all harvested energy will still go to the battery before it is able to be a supply for the load, this process also damages the battery.

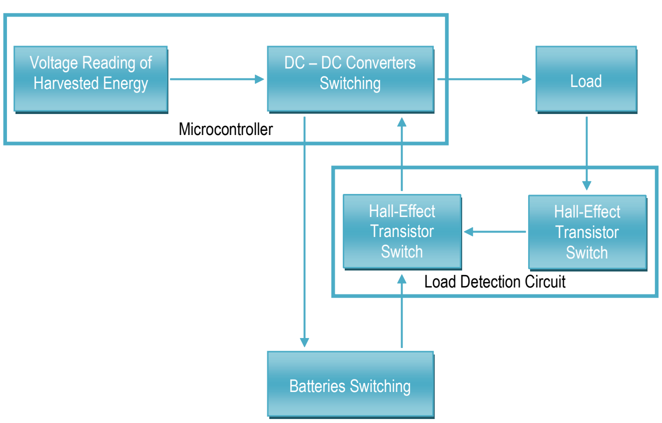

Fig. 1 Block Diagram of the Charge Controller

III. PROCESS AND METHODS

A. *Methodology*

The approach used in synthesizing this engineering design was generally top-down with a little concept of bottom-up. These methods were adapted from the book of R.M Ford, Design for Electrical and Computer Engineers 2008 ed., where he defined the top-down as an approach analogous to the concept of divide and conquer. While the bottom-up approach is applicable when there are constraints on the components that can be used. After the team has conceptualized the overall function of the system to be designed, it is divided into subsystems which will work together to achieve the overall goal.

In the case of this design project, the usage of a microcontroller falls down in the bottom-up approach as well as the ACS758 for the current sensing. These components where dictated from the beginning of the design development by the team's adviser. As for the top-down approach, the team divided the system into two sub circuits: the load detection circuit, and the battery switching circuit.

IV. PROJECT CONSTRUCTION

The block diagram and the flowchart of the charge controller designed are shown in Fig. 1 and Fig. 2 respectively. The system has three divisions of operation: microcontroller, load detection circuit and the battery switching circuit.

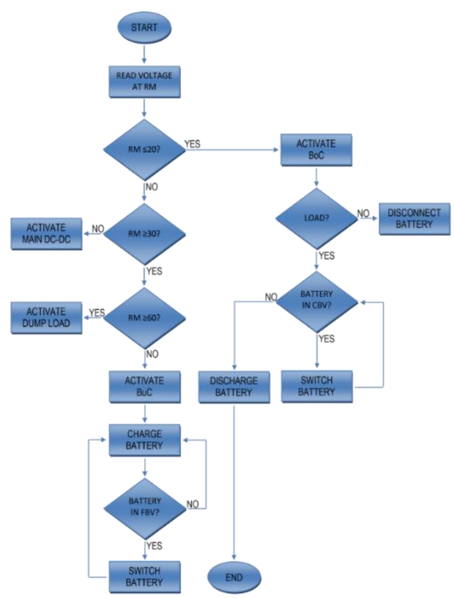

Fig. 2. Flowchart of the Charge Controller

Basically, there are five stages in the system, as shown in Fig. 1. The voltage level of the harvested energy was first read by a microcontroller then a dc – dc converter will be switched on depending on the voltage value read. If the energy harvested is high, the batteries will be charged, switching to the next battery if the other one was full. When the energy harvested is deficit, the current sensing will detect if there is a load connected to the system. The hall – effect transistor switch will only be saturated once a load is connected, letting the battery discharge for normal operation. The batteries will also be switched one by one during the discharging phase in the similar manner when charging. It is composed of the following sub-circuits:

A. Current sensing

- circuit that senses the current flowing in the circuit to detect whether a load was connected to the system or not.

B. Hall Effect transistor

- a magnetic field – based transistor switch which will saturate when the current sensing detects that there was a load connected to the system.

