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Design and Prototyping of Solar Hybrid Switch Controller and Monitoring System

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Abstract: *Facing many issues of insufficient electricity from the grid and especially frequent blackout, most factories, apartments, and hotels that are operating a cooking machine, extruder machine, and server spend much cost on waiting time, machine maintenance, replaced raw material, and labor. Therefore, ensuring sufficient and stable electricity becomes the main role to solve this problem. This paper provides SOGE hybrid system design concept that can ensure sufficient power for the users. This system is to manage the input multiple power sources such as renewable, a grid power source, or a genset. All the AC voltage sources are converted to DC voltage before being linked to DC voltage from the solar panel and then converted to AC voltage via an inverter for use with a load. A prototype of the system consisting of hardware and software has been built and experimented. It includes the system of parameters monitoring and feedback control from the voltage level of the battery. From the result of the experiment to validate its key features, the SOGE hybrid system is concluded to be a good solution for the users to get a blackout-free power supply and prolong the life span of their appliances.*

Keywords: SOGE hybrid; DC voltage; AC voltage; Grid

1. INTRODUCTION

Facing many issues of a blackout from the grid, most food processing in apartments, hotels, and factories which are running with extruder machine, cooking machines, spend much cost for waiting time, the cost for fixing the machine, labor cost, and replaced raw materials. Therefore, the Solar hybrid power system is standing in the main role in solving this problem.

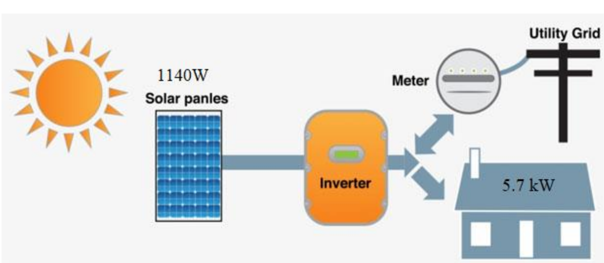

Fig. 1. Solar on-grid for load max 5.7kW

It is an autonomous power system that manages solar power from photovoltaic cells, a grid power system, a diesel generator, and batteries. According to a solar power from photovoltaic cells, a grid power system, a diesel generator, and batteries. According to a SOGE's customer experience in Phnom Penh, he complained about the blackout of public electricity distribution from Electricité Du Cambodge (EDC) which halt his solar on-grid power that is shown in Fig.1.

Table 1 Load profile of SOGE's customer

Name	Quan.	Power (W)	T.Power (W)	Time (h)	Energy (kWh)
Pump	1	745	745	1	745
Refrigerator	2	66	132	24	3168
Electric Iron	1	2000	2000	1	2000
Aircon.	2	745	1490	20	29800
Colour TV	1	109	109	2	218
Fan	1	180	180	8	1440
LED bulb	7	15	105	16	1680
Oven	1	1000	1000	2	2000
Total power			5761	Total Energy	41051

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This system consisted of 6 pieces of solar panels with power of 190W and the power of the grid line is 5kW. These two main electrical sources were designed to supply 5.7kW loads, shown in Table 1.

After he had been using an on-grid solar power system for a while, he thought that using this system was notbeneficial and convenient under the reasons of the blackout of the gridline causing the inverter on-grid to turn off. Therefore, the load could not be supported by these sources. After these problems happened repeatedly, he informed the company about them. So, the company decided to design a new solar power system that is called "Solar Hybrid System". Because this system is presented with SOGE's controller which is mentioned in this paper and SOGE's inverter, it is called "SOGE Hybrid".

In the recent decade, this autonomous solar system switching controller is designed in different ways based on the grid sources in each site and application requirements. According to Feroldi, D., & Zumoffen, D. [1], the solar hybrid system is designed by the combination of the three sources which are photovoltaic array, wind turbines, and bioethanol reformer sources working together. In the connection of each power, it is decided to link these sources by converting wind turbines from AC to DC power and converting all these DC powers which are not only the power of the source but also the power from the batteries to AC power for sending to the load.

