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Research Article

Design and Implementation of a Charge Controller for Solar PV Systems for Emergency Situations in Health Facilities in Rural Areas of Uganda

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Abstract: This paper presents the design and implementation of a solar charge controller system (SCCS) for emergencies in health facilities located in rural areas of Uganda. The SCCS is a Direct Current (DC) voltage regulator and controller that controls the production of power from solar panels and stores the power in battery backup systems. The charge controller reduces the voltage to prevent overcharging of the battery, which reduces its life expectancy. The SCCS also prevents the batteries from over-discharging, protecting the system from electrical overloading. The methodology utilized in this study is clearly outlined, detailing the design and implementation process of the SCCS. The experimental setup and testing show that the SCCS works accurately and low sunlight does not affect its efficiency. The SCCS efficiently protects the system from excessive current flow due to overloading and overvoltage. The average efficiency of the designed renewable energy system is 96.52% over eight days of testing. The SCCS presented in this paper is a cost-effective solution for emergencies in health facilities located in rural areas of Uganda, where access to electricity is limited.

***Keywords*:** solar charge controller, emergency situation, health facilities, Uganda, voltage regulator, efficiency, renewable energy

1. Introduction

The Solar Charge Controller System (SCCS) is known as a DC voltage regulator and controller [1]-[3]. A SCCS is required in almost all solar power and energy systems that use batteries connected in various ways. The purpose of the solar charge controller system is to control the production of power from the solar panels and store the power in the battery backup systems [4]-[6]. In a solar panel generally 164 to 24 volts is produced. But when charging the battery, the required voltage is between 12 V and 14.6 V. A charge controller reduces the voltage.

The basic purpose of a charge controller is to stop the battery from overcharging [7]-[9]. The routine overcharging of the battery reduces its life expectancy. So the charge controller is used in this case to sense the voltage of the battery and stop or reduce the charging current in case of voltage increase. Change controllers are also used to prevent the batteries from over-discharging hence protecting the system from electrical overloading. Figure 1 shows the operational block diagram of a solar charge controller system. Current is kept in the battery from the solar photovoltaic array in the charge controller which delivers it when required. This current is then supplied to the DC load from the battery backup

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system through the charge controller. Now for the Alternating Current (AC) loads an inverter of various types depending on the requirement is used to change the DC voltage to AC power.

Furthermore, there is a possibility of using remote telemetry for transmitting data, temperature, data, lighting control compensation probe, etc. The buck converter is mostly used which changes high voltage into low voltage. For this operation to take place, two types of switches are utilized namely: solid-state and relay-type switches.

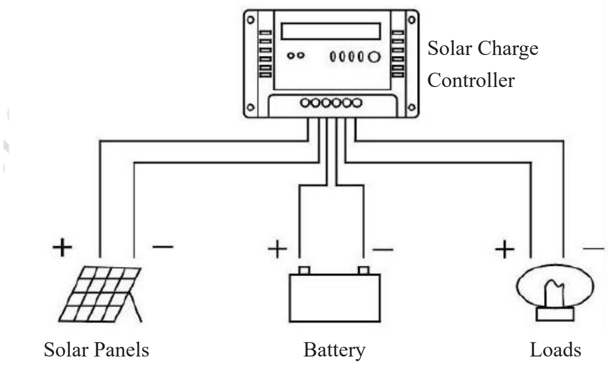

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Figure 1. Operating principle of the charge controller

1.1 *Switching mechanism of charge controller*

During the normal operation of a charge controller system discharge or overcharge of the battery backup system will be reduced or rather stopped irrespective of the system sizing, construction, changes in the load profile, systems operating temperatures, and design. The controller strategy, method, or algorithm of the charge controller of the battery backup system is used to establish how effective the charging system of batteries and PV array used are in the entire system, and eventually the capability of the system to encounter the load demands as designed or constructed. Extra features such as alarms, temperature compensation, and other superior algorithms can be used to improve the capacity of a charge controller to uphold the system's health, exploit capacity, and increase the lifetime of a battery system. The controller also shields against sulfating of batteries, short circuit conditions, and overloads. The charge controllers based on Micro-processors measure the ampere-hour of the battery system instead of its state of charge of the battery system to control the supply of current.

Outstandingly, the controller algorithm describes the technique in which a PV array power system is used to the battery in the system structure. Interruption of on-off type charge controllers necessitates a higher regulation of points set to bring batteries up to a full capacity of charge other than controllers that slowly bound the array current. There are three switching mechanisms namely: pulse width modulation (PWM), Maximum power point tracking (MPPT), and on-off.

1.1.1 *On-Off mechanism analysis*

Battery backup charging of a solar photovoltaic system is a multipart process and thought-provoking. In the past, regulators of the simple on-off mechanisms were utilized to bind battery outgassing when a solar PV panel gave off an excess amount of energy and power. Charge controller systems that control the charge flowing in the battery by switching the state of current on fully off or fully On stage condition are called On/Off control system mechanisms. On-off regulators had late to early battery backup systems failures, increasing load disconnect and disengagements, and raising user and operator dissatisfaction and discomfort.