C. Batteries

- Multiple battery packs that can store energy and will be treated separately with one another. They will be connected or disconnected to the system depending if a load was applied or not.

D. Load

- Any device plugged into the output of the system that needs to be powered.

The voltage values for converter circuits switching is shown in Table 1. Each converter circuit will be activated depending on their respective corresponding voltage values produced by the Rectifier Matrix.

TABLE 1
RECTIFIER MATRIX VOLTAGE CONTROL HYSTERESIS

Converter Circuit	Voltage Set Points
BoC – Boost Converter	$V_{RM} \leq 20$ V
BuC – Buck Converter	30 V $\leq V_{RM} < 60$ V
Main DC – DC Converter	20 V $< V_{RM} < 30$ V
Dump Load	$V_{RM} \geq 60$ V

The battery voltage control hysteresis used in the system is shown in Table 2. These set points are configured according to the standards of Lithium Ion battery.

TABLE 2
BATTERY VOLTAGE CONTROL HYSTERESIS

Control Set points	Voltage Set Points
FBV – Full Battery Voltage	25.5 V (±1%) ≈ 100%
CBV – Cut-off Battery Voltage	20 V (±1%) ≈ 80%

Fig. 2 presents how the charge controller works, focusing in the switching of the system. First, the microcontroller reads the voltage harvested through the voltage divider. It then makes a decision after evaluating the generated energy. If it is producing less than 20V, the boost converter will be activated which will prompt the load detection circuit to sense if there is a load connected. If there is no load, the batteries will be prevented from discharging. On the other hand, if there is a load, the battery switching will start by reading and evaluating the voltage level of the first battery; if it is not in the CBV, it will be discharged. It will then switch to the next battery if it reaches CBV. The charge controller will stop its operation when all the batteries are in cut-off voltage level. It will resume operation once the Rectifier Matrix starts producing enough energy to supply the load or to charge the batteries.

If the energy harvested is between 20 V and 30 V, it will be directed to the main dc-dc converter without passing through the battery. If the generated energy is greater than 30 V, the buck converter will be activated to charge the battery. The battery switching will start by reading the voltage level of the first battery. If it is not in FBV, it will be charged until it reaches FBV then it will switch to the next battery.

If the energy harvested exceeds 60 volts, a dump load will be activated. This is for the safety of the dc – dc converters in the harvesting system.

V. TESTING PROCEDURES

The prototype was tested by module, similar to the tradeoffs evaluation. Each part of the design was tested separately and made sure that was working properly before integrating the parts together to make the debugging easier and to present the results more clearly.

All of the tests fell under the *white box test* which is conducted with the knowledge of the internal working of the system. Matrix tests and step-by-step tests were done to trace the accuracy of the voltage and current monitoring as well as the voltage drops in each component to ensure that the requirement of low power dissipation was achieved.

A. *Voltage Monitoring Testing*

This test procedure was done for the energy harvested and batteries to evaluate the accuracy of the monitoring operation. The set-up for the testing is shown in Fig. 3.

Fig. 2 Voltage monitoring testing set-up

The energy harvested and the batteries were represented by power supplies with the labels EH, B1 and B2. The actual voltage and the output of the voltage divider bias were monitored by digital multi-meters, with the respective labels as shown in the figure. The monitoring was displayed in the LCD.

B. *Load Current Monitoring Testing*

This test procedure was used to evaluate the accuracy of the load current monitoring. The set-up for the testing is shown in Fig. 4.