As studeid by Durrani, S., Ali, H., Zahir, A., & Khan, S. [2], the solar hybrid was designed based on three different main sources for supplying to the load under the action of a controller-based automatic power changeover which can provide various applications under the reason of discontinuity of these main sources supply as shown in Fig. 2. Furthermore, the controller was designed based on the main components as shown in Table 2.

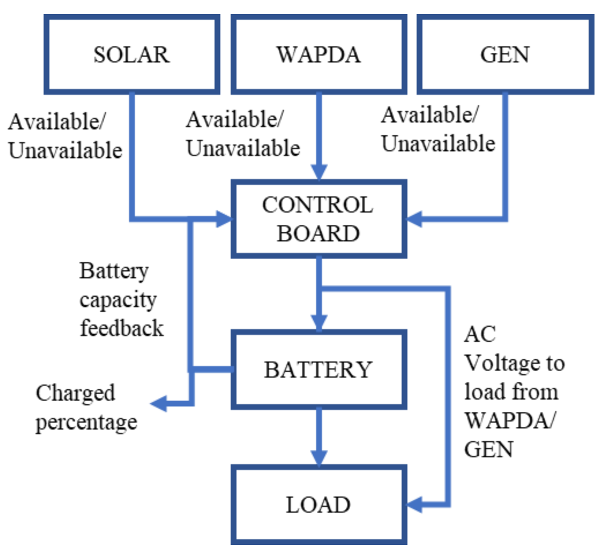

Fig. 2. Flow diagram of the power control system [2]

Table 2 Main components for controller [2]

Component Name	Description	Specification
Voltage sensor	It is used to prevent overcharging of the batteries	Potentiometer LD2420C 12V/24V 20A
Relays	It is an electrical switch that is used to control circuits by a low power	24VDC and 220VAC
DC current sensor	It is used to measure the current flowing from the solar panel to the battery	ASC712 100mV/A
Micro-controller	It is used as a general-purpose computer on an integrated circuit	PIC 16F877A 40 pins IC and 33 I/O pins
LCD	It is used to display the overall parameters of the system	16 X 2 LCD
AC current sensor	It is used to measure the current drawn by the AC load	Current Transformer (CT)
Inverter driver	It is used to give pulses to the inverter when to start and stop the inverter	Self-made for the 1500watt Inverter

According to Madaci et al.[3], the solar hybrid system was designed including photovoltaic (PV), wind turbine, fuel cell (PEMFC), storage systems, and a dump load (in their case, an electrolyzer). In this solar hybrid system, the power management is designed as shown in Fig. 3. The battery was charged based on the power net where:

$$P_{net} = P_{source} - P_{load} \qquad \text{(Eq. 1)}$$

The fully functional for this SOGE hybrid controller composes the energy record and battery control. This research study covers the follows:

- SOGE hybrid concept illustrated by a diagram
- SOGE controller hardware
- SOGE controller Software
- Development to a field

After this controller is built, it contributes to invent a new hybrid controller for SOGE which allows the possibility of designing a more flexible solution on the performance trade-off selection between the controller functions and the cost. Therefore, the use of the system brings more benefit to users who adopts the system to use for their factories. In this paper, the methodology is described in section 2. In section 3, the discussion and the results are shown. The conclusion is given in section 4.