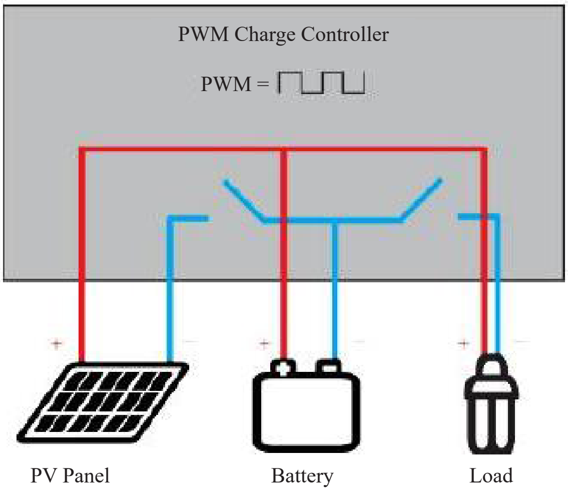

Figure 2. Schematic diagram of PWM

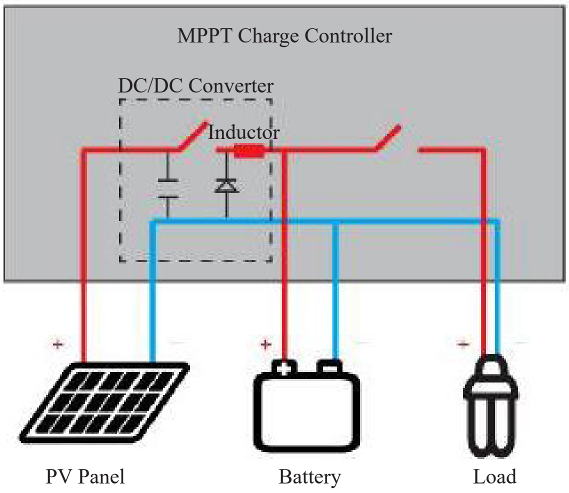

Figure 3. Schematic diagram of MPPT

1.1.2 *PWM*

PWM mechanism has lately come out as the first substantial advanced method of solar battery charging. Pulse-Width Modulation (PWM) comes into use when the battery bank system is charged to full capacity. Throughout charging, the controller permits as great a current as the PV panel or array can produce to attain the target voltage and power for the charge stage within which the controller is located. Once the battery assumes this target voltage and power, the charge controller system rapidly switches between connecting the battery backup system to the solar panel array and disengaging the battery bank system which controls the battery voltage at a constant level. This rapid and fast switching is known as PWM and it guarantees the battery bank is charged efficiently at the same time shielding it from being overcharged by the PV array or panel. Figure 2 presents a schematic PWM diagram.

1.1.3 *MPPT*

Maximum PowerPoint tracking features show an indirect connection between the battery backup system and the PV array. Figure 3 presents a schematic MPPT diagram. The indirect connection includes a DC/DC voltage and power converter that can take and sustain an excess amount of PV voltage and change it into extra current at a lower voltage enabling no loss of power. MPPT controllers always achieve this through an adaptive mechanism and algorithm that traces the maximum power point of the PV array and then changes the incoming voltage and its power to sustain the most efficient amount of power for the system, especially during its use. Some of the most commonly used MMPT algorithms and techniques include Perturb and observe (P&O), Online MPP Search Algorithm, Incremental Conductance method, Temperature method, Fractional short circuit current, Three Point Weight Comparison, Fractional open circuit voltage, PV Output Senseless Control, Fuzzy logic, Biological Swarm Chasing, Neural networks, Variable Inductor, Ripple Correlation Control, Incremental Resistance (INR), Current Sweep, Array Reconfiguration, DC-link capacitor droop control, Linear Current Control, Load current or load voltage maximization, IMPP and VMPP Computation, Voltage or current Feedback control, One-cycle Control Method, β Method, Best Fixed Voltage algorithm, System Oscillation Method, Linear Reoriented Coordinates, Constant Voltage Tracker, Slide Control, Lookup Table Method, and Solid State-Based MPPT. Solid State-Based MPPT was chosen for the design and implementation of the charge controller. The choice of Solid-State-Based MPPT for the charge controller design ensures optimal performance, reliability, and cost-effectiveness, making it suitable for emergencies in health facilities in rural areas of Uganda.

1.1.3.1 *Characteristics of MPPT*

High Voltage Wire Runs- Smaller conductors and cables can be utilized and better distances are attained using higher voltage solar PV input due to the reduced voltage drop and changes. A great benefit to having a higher voltage solar panel array is that smaller gauge conductors can be used in the charge controller system. And since a solar photovoltaic panel array can occasionally be over 100 feet away from the charge controller system, reducing the cost of the wiring lower to its minimum value is frequently a significant financial economic goal of the entire project and design. When voltage is doubled (e.g., from 12 to 24 volts), it is recommended that the current through the cables is reduced by a half which translates into a quarter or even less of the copper wire to be used as much (or conductor whose diameter is a half).

Shading and Cloud Irradiance Effects- The Cloud edge effect can cause the module to surpass its rated active power. Shading can cause complicated IV curve shapes and characteristics. MPPT can follow both changes equally to guarantee maximum power during this prevailing operation condition.

Low Battery Protection- When the battery capacity is very low, a high voltage difference and voltage drop between the battery voltage and solar PV leads to an even greater power increase. This can prevent an LVD when the power is most desired.

Reduced Power Loss- The MPPT charge controller reduces power loss. The Low voltage in the conductors running from the solar panels to the charge controller comes from the higher increased energy loss in the cables than higher voltage values. When using a PWM charge controller with 12 V batteries, the voltage connected between the solar panel or the charge controller typically has to be 18 V and above. MPPT controller permits much higher voltages in the conductors to flow from the solar panels to the solar charge controller unit. The MPPT controller does the work of changing the excess voltage into additional electric current. Note that by running higher voltage in the cables from the solar photo voltaic panels than the charge controller system, the loss of power in the cables is reduced. Table 1 presents some specific pros and cons of both PWM and MPPT charge controllers.