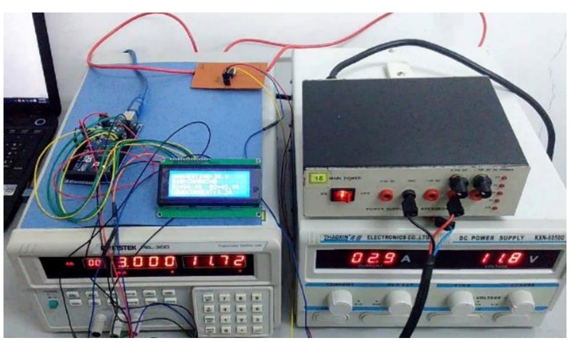

Fig. 3 Load current monitoring testing set-up

The supply voltage and the load were represented by the power supply and electronic load, respectively. The supply voltage was set to 12V, and the load current was varied from 0 ampere to 9 amperes with an increment of 0.5 amperes with the use of e-load. The current during the actual testing was limited to 9 amperes as it was the maximum rating of the electronic load and power supply used. The monitored current was displayed in the LCD.

C. *Battery Switching Testing (Discharging)*

This test procedure was done to assess if the batteries were switched when it reaches the cut-off battery voltage set which is 20 volts (≈80%). The set-up for the testing is shown in Fig. 5.

Fig. 4 Battery discharging testing set-up

The batteries and energy harvested were represented by power supplies labeled as EH, B1 and B2, respectively. The actual voltage levels were monitored by digital multi-meters placed above each power supply. The power supply representing the energy harvested was set to 5 volts as the batteries will discharge when the energy harvested is less than 20 volts. The discharged voltage was monitored with a digital multi-meter, labeled with V_{OUT}.

D. *Battery Switching Testing (Charging)*

This test procedure was done to assess if the batteries were switched when it reaches the full battery voltage set which is 25.5 volts (≈100%). The set-up for the testing is shown in Fig. 6.

Only one 12 – volt battery was used during the testing since it was the only available resource. The charging voltage was produced from a power supply, labeled B1 which is set to 14 volts and was monitored by a DMM. A digital multi-meter was connected in series with the positive side of the battery to monitor the current which will tell if the battery was charging or not. Another power supply, labeled as B2, was used to represent the second battery. The power supply and the 12 – volt battery will be interchanged later to see if the switching of the batteries will be performed.

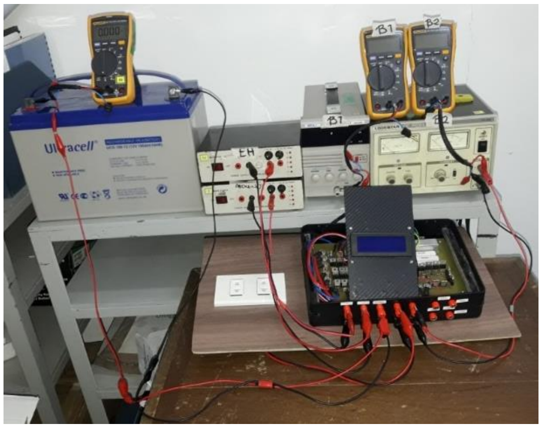

Fig. 5 Battery charging testing set-up

E. Battery Switching Testing (Voltage Drop)

This test procedure was done to evaluate if the output during the charging and discharging phase is within the 10% drop of the input voltage. The same set-up shown in Fig. 5 was used but the voltage across each active component was measured with a digital multi-meter.

F. Load Detection Testing

This test procedure was done to check if the batteries are prevented to discharge when no load is connected into the system. Thus, the microcontroller and the current sensing component are the only ones who are powered up when no load is connected into the system. The set-up for the testing is shown in Fig. 7.

Fig. 6 Load detection testing set-up

The batteries are represented by power supplies as well as the energy harvested. The load was represented by an electronic load. A set of digital multi-meters were connected in the input and output sections to measure the voltage and current which will be used in determining the ower consumption of the system. The output current will be monitored with the display value of the electronic load.

G. Thermal Testing

The final board undergone thermal testing to see if it was safe to operate in a long period of time and if it consumed excessive energy which will be determined when there are overheating components. The temperature of the critical components was monitored with Thermal Fluke to see if it was overheating during operation. The set-up for the testing is shown in Fig. 8.