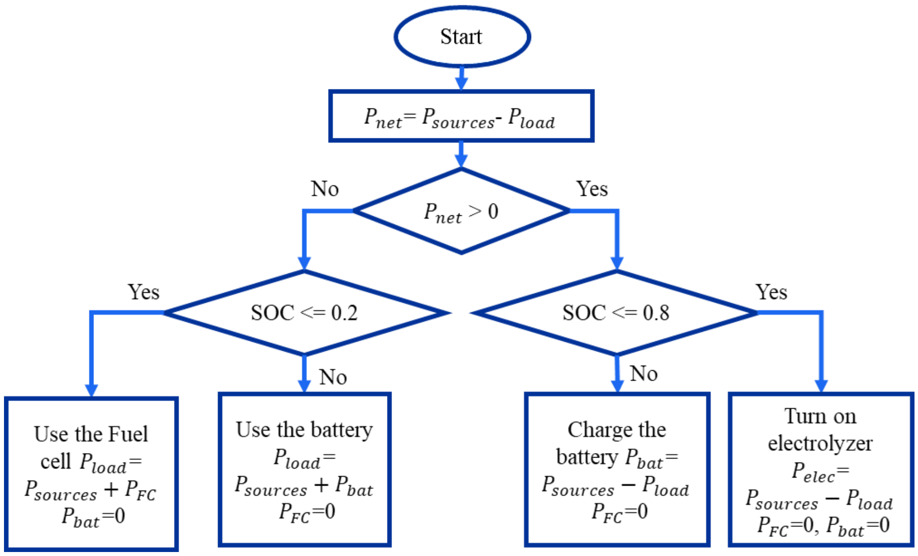

Fig. 3. Power management flow chart of hybrid energy system [3]

2. METHODOLOGY

As shown in Fig. 4, this SOGE Controller hardware is developed with two main functions that are an automatic power source changeover switch and a monitor. The first main role is that it can decide whether it should connect or disconnect the AC source and connect or disconnect the battery from the load. This control scenario can be developed under the analysis of the battery voltage information.

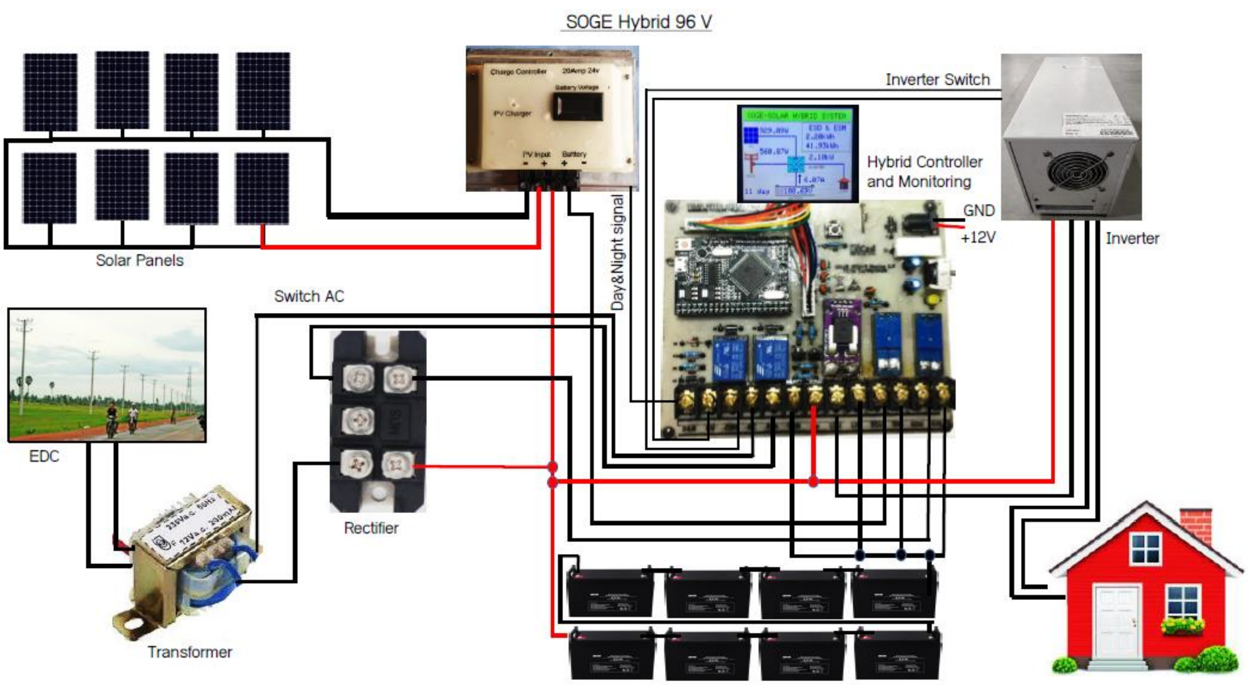

Fig. 4. SOGE hybrid diagram for 96V system

The second main role is that it is designed to display most of the abnormal battery voltage, power, and energy from the solar branch, power and energy from the AC branch, and power and energy from the load branch. This scenario is decided based on the battery voltage, solar current, AC source current, and load current. To illustrate and elaborate the features of the system, there are four main steps to be considered.