Table 1. Pros and Cons of Both Types of Controllers

	PWM Controller	MPPT Controller
Pros	1/3-1/2 the cost of an MPPT controller	Highest charging efficiency (Especially in cool climates).
	Longer expected lifespan due to fewer electronic components and less thermal stress	Can be used with 60-cell panels
	Smaller size	Possibility to oversize array to ensure sufficient charging in Winter months.
	Lower controller cost	30% more efficient than PWM
Cons	PV arrays and battery banks must be sized more carefully and may require more design experience.	2-3 times more expensive than a comparable PWM controller.
	Cannot be used efficiently with 60-cell panels	Shorter expected lifespan due to more electronic components and greater thermal stress.
	Higher wiring cost and less efficiency than MPPT	Higher controller cost
	PWM controller is used with off-grid modules	Higher frequency charge control and suitable for more than 200 W solar panel

1.2 *Charge controller selection*

Charge controller systems selection in any given PV system is dependent on some of the following factors and these include preventing overcharging of the battery [10]-[12], high voltage disconnect (HVD) [13], [14], low voltage disconnect (LVD) [15], regulation and control for the loads [16], backup energy sources control [17], and monitoring of system functionalities [18]. For a given needed application, particular designs are required. A given charge controller must be positioned to hold the expected rise or fall conditions besides the typical control of current and voltage. It is significant to be sufficiently sized for the proposed application such as home solar domestic system loads, solar for commercial systems and buildings, solar irrigation systems, solar systems for industrial use, solar power grid station solar for water pumping, etc. MPPT methods allow the functioning of the solar module in a maximum power-generating mode. MPPT procedures are used to gain the maximum power from the solar array founded on the dissimilarity in temperature and irradiation. The voltage at which the PV module is capable of yielding maximum power is named "maximum power point" (or peak power voltage). Maximum power fluctuates with ambient temperatures, solar cell temperature, and solar radiation.

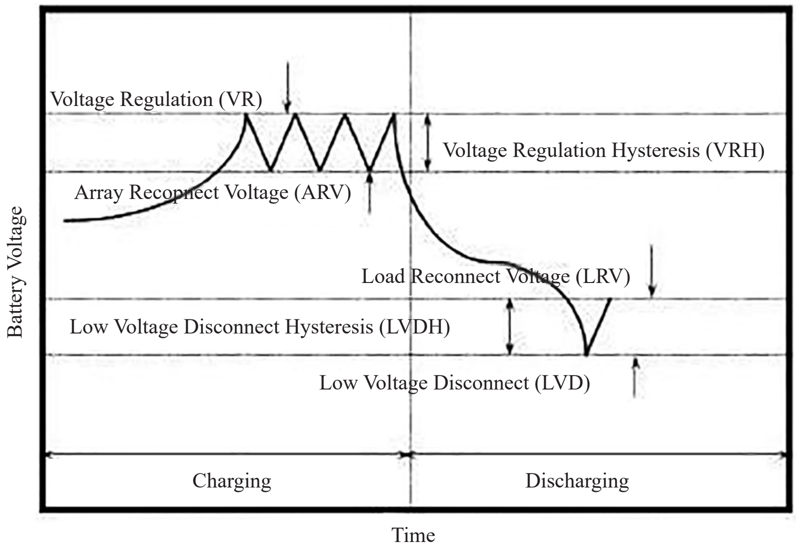

Figure 4. Charge controller set points [19]

1.3 *Charge controller set points*

Charge controller set points are graphically shown in Figure 4. While the exact control algorithm and method differ among charge controller units, all have basic parameters and features. Manufacturers' data generally provide this information; limits of the charge controller applications such as currents of the loads and PV losses, set points, hysteresis values, and the operating temperatures. In most cases, the set points may be reliant upon the temperature of the controller and battery, and the extent of the current of the battery. The discussion of the four charge controller set points is presented below.

1.3.1 *Voltage Regulation (VR) set point*

This set point is the extreme voltage a charge controller permits the battery to attain [19]. At this moment a controller will either suspend the charging of the battery or begin to control the quantity of current sent to the battery. To make proper selections of the set point rest on the precise battery operating temperature and chemistry.

1.3.2 *Voltage Regulation Hysteresis (VRH)*

The set point is the voltage length or difference between the VR set point and the voltage when the complete array current is reconnected [20]. The greater this voltage span, the longer the array current is interrupted from charging the battery. If the VRH is too small, the control element will oscillate, inducing noise and possibly harming the switching element. The VRH is an important factor in determining the charging effectiveness of a controller.

1.3.3 *Low Voltage Disconnect (LVD)*

The set point is the voltage at which the load is disconnected from the battery to prevent over-discharge [14]. The LVD defines the actual allowable maximum depth of discharge and available capacity of the battery. The available capacity must be carefully estimated in the system design and sizing process. Typically, the LVD does not need to be temperature compensated unless the batteries operate below 0 °C frequently. The proper LVD set point will maintain good battery health while providing the maximum available battery capacity to the system.

1.3.4 *Low Voltage Disconnect Hysteresis (LVDH)*

This set point is the voltage span or difference between the LVD set point and the voltage at which the load is reconnected to the battery [21], [22]. If the LVDH is too small, the load may cycle on and off rapidly at a low battery state of charge, possibly damaging the load and controller. If the LVDH is too large, the load may remain off until the array fully recharges the battery. With a large LVDH, battery health may be improved due to reduced battery cycling, although it will reduce load availability.