Fig. 7 Thermal testing set-up

The energy harvested and the batteries were represented by power supplies as shown with the labels. The voltages were monitored by the digital multi-meters placed on top of each power supply. The system was tested only in discharging mode since the operation of the system in charging mode is similar with a reversed current flow. In addition to this, the load detection circuit will operate only in discharging mode.

VI. RESULTS AND DISCUSSION

A. Voltage Monitoring

Table 3 shows the result of the matrix test for the energy harvested monitoring. The display value was limited to one decimal value. The increment of the input voltage was set to 2V as the input voltage is up to 60V. The actual testing was conducted up to the input voltage of 31V because the rating of the electronic load available was only 300W, the said rating will be exceeded with higher voltage input. The data presented from 31V was gathered from the simulation of the circuit.

TABLE 3
MATRIX TEST FOR ENERGY HARVESTED MONITORING

Test Case Name:		ADC unit test			
Description:		Verify that the voltage level reading for the harvested energy displayed in the LCD is accurate.		Type:	☑ white box ☐ black box
Set up:		Connect the assigned pin of the microcontroller to the voltage divider circuit for the energy harvested and to the LCD. Connect the power supply and electronic load to the input of the VDB. Monitor the voltage output of the VDB using a DMM and the value displayed on the LCD.			
Test	V_{IN}	V_{OUT} (VDB)	Displayed Value	Pass	Fail
1	5	0.357	5	✓	
2	7.12	0.497	7.1	✓	
3	9.16	0.638	9.2	✓	
4	11.16	0.772	11.2	✓	
5	13.12	0.902	13.1	✓	
6	15.1	1.039	15.1	✓	
7	17.08	1.168	17.1	✓	
8	19.04	1.302	19.1	✓	
9	21.35	1.451	21.3	✓	
10	23.09	1.569	23.1	✓	
11	25.52	1.735	25.5	✓	
12	27.08	1.832	27.1	✓	
13	29.12	1.98	29.1	✓	
14	31.05	2.085	31.1	✓	
15	33	2.216	33	✓	
16	35	2.35	35	✓	
17	37	2.485	37	✓	
18	39	2.619	39	✓	
19	41	2.753	41	✓	
20	43	2.888	43	✓	
21	45	3.022	45	✓	
22	47	3.156	47	✓	
23	49	3.29	49	✓	
24	51	3.425	51	✓	
25	53	3.56	53	✓	
26	55	3.693	55	✓	
27	57	3.828	57	✓	
28	59	3.962	59	✓	
29	60	4.029	60	✓	
Overall test result				✓	

The test result of the battery voltage monitoring is shown in Table 4. The test was conducted for only one battery since the same set up and values were used for the two batteries. The displayed value was set in the percentage of the battery voltage level as it was the standard for battery monitoring. The increment was set to 1V and 0.5V. The batteries were allowed to discharge up to 20V ≈ 80% but the test was conducted until 5V just to prove the accuracy of the monitoring.

TABLE 4
MATRIX TEST FOR BATTERY VOLTAGE MONITORING

Test Case Name:		ADC unit test			
Description:		Verify that the status of the battery voltage displayed in the LCD is accurate.		Type:	☑ white box ☐ black box
Set up:		Connect the assigned pin of the microcontroller to the voltage divider circuit for the battery and to the LCD. Connect the power supply to the input of the VDB. Monitor the voltage output of the VDB using a DMM and the displayed value in the LCD.			
Test	V_{IN}	V_{OUT} (VDB)	Displayed Value	Pass	Fail
1	5.063	0.956	17%	✓	
2	6.01	1.137	21.40%	✓	
3	7.09	1.339	25.70%	✓	
4	8	1.511	29.5%	✓	
5	9	1.703	33.60%	✓	
6	10.04	1.89	37.80%	✓	
7	11.01	2.083	41.80%	✓	
8	12.05	2.28	46.00%	✓	
9	13	2.457	49.80%	✓	
10	14	2.65	54%	✓	
11	15.01	2.84	58.10%	✓	
12	16.11	3.047	62.60%	✓	
13	17.15	3.245	66.80%	✓	
14	18.08	3.419	70.40%	✓	
15	19.01	3.6	74.60%	✓	
16	20.02	3.781	78.70%	✓	
17	20.51	3.985	80.08%	✓	
18	21.05	4	82.80%	✓	
19	21.54	4.082	85%	✓	
20	22.03	4.175	87%	✓	
21	22.51	4.265	88.90%	✓	
22	23	4.358	91%	✓	
23	23.57	4.464	93.20%	✓	
24	24	4.544	94.9%	✓	
25	24.5	4.646	97.1%	✓	
26	25.02	4.751	99.40%	✓	
27	25.5	4.842	100.0%	✓	
Overall test result				✓	