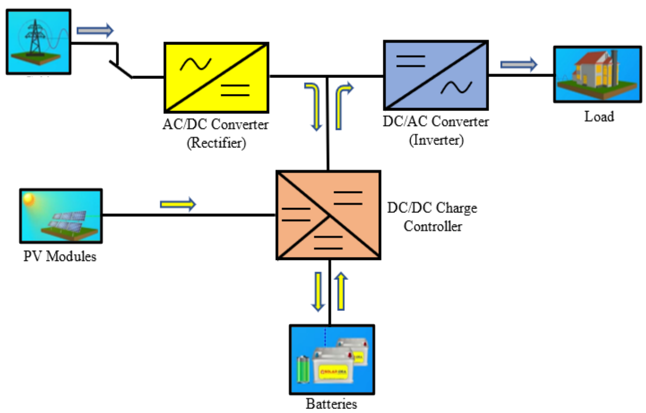

Fig. 5. SOGE hybrid schematic

2.1 The SOGE hybrid tropology

As shown in Fig. 5, there are two main electricity sources, from grid and PV modules, being controlled based on load and batteries power level. These two sources are linked to the batteries in direct current (DC) form and supplied to the load in alternative current (AC) form. In Cambodia, public electricity is distributed in AC form by Electricite Du Cambodge (EDC). Therefore, this power source has to be converted into a DC source which is the same type as the power source from photovoltaic cells. Furthermore, for saving battery life, the grid source must be stepped down to the desired voltage which is used as the voltage reference for controlling the battery voltage level. Also, based on Fig. 5. the ground from the grid, and ground from the load are separated by a rectifier block which also includes a transformer. So, it is safer for the users.

2.2 The design of SOGE hybrid controller hardware

2.2.1 Parameters consideration

The customer needs sufficient power to supply load maximum at 5.7kW as shown in Table 1. Before this load requirement is designed, the load profile, backup powers, and existed components must be gathered. Table 3 shows the new design components selection for satisfying load requirement. As shown in the Table 3, the system uses the power from solar panels at least 50% per day of total load requirement and the power from solar is 3.12kW (190W x 8pcs + 100W x 16pcs = 3120W) and back-up power from the battery can supply to the maximum load at least for 5 hours (t = (12V x 24 pcs x 150Ah) / (5761W x 1.4) = 5.35 hour). These sources can be managed by SOGE controller whose feature is described in the following section.

Table 3 New design components selection for sufficient use

Component Name	Specification	Functions
Solar Panel	190W x 8pcs, Vmp = 18V, and Imp = 5.56A 100W x16pcs, Vmp = 36V, Imp = 5.2A, typical current = 21.51A	Renewable energy source
National public grid	Vrms = 220VAC, 50Hz, I = 15A	Back-up energy source
Battery	Lead-acid battery 150Ah x 24, V = 12V	Back-up power or power storage
Inverter	Can be operated with a normal battery voltage of 96V	Convert voltage from DC phase to AC phase
DC power supply	V = 48V x 2, I = 30A	Replace transformer and rectifier from the grid branch
SOGE's controller	Operating voltage = 12V	Changeover switch and parameters display
Charge controller	V = 96V and I = 50A	Charge current to the battery

2.2.2 Features requirement

This SOGE controller is designed by dividing into five main functions. The main role of this controller is to automatically switch the power consumption from the grid to solar power or a combination of both sources to ensure that the system will supply suitable and secure electrical power. The next function, the SOGE hybrid inverter can be turned on and off automatically by the switch of the controller. For the 96VDC solar hybrid system, if the voltage of the battery goes down until reaching 88VDC, an inverter turns off. The inverter turns on again if the battery voltage goes up to 110VDC. The third role is data display. They are voltage of the battery, current in and out of the battery, power from solar, power from the grid, power from the load, energy of solar, energy of grid, the energy of load, number the day and night for each month. The last function, this controller is designed by including the voltage of the battery, the voltage from the charge controller (for counting number of days and night), current from the grid, current from solar, and current from load measurement.