1.3.5 *Effect of duration of load on set point*

Due to "On Load" at night, the charge controller will save the total current to the battery. Due to the "On Load" condition during the daytime, the charge controller will supply a portion of current from the solar panel to the load directly and save a portion of current to the battery according to the requirement.

1.3.6 *Depth of charge effect*

If the battery is used excessively, the voltage decreases to a low level. It can happen if the total ampere-hour is not used for a certain duration of time. In that case, a sulfation problem occurs. To return the battery to its normal condition, boost charging is necessary (2.50 or 2.58 volt/cell) [23].

1.3.7 *Temperature effects on battery*

Normally, the set point of a controller is set to 25 °C. Temperature compensation is necessary. For temperature variation, the compensation factor is -5 mV/cell/°C [23].

2. Component list

Individual representation of components used to construct the charge controller is listed in Table 2.

Table 2. Component List

S. No	Product	Model	Quantity
01	Microcontroller	PICI6F877A	02
02	Capacitor	0.1 µF	04
		10 µF 50 V (Electrolyte)	09
		470 µF 50 V (Electrolyte)	08
		1,000 µF 16 V (Electrolyte)	01

Table 2. (cont.)

S. No	Product	Model	Quantity
03	Inductor	100 μH	02
04	MOSFET	IRFZ44N	11
05	MOSFET Driver	IR2104	01
06	Voltage Regulator	LM7805	01
		LM7812	01
07	Inverting Switching Regulator	MC34063A	01
08	Diode	IN4917	07
09	Current sensor	ACS712ELCTR-30A-T	02
10	LED	Green	02
		Red	04
		Blue	01
11	LCD Display	JHD204A	01
12	Transistors	T-MCU	03
13	Opto-coupler	PC817	01
14	Resistor	220 Ω	03
		1 KΩ	12
		3.3 KΩ	02
		10 KΩ	05
		100 KΩ	02
15	Fuse	T8AL250V	04
		25 A	01
16	Wire socket	-	03
17	USB port	-	02

3. Hardware design

The schematic diagram of the designed charge controller is shown in Figure 5; it is designed by Proteus software. The top right side shows the Microcontroller and LCD interfacing connection. The input power connector to the solar panels is the screw terminal JP1 and JP2 is the output screw terminal connector to the battery. The third connector JP3 is the connection for the load. FU1 and FU3 are 8A, and FU2 is the 25A 77 safety fuses. The buck converter is made with synchronous MOSFET switches Q2 and Q3 and the energy storage devices inductor L1 and capacitors C8. The inductor smoothes the switching current. The capacitor C8 smoothes the output voltage. Capacitor C8 and R6 are a snubber network, used to cut down on the ringing of the inductor voltage generated by the switching current in the inductor. The third MOSFET Q1 is added to allow the system to block the battery power from flowing back into the solar panels at night. As all diodes have a voltage drop a MOSFET is much more efficient than diodes. Q1 turns on when Q2 is on from the voltage through D1. R1 drains the voltage off the gate of Q1 so it turns off when Q2 turns off. The diode D3 (UF4007) is an ultra-fast diode that will start conducting current before Q3 turns on. It is supposed to make the converter more efficient. The IC IR2104 is a half-bridge MOSFET gate driver. It drives the high and the low side MOSFETs using the PWM signal from the microcontroller. The IR2104 can also be shut down with the control signal from the microcontroller.