B. *Load Current Monitoring*

The matrix test for the load current reading is presented in Table 5. The V_L (load voltage) was set to 12V and the current has an increment of 0.5A. The actual testing was limited to 10A since it was the maximum capacity of the power supply available. The data from 10.5A to 15A was obtained from the simulation.

TABLE 5
MATRIX TEST FOR LOAD CURRENT MONITORING

Test Case Name:		ADC unit test				
Description:		Verify that the load current displayed in the LCD is accurate.		Type:	☑ white box ☐ black box	
Set up:		Connect the assigned pin of the microcontroller to ACS758 and to the LCD. Properly connect the power supply electronic load and ACS. Monitor the voltage output (pin3) of the ACS using a DMM and the value displayed on the LCD.				
Test	I_{IN} (A)	V_{OUT}	Displayed Value (A)	Percent Error	Pass	Fail
1	0	2.502	0	0%	✓	
2	0.5	2.507	0.5	0%	✓	
3	1	2.518	1	0%	✓	
4	1.5	2.526	1.5	0%	✓	
5	1.998	2.527	2	0.05%	✓	
6	2.5	2.541	2.5	0%	✓	
7	3	2.553	3	0%	✓	
8	3.41	2.564	3.4	0.15%	✓	
9	3.94	2.575	3.9	0.51%	✓	
10	4.48	2.585	4.4	0.90%	✓	
11	5.002	2.595	5	0.02%	✓	
12	5.491	2.605	5.4	0.83%	✓	
13	5.994	2.615	5.9	0.79%	✓	
14	6.498	2.625	6.4	0.76%	✓	
15	6.997	3.635	6.9	0.70%	✓	
16	7.48	2.645	7.4	0.54%	✓	
17	7.9	2.655	7.8	0.64%	✓	
18	8.5	2.666	8.5	0%	✓	
19	9	2.676	9	0%	✓	
20	9.5	2.685	9.4	0.53%	✓	
21	10	2.695	10	0%	✓	
22	10.5	2.705	10.5	0%	✓	
23	11	2.715	11	0%	✓	
24	11.5	2.725	11.5	0%	✓	
25	12	2.735	12	0%	✓	
26	12.5	2.745	12.5	0%	✓	
27	13	2.755	13	0%	✓	
28	13.5	2.765	13.5	0%	✓	
29	14	2.775	14	0%	✓	
30	14.5	2.785	14.5	0%	✓	
31	15	2.795	15	0%	✓	
Overall test result					✓	

C. *Battery Switching (Discharging)*

The result of the testing of the battery switching in discharging phase is presented in Table 6. The table shows the steps done during the testing and the expected operation of the system. The discharging battery will be switched to the other one when it reaches the cut-off battery voltage of 20 volts (≈80%) and the system will be on standby mode, with no output voltage when both of the batteries reach the cut off battery voltage level.