2.2.3 Hardware selection

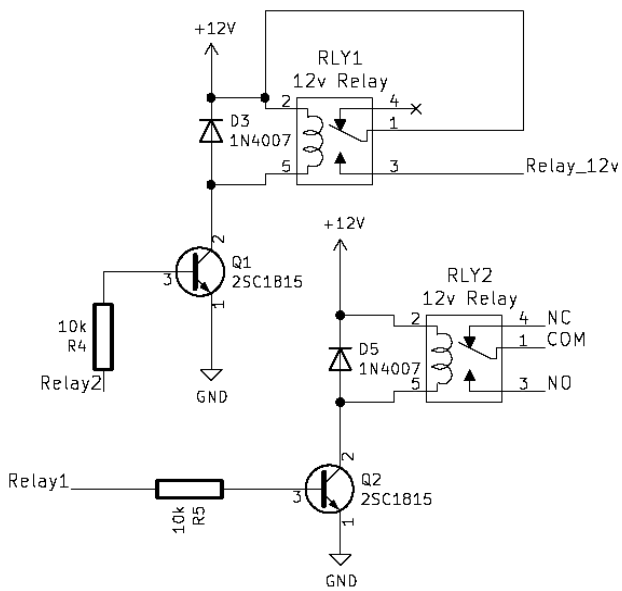

Fig. 6. Switching block schematics

From the features of the switching controller, power demand, and power sources, we can select the components that are used to build this SOGE's controller. The main component is the microcontroller. There is a vast variety of microcontrollers in the market. Each microcontroller has its unique ability and advantages. Choosing the right component leads to achieving better performance at a lower cost. Since this project needs high performance and a small microcontroller, the Mega Pro 2560 (embed) is the most suitable one. It is designed to control many functions like data collection, data calculation, monitoring the data, and switching on and off of the system. The second main component is the current sensor. There are many kinds of current sensors, namely hall effect sensor, resistive shunt, and current transformer. Among these, the hall effect sensor is the most essential one. It is the product of an output voltage signal independent of the rate of the detected field, ambient conditions prevention. The next important component is LCD, LCD TFT 2.4 inches Arduino Shield is chosen as the controller monitor because it has many features such as a touch screen, SD card reader, screen to display and operate at low power. It is used for displaying the data of the system. The fourth main component is the relay. It is used as the switch of AC source and inverter. As shown of relay block in Fig. 6, controlling relay directly from micro-controller is not a good deal because relay operates at voltage 12V and it has a coil which can damage micro-controller so diode 1N4007 and transistor are needed. The last main part is the power supply block. It is an important part that is used for the operating microcontroller, LCD, Relay, and current sensors. They are required to operate voltage 5V. Then, IC 7805 is standing in an important role for stepping the voltage down from voltage 12V to 5V. All of these components are beneficial for this design. They can handle all the functions that are assigned. For more information about each component function and specification, they are shown in the Table 4.

Table 4 The main components for SOGE hybrid controller

Component Name	Specification	Power Consumption	Functions
Mega Pro	Operating voltage = 5.0V and operating current = 220 mA	1.1 W	It is used to control the whole systems
LCD TFT 2.4 inch	Operating voltage = 3.3V/ 5.0V and operating current = 100 mA	0.6 W	It is used to display the system parameters
Relay	Operating voltage = 12.0V and operating current = 37.5mA	2 of relays = 0.9W	It is used as a switch of AC source and load branch
ACS758	Operating voltage = 5.0V and operating current = 10mA	3 of ACS758 = 0.15W	It is used to measure the DC current
Voltage sensor	The resistor for output is 8.2kΩ and another resistor is 470kΩ, Voltage input maximum = 120V, Voltage input minimum = 88V		It is used to detect the voltage of the battery at normal voltage is 96V
Total power consumption		2.75W	

2.3 The design of SOGE hybrid controller software

Another important part is about software design. It is built by Arduino IDLE which is divided into three main blocks. The first block is about declaration parameters of the system such as power, current, voltage, time, controller pin name, and number. In this part, the program executes only one time. The second block is about the declaration pin function. They can be input pins or output pins. It is in the void setup () block of the Arduino program IDLE. This setup block executes only one time. The third block is the main operating program. It is programmed as a loop function. All the parameters of the system including energy recorded are read and shown on the LCD screen in this loop as shown in Fig. 7.