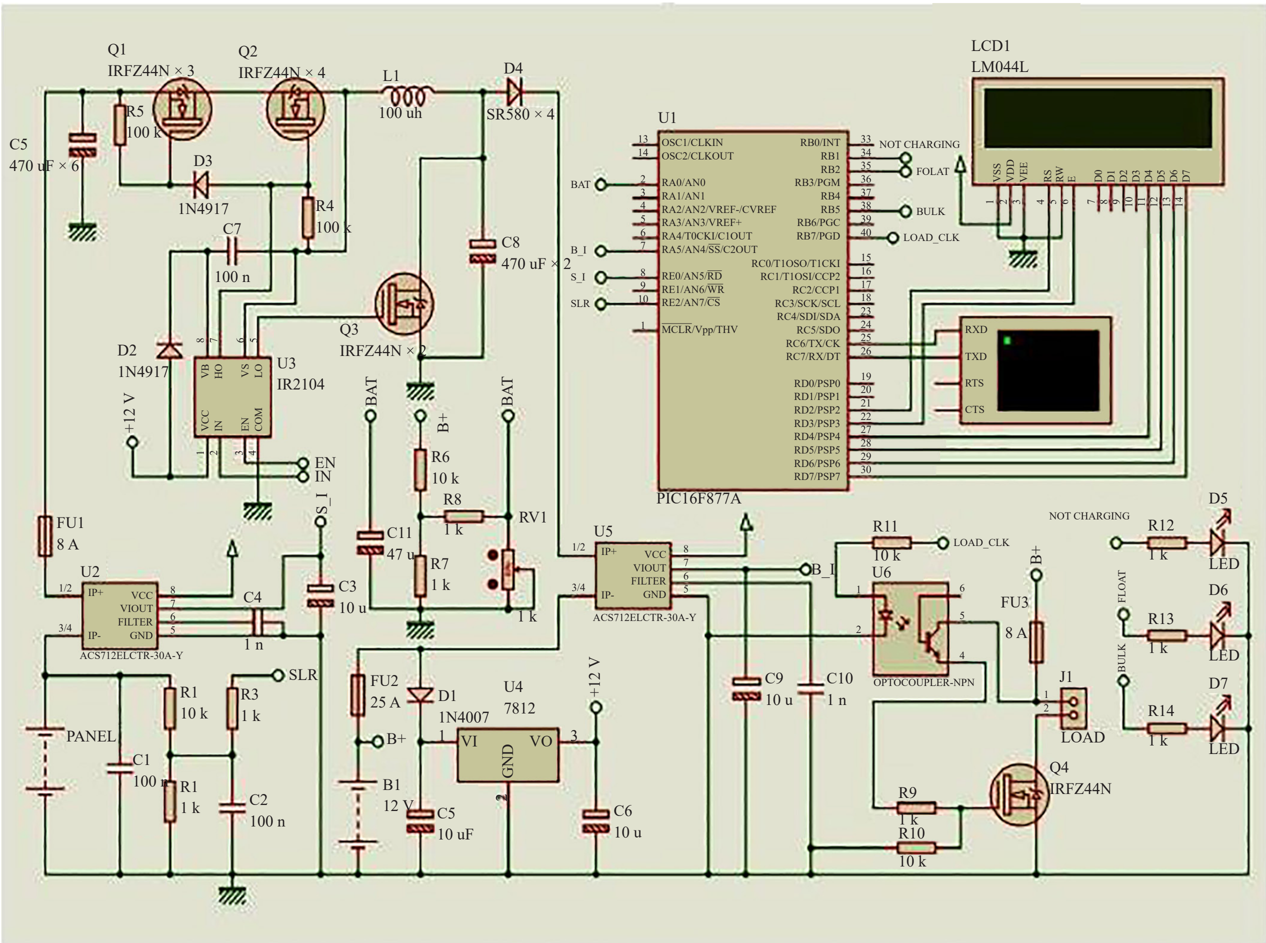

Figure 5. Schematic circuit layout of designed solar charge controller

D2 and C7 are part of the bootstrap circuit that generates the high side gate drive voltage for Q1 and Q2. The software keeps track of the PWM duty cycle and never allows 100% or always on. It caps the PWM duty cycle at 99.9% to keep the charge pump working. Two voltage divider circuits (R1, R2, and R3, R4) measure the solar panel and battery voltages. The output from the dividers feeds the voltage signal to Analog pin-0 and Analog pin-2. The ceramic capacitors C3 and C4 are used to remove high-frequency spikes. The MOSFET Q4 is used to control the load. The driver for this MOSFET consists of a transistor and resistors R9, and R10. D4 and D5 are TVS diodes used for overvoltage protection from the solar panel and load side. The current sensor ACS712 senses the current from the solar panel and feeds it to the microcontroller pin-1. The three LEDs are connected to the digital pins of the microcontroller and serve as an output interface to display the charging state. The reset switch is helpful if the code gets stuck. The backlight switch is to control the backlight of the LCD.