TABLE 6
STEP-BY-STEP TEST OF BATTERY SWITCHING IN DISCHARGING PHASE

Test Case Name:	Battery Switching in Discharging Phase			
Description:	Verifies if the switching of the batteries is operating accordingly to the voltage hysteresis set.			
Set-up:	Connect the power supplies which will represent the batteries in the respective battery inputs. Set both power supplies to 25.5 volts. Connect another power supply to the input of the energy harvested and set it to 5 volts. Monitor the voltage levels of the power supplies as well as the output voltage with digital multi-meters.			
Step	Action	Expected Result	Pass	Fail
1	Turn-on all of the power supplies and set all of the digital multi-meters to voltage mode.	There will be an output voltage with more or less 2 volts less than the set battery 1 voltage.	✓	
2	Lower the voltage of the battery 1 to 25 volts.	The output voltage will also lower, following the voltage of battery 1.	✓	
3	Continue to lower the voltage of battery 1 until 19 volts.	The output voltage will continue to lower until the battery voltage drops to 20 volts. When it is less than 20 volts, the output voltage will be almost equal to the battery 2 voltage.	✓	
4	Lower the voltage of the battery 2 to 23 volts.	The output voltage will also drop, following the voltage of battery 2.	✓	
5	Continue to lower the voltage of battery 2 to a little bit less than 20 volts.	The output voltage will continue to drop as the voltage of battery 2 drops. When it is less than 20 volts, the output voltage will become zero volts.	✓	
Overall test result			✓	

D. *Battery Switching (Charging)*

The result of the test procedure done in the battery switching (charging mode) is shown in Table 7. This testing was verified multiple times in the simulation since there was only one available battery to use for testing. Power supplies were used to represent the batteries and might cause short circuit which would damage the power supplies when the switching fails.

Test Case Name:	Battery Switching in Charging Phase			
Description:	Verifies if the switching of the batteries is operating accordingly to the voltage hysteresis set.			
Set-up:	Connect the power supply to the input if the energy harvested and output of the buck converter. Set the energy harvested to 32 volts to set the system in charging mode. Set the power supply connected to the output of the buck converter to 14 volts, this will serve as the charging voltage. Monitor the voltage level of the battery and power supplies with DMMs. Connect another DMM in series with the positive side of the battery to show if the battery is being charged.			
Step	Action	Expected Result	Pass	Fail
1	Turn-on all of the power supplies and set the digital multi-meters to voltage and current mode, respectively.	There will be a positive current reading on the DMM in series with the positive side of the battery connected in the input of battery 1.	✓	
2	Turn of all of the power supplies. Connect a power supply to the input of battery 1 and set it to 25.5 volts (100%). Connect the battery to the input of battery 2. Monitor the charging current with a DMM in series with the positive side of the battery.	There will be a positive current reading on the DMM in series with the positive side of the battery connected in the input of battery 2.	✓	
Overall test result			✓	

This switching of multiple batteries was designed in order to store more energy. Combining different energy harvesters or upgrading the capacity of the harvesters will gather huge amount of energy. It will be such a waste to limit the energy being stored to only one battery. With this battery switching, the energy being stored will be maximized with the capacity of the harvesters.

For example, the harvesters have an overall rating of 400 Watts and a battery has a rating of 100 Ah. The charging current was set to 14 amperes. The charging time can be computed with the equation:

$$\text{Time} = \text{Battery Rating} / \text{Charging Current} \qquad (1)$$

With the given parameters:

$$\text{Time} = 100 \text{ Ah} / 14 \text{ A} = 7 \text{ hours and } 8.4 \text{ minutes}$$

One battery will be fully charged in 7 hours and 8.4 minutes. After the battery has been fully charged, the harvesters will be disconnected from the circuit halting its operation. Assuming that the harvesters can produce the constant amount of energy for 20 hours a day, the energy that will be produced in the remaining 12 hours and 51.6 minutes will be wasted.

Employing multiple batteries switching will make a way to store the excess energy that can be produced by the harvesters. The total amount of energy stored will be limited to the capacity of the harvester instead of the battery capacity. This shows that for a 400 - Watt harvester operating for 20 hours, a total of 2.5 batteries with a capacity of 100Ah can be fully charged.