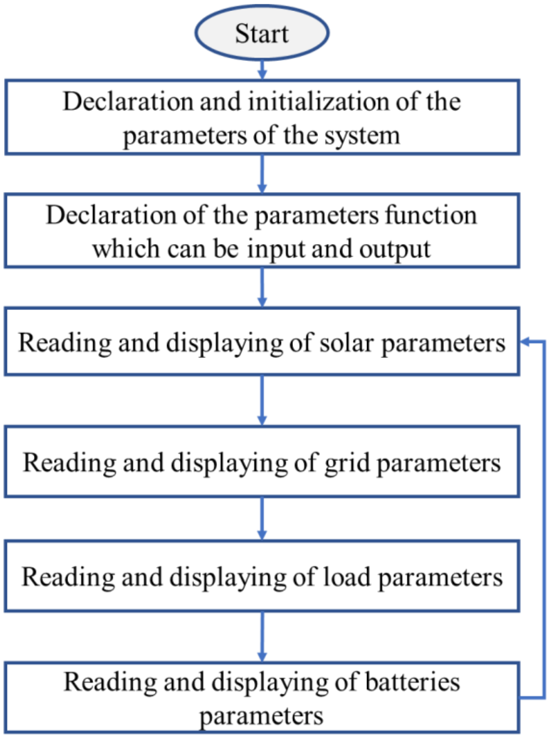

Fig. 7. Program flow chart

The parameters that are shown on the LCD screen are solar power, grid power, load power, and battery voltage. These parameters can be defined by the formula as shown in Eq.2, Eq.4, and Eq.6, respectively. Furthermore, the data are recorded for each month are energy from solar, grid, and load. They can be calculated by (Eq. 3), (Eq. 5), and (Eq. 7), respectively.

$$P_s = V_b.I_s \quad \text{(Eq. 2)}$$

$$E_s = \int_0^t P_s dt + E_{s0} \quad \text{(Eq. 3)}$$

$$P_g = V_b.I_g \quad \text{(Eq. 4)}$$

$$E_g = \int_0^t P_g dt + E_{g0} \quad \text{(Eq. 5)}$$

$$P_l = V_b.I_l \quad \text{(Eq. 6)}$$

$$E_l = \int_0^t P_l dt + E_{l0} \quad \text{(Eq. 7)}$$

Where: P_s : solar power, P_g : grid power, P_l : load power, V_b : battery voltage, I_s : Solar current, I_g : Grid current, I_l : Load current, E_s : Solar energy, E_g : Grid energy, E_l : Load energy, t : time, E_{s0}, E_{g0}, and E_{l0} are energy at time zero of the solar, grid, and load, respectively.

To calculate the power, solar current, grid current, load current, and voltages of batteries are read by using current sensors, and voltage dividers whose description is shown in Table 4 and 8. Furthermore, time is defined by the internal clock of the microcontroller. Therefore, the power is computed every one second and sum together.