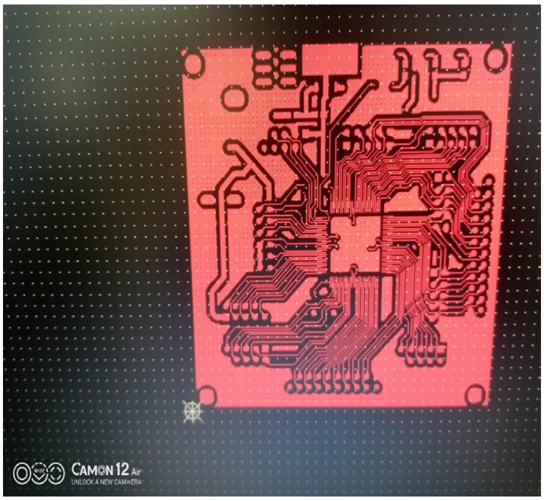

Figure 6. PCB design of solar MPPT charge controller

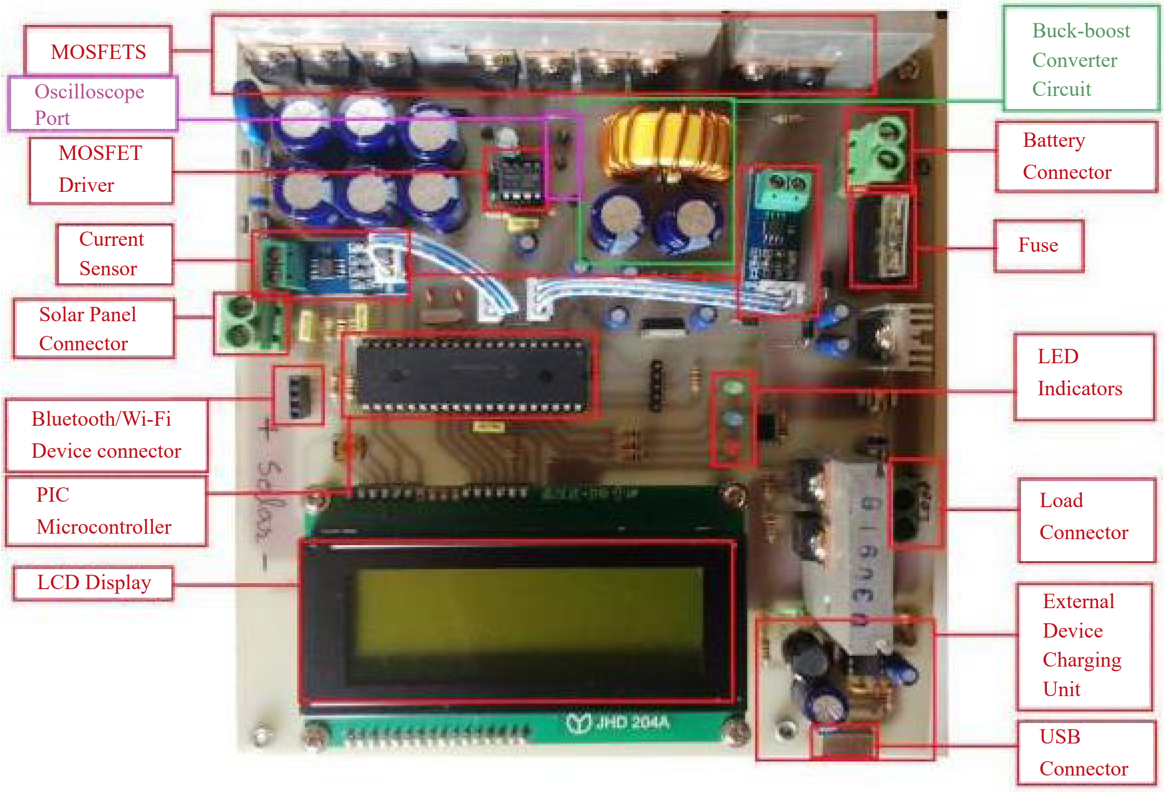

Figure 7. Designed MPPT solar charge controller

3.1 *PCB design*

A custom printed circuit board (PCB) was designed for hardware implementation of the solar MPPT charge controller shown in Figure 6. The board is designed using circuit board design software, CadSoft's Eagle PCB Design. A designed PCB allows for the best performance and optimization, along with a nice clean look.

3.2 *Final design*

Figure 7 presents the designed hardware device, indicating all the parts integrated to work it as an MPPT solar charge controller. Input is the solar panel output connected through the left side of the device. Output as the load and external device charging USB unit in the right side of the device, battery connector is also the same side. Two current sensors ensure high excessive current protection of the total system. Two fuses are used on both the panel and battery sides, a 10 A fuse on the panel side and a 25 A fuse on the battery side.

4. Cost analysis

Parts are bought in December 2022 and the price list in UGX is shown in Table 3. This price may vary with the current price. The total price of the parts is UGX 85,000. The highest value among the parts is the LCD (UGX 13,500), the current sensor (UGX 7,500), and the Bluetooth device (UGX 8,100).

Table 3. Price List

MPPT solar charge controller, 12 V, 10 A					
S. No	Product	Model	Quantity	Unit Price	Total Price
01	Microcontroller	PICI6F877A	02	6,000	12,000
02	Capacitor	0.1 µF	04	15	60
		10 µF 50 V (Electrolyte)	09	35	315
		470 µF 50 V (Electrolyte)	08	250	2,000
		1,000 µF 16 V (Electrolyte)	01	350	350
03	Inductor	100 µH	02	150	300
04	MOSFET	IRFZ44N	11	800	8,800
05	MOSFET Driver	IR2104	01	3,600	3,600
06	Voltage Regulator	LM7805	01	450	450
		LM7812	01	450	450
07	Inverting Switching Regulator	MC34063A	01	300	300
08	Diode	IN4917	07	35	245

Table 3. (cont.)

		MPPT solar charge controller, 12 V, 10 A			
S. No	Product	Model	Quantity	Unit Price	Total Price
09	Current sensor	ACS712ELCTR-30A-T	02	7,500	15,000
10	LED	Green	02	15	30
		Red	04	15	60
		Blue	01	15	15
11	LCD Display	JHD204A	01	13,500	13,500
12	Transistors	T-MCU	03	8,100	24,300
13	Opto-coupler	PC817	01	150	150
14	Resistor	220 Ω	03	15	45
		1 KΩ	12	15	180
		3.3 KΩ	02	15	30
		10 KΩ	05	15	75
		100 KΩ	02	15	30
15	Fuse	T8AL250V	04	150	600
		25 A	01	15	15
16	Wire socket	-	03	500	1,500
17	USB port	-	02	300	600
		Total			85,000

5. Working procedure

The solar charge controller system (SCCS) continuously monitors the voltage and current output of the solar panels. These parameters are essential for determining the power output of the solar array. Using the Solid State Based MPPT algorithm, the controller dynamically adjusts the operating point of the solar panels to ensure that they operate at their maximum power point (MPP). This is achieved by varying the duty cycle of the converter to optimize the power transfer from the solar panels to the battery bank. The controller regulates the voltage output from the solar panels to ensure that it matches the voltage requirements of the battery bank. This prevents overcharging of the batteries, which can reduce their lifespan. The controller also manages the charging process to ensure efficient and safe charging of the batteries.

The controller also manages the distribution of power to the load connected to the system. It ensures that the load receives the required amount of power while also prioritizing battery charging when necessary. This helps to maintain a stable power supply to critical loads, such as medical equipment in health facilities. Throughout the operation, the controller continually optimizes the efficiency of the system by adjusting parameters such as duty cycle, charging current, and load distribution. This ensures that the system operates at its highest efficiency level, maximizing the utilization of solar energy and extending the battery life.

Overall, the SCCS provides a reliable and efficient solution for managing solar PV systems in emergencies, particularly in rural health facilities in Uganda. By dynamically optimizing power generation, battery charging, and load management, the system ensures uninterrupted power supply, contributing to improved healthcare delivery and patient outcomes.