E. *Battery Switching (Voltage Drop)*

The battery switching circuit was tested in order to trace the voltage drops in the components. The load was set to 1.5A. The column V_S pertains to the battery voltage, V_g is the gate voltage induced by the driver, V_{gs} is the gate to source voltage, V_{ds} is the drain to source voltage, V_{DIODE} is the diode in series with the high-side MOSFET, V_{DL} is the diode in series in the low-side MOSFET and V_{OUT} is the output voltage which will be the input of the boost converter. As seen in the table the difference between the supply voltage and the output voltage ranges from 0.8V to 1V. The requirement specification of an output voltage with a voltage drop of 10% of the input was met. The charging phase of the battery switching has the same voltage drops as seen in the table with an input voltage of 27 V and output voltage of approximately 26V.

TABLE 7
VOLTAGE TEST OF THE BATTERY SWITCHING

V_s	V_g	V_{gs}	V_{ds}	V_{DIODE}	V_{DL}	V_{OUT}
11.12	26.79	15.8	0.054	0.513	0.512	10.24
12.02	27.73	15.82	0.055	0.497	0.516	11.1
12.99	28.69	15.83	0.056	0.485	0.51	12.06
13.99	29.71	15.84	0.057	0.482	0.507	13.06
15.02	30.74	15.84	0.057	0.482	0.506	14.04
16.01	31.76	15.85	0.057	0.481	0.507	15.08
17.01	32.74	15.85	0.057	0.491	0.509	16.02
17.92	33.79	15.85	0.057	0.497	0.507	16.96
18.83	34.6	15.86	0.057	0.49	0.51	17.88
20.13	35.89	15.86	0.057	0.491	0.51	19.2
21.1	36.87	15.87	0.057	0.49	0.508	20.16
22.02	37.82	15.88	0.057	0.48	0.509	21.08
23.06	38.84	15.89	0.058	0.48	0.51	22.14
24.11	39.92	15.9	0.058	0.482	0.507	23.18
25.15	40.94	15.91	0.058	0.484	0.508	24.2
26.07	41.88	15.92	0.058	0.483	0.507	25.12

F. *Load Detection*

The measured voltage and current values during the testing was used to determine the power consumption of the system when a load is connected into the system. Fig. 9 shows the graph of the power consumption of the system when a load is connected and when there is none.

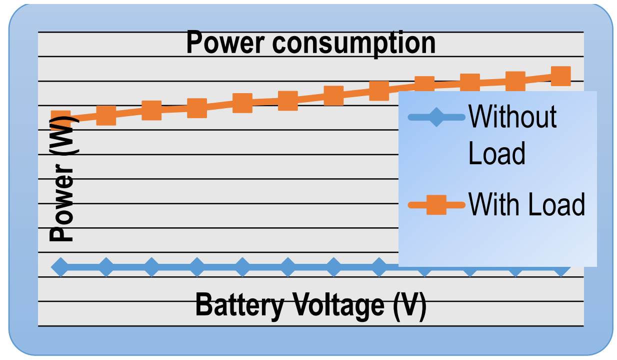

Fig. 8 Power consumption with load vs. no load

The figure above shows that the power consumption when a load connected into the system ranges from 8 watts to 10.5 watts, depending on the voltage level of the discharging battery. This power consumption does not include the dc-dc converters which will be connected into the system. With the load detection circuit, the power drops to 2.4 watts when no load is connected into the system because the microcontroller and the current sensing component were the only ones powered up. The battery switching circuit and other circuits connected into the system were not supplied by the batteries during this phase.

G. *Thermal Test*

The temperature of each active component with respect to the battery voltage is shown in Fig. 10. The test was done to determine if there is an excessive heating of components which can lead to the system failure.

Fig. 10 shows that there was no excessive heating in the components during normal operation. With the Arduino having the highest temperature, with a peak of 41.2°C, the system was safe to operate in a long period of time. With the presented temperatures, it ensures that the system is not consuming excessive energy. When a system consumes excessive energy, it will be considered as additional losses in the system.

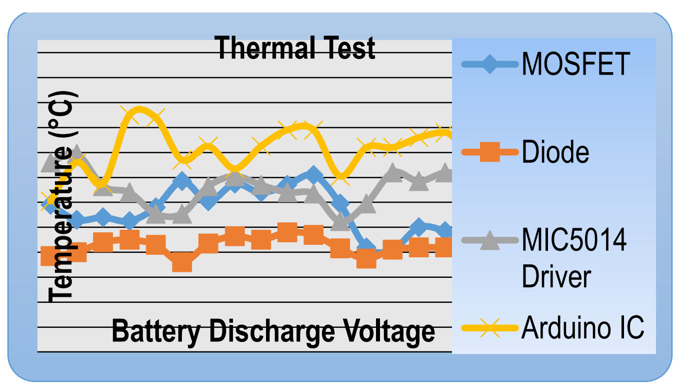

Fig. 9 Temperature vs. Battery voltage

VII. CONCLUSION

The design were able to make a way for charge controllers to minimize the losses in the energy stored and effectively store more energy with the load detection circuit and battery switching circuit. With the series of tests conducted, the results prove that the monitoring of the voltage levels and load current were accurate based on the actual reading and the displayed reading in the LCD. The battery switching circuit was able to charge and discharge each battery separately and the load detection circuit was able to prevent the battery from discharging when no load is connected in the system. The battery switching circuit and the load detection circuit were also able to work together when integrated.

Although the actual testing were limited to the maximum rating of the available equipments like the electronic load; the data gathered were enough to allow the designers to extrapolate the data. The data from the simulations were also almost equal to the actual values tested – with minor differences as expected since the simulations were running in ideal mode.

REFERENCES

[1] Andorka, F. (10 May, 2012). *Solar Power world online*. Retrieved from http://www.solarpowerworldonline.com/2012/05/3-things-you-need-to-know-about-solar-charge-controllers/

[2] Boveri, A. (. (2013). http://new.abb.com/power-electronics. Retrieved from http://new.abb.com/: http://new.abb.com/power-electronics/home/focs/applications-and-benefits

[3] Celina Mikolajczak, M. K. (2011). Lithium-Ion Batteries Hazard and Use Assessment. California, United States of America: Springer.

[4] Chang, L. (2006). Patent No. US 7476987 B2. United States of America.

[5] Ford, R. M., & Coulston, C. S. (2005). Design for Electrical and Computer Engineers. McGraw-Hill Education.

[6] Gordon, L. (9 November, 2015). Retrieved from Renewable energy focus: http://www.renewableenergyfocus.com/view/43172/planning-the-future-of-renewables-storage-legal-issues-to-consider/

[7] Maryniak, G. (20 July, 2012). Forbes.com. Retrieved from http://www.forbes.com/sites/singularity/2012/07/20/storage-not-generation-is-the-challenge-to-renewable-energy/#378e116e37cc

[8] Matin, M., Rahaman, A., Sarker, A., & Uddin, R. (2015). A cost effective solar charge controller. International Journal of Research in Engineering and Technology , 6.

[9] Nowshad Amin, L. Z. (2009). MICROCONTROLLER BASED SMART CHARGE CONTROLLER FOR STANDALONE. Electronics & System Engineering and Solar Energy , 4.

[10] Satell, G. (1 April, 2016). Why Energy Storage May Be The Most Important Technology In The World Right Now. Retrieved from Forbes.com: http://www.forbes.com/sites/gregsatell/2016/04/01/why-energy-storage-may-be-the-most-important-technology-in-the-world-right-now/#384c0e344869

[11] Shaun D. Milano, W. C. (2014). Patent No. US8907437 B2. United States of America.

[12] Taufik, T. (2015). The DC House Project: An Alternate Solution for. 6.

[13] Weinhardt, R. A. (1986). Patent No. US4626764 A. United States of America.

[14] Yeon, S.-H. (1998). *Patent No. US6133712 A.* United States of America.