6. Experimental setup

Figure 8 shows the experimental setup and testing of the charge controller. It’s evident that the system is working extremely well and it has been continuously and endlessly tested and analyzed for two months.

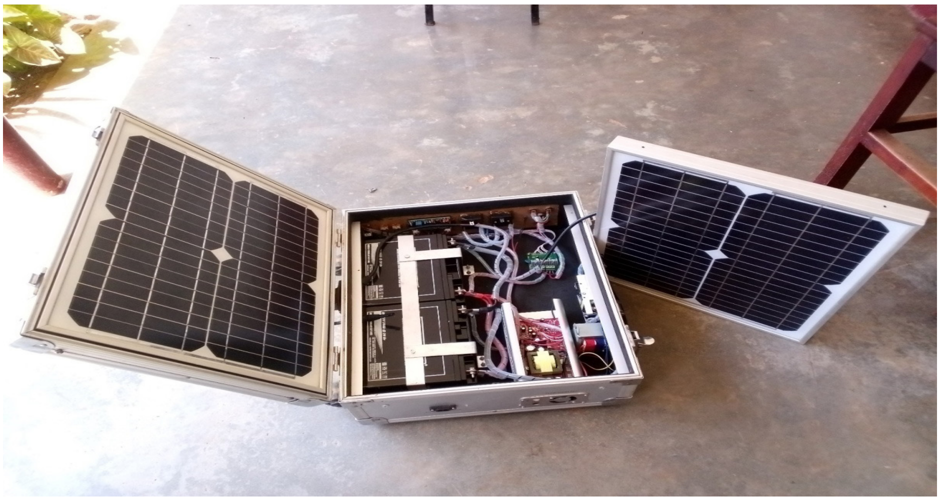

Figure 8. Experimental setup of the charge controller

6.1 *Experimented data*

The charge controller has been tested for eight (08) days. Among the experimented days, the data of 28 January 2023 is shown in Table 4, recorded from 8:55 AM to 5:00 PM. Table 4 shows the panel and battery voltage, current, and power. Efficiencies are also determined from Table 4. Average efficiency is 96.03%. Figure 9 shows the efficiency recorded from the designed charge controller. At the beginning of the day at 8:55 AM panel power was 22.75 W. Battery power was 22.18 W and charge controller efficiency was 97.47%. At the end of the day, at 5:00 PM panel and battery power were recorded 6.25 W and 6.02 W respectively, and the efficiency measured 96.24%.

The total eight days of the experiment it was noted that the average systems efficiency of the designed renewable energy system is 96.52%. Table 5 shows the average efficiency of the charge controller for eight days.

Table 4. Experimented Data with Efficiency of the Designed Charge Controller

Sr. No	Time	Panel			Load			Efficiency (%)
		Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	
1	08:55 AM	14.4	1.58	22.75	12.6	1.76	22.18	97.47
2	09:25 AM	13.9	2.89	40.17	13.4	2.83	37.92	94.40
3	09:55 AM	14.2	1.99	28.26	13.0	1.74	22.62	80.05
4	10:25 AM	13.6	1.89	25.70	13.3	1.92	25.54	99.35
5	10:55 AM	14.0	2.45	34.30	13.6	2.51	34.14	99.52
6	11:25 AM	14.1	2.58	36.39	13.9	2.61	36.27	99.73
7	11:55 AM	14.2	0.26	03.69	12.2	0.25	03.05	82.61
8	12:25 PM	14.2	2.78	39.48	13.9	2.82	39.19	99.30
9	12:55 PM	13.8	1.92	26.49	13.5	1.95	26.33	99.35
10	01:22 PM	14.0	2.59	36.26	14.1	2.53	35.68	98.38
11	01:52 PM	14.3	1.77	25.31	13.5	1.87	25.25	99.74
12	02:10 PM	13.9	0.47	06.53	12.8	0.47	06.02	92.09
13	02:30 PM	14.0	1.79	25.06	13.5	1.80	24.30	96.97
14	02:55 PM	14.5	2.64	38.28	14.1	2.68	37.78	98.71
15	03:25 PM	13.4	0.51	06.83	12.9	0.52	06.71	98.16
16	04:00 PM	13.4	0.47	06.29	12.9	0.47	06.06	96.27
17	04:25 PM	13.3	0.45	05.98	12.9	0.46	05.93	99.15
18	04:55 PM	13.3	0.55	07.32	12.9	0.55	07.09	96.99
19	05:00 PM	13.3	0.47	06.25	12.8	0.47	06.02	96.24
				Average				96.03

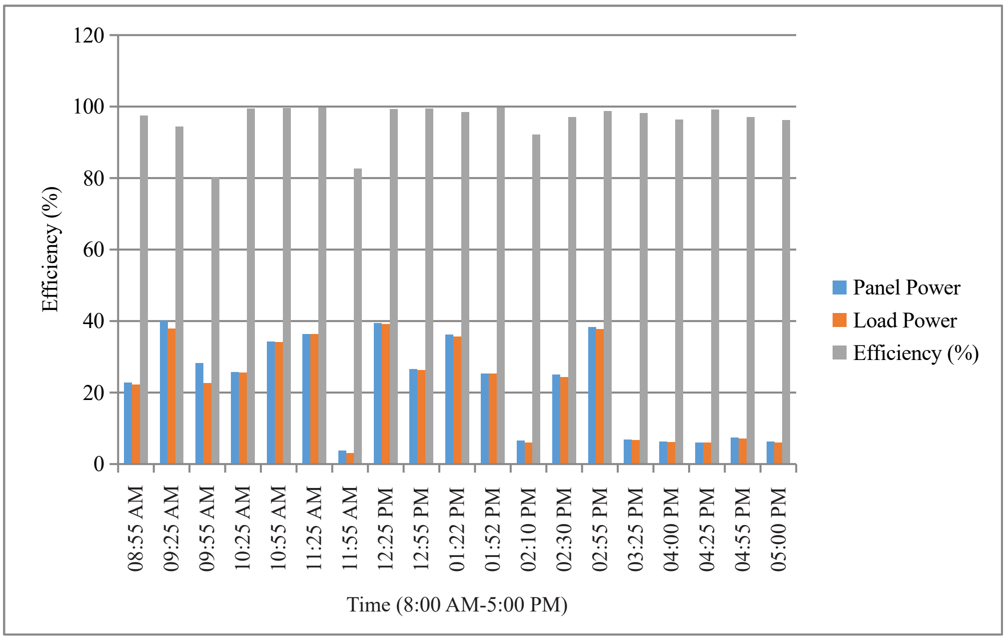

Figure 9. Graphical representation of table data

Table 5. Average Efficiency for Experimented Days

Date of Experiment	Time	Average Efficiency (%)
28.1.23	8:56 AM-2:46 PM	98.50
29.1.23	9:50 AM-3:18 PM	97.87
30.1.23	8:55 AM-5:05 PM	97.49
31.1.23	8:52 AM-3:52 PM	98.21
01.2.23	8:17 AM-11:06 PM	91.49
02.2.23	8:22 AM-5:38 PM	93.74
03.2.23	8:23 AM-3:10 PM	97.68
04.2.23	8:04 AM-3:04 PM	97.16
08 Days	44 Hours 42 Minutes	96.52

7. Evaluating performance against traditional and conventional methods

Traditional PWM charge controller typically exhibits lower efficiency, especially under varying weather conditions [24]. Conventional MPPT algorithms, while more efficient than PWM controllers, may struggle in partial shading scenarios or with rapidly changing irradiance levels [25]. The implemented SCCS demonstrates superior efficiency due to its adaptive nature and precise tracking of the maximum power point, resulting in optimal energy harvest even under challenging conditions.

Traditional PWM charge controllers exhibit a limited ability to maximize power generation, especially during peak sunlight hours [26]. Conventional MPPT algorithms offer improved power generation compared to PWM controllers but may not fully exploit the solar panel's potential under varying conditions [27], [28]. The implemented SCCS effectively tracks the maximum power point of the solar array, ensuring maximum power generation throughout the day, leading to higher energy output and increased system performance.

Traditional PWM charge controller may lead to overcharging or undercharging of batteries, affecting their lifespan and overall performance [29]. Conventional MPPT algorithms improve battery charging efficiency compared to PWM controllers but may still experience inefficiencies under certain conditions [30]. The implemented SCCS optimizes the battery charging process, preventing overcharging and prolonging battery life, resulting in more reliable energy storage and availability during emergencies.

Traditional PWM charge controllers have limited ability to prioritize load management, potentially leading to an unstable power supply to critical loads [27]. Conventional MPPT algorithms offer better load management capabilities compared to PWM controllers but may not efficiently balance power distribution between loads and battery charging [31]. The implemented SCCS efficiently manages power distribution, ensuring stable power supply to critical loads while prioritizing battery charging when necessary, enhancing overall system reliability and performance.

Traditional PWM charge controllers are susceptible to environmental factors and noise, potentially affecting system stability and reliability [27]. Conventional MPPT algorithms offer improved reliability compared to PWM controllers but may still experience performance issues under challenging conditions [32]. The implemented SCCS provides enhanced reliability and robustness, with better noise immunity and environmental tolerance, ensuring stable operation even in adverse conditions, thus enhancing overall system reliability.

Traditional PWM charge controllers have lower initial costs but may incur higher long-term maintenance and operational costs due to lower efficiency and potential battery degradation [33]. Conventional MPPT algorithms have higher initial investment compared to PWM controllers but offer better energy savings and reduced maintenance costs over time [33]. The implemented SCCS has moderate initial investment with significant long-term benefits, including improved energy savings, extended battery life, and reduced maintenance requirements, making it a cost-effective solution in the long run.

Overall, the implemented SCCS demonstrates superior performance and reliability compared to traditional PWM controllers and conventional MPPT algorithms. Its efficiency, effectiveness in power generation, battery charging efficiency, load management capabilities, reliability, and cost-effectiveness make it an ideal solution for addressing the energy needs of health facilities in rural areas of Uganda, especially during emergencies.

8. Conclusion

The design and implementation of a charge controller for solar PV systems for emergencies in health facilities in rural areas of Uganda has been successfully achieved. The charge controller can regulate and control the production of power from the solar panels and store the power in the battery backup systems. The charge controller is also able to prevent the battery from overcharging and overcharging, thus protecting the system from electrical overloading. The experimental setup and testing of the charge controller have been conducted. The charge controller has been tested for eight days, and the average efficiency of the system is 96.52%.

Overall, this project is significant in improving energy access in rural areas of Uganda, especially in health facilities during emergencies. This renewable energy system is efficient, reliable, and cost-effective, and it can contribute to the sustainable development of rural areas in Uganda.

Conflict of interest

The authors declare no competing financial interest.

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