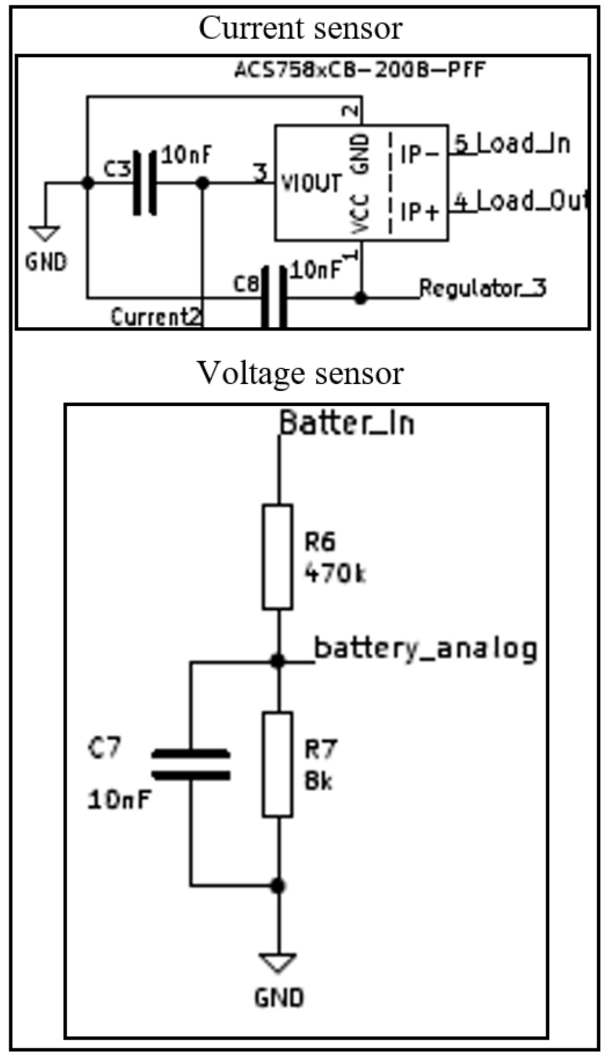

Fig. 8. Current sensor and voltage sensor schematic

In addition, for the condition energy recorded for each month, the voltage from solar has been read as the digital 1 and 0 (1 is in the daytime and 0 is the nighttime). In some cases, when it is raining in the nighttime, lightning exists and the solar voltage appears as well. Then, the program will count as one day or two days based on the number of lightning. An important method to overcome this issue is that the number of days is counted after 10 seconds when the solar panel gets light as shown in Fig. 9.

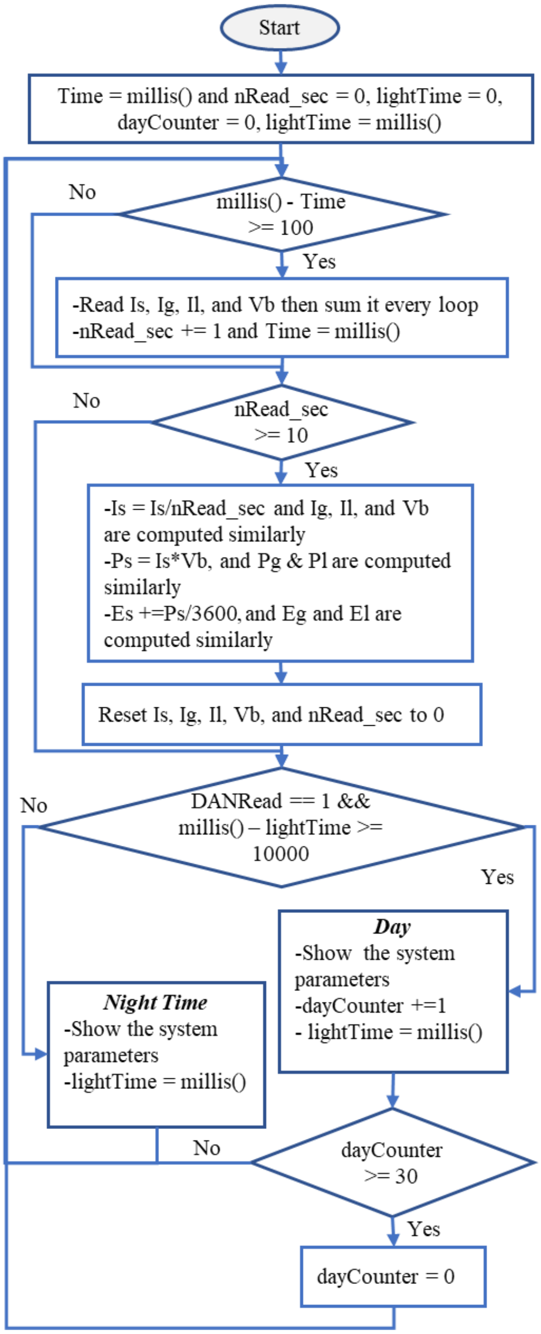

Fig. 9. Algorithm avoiding days counting due to lightning

Furthermore, after the battery voltage (Vb) is read, it is used to control the whole system. For the 96VDC solar hybrid system, the AC source is connected if the voltage of the battery equals 96VDC or less than this voltage level. If the voltage still goes down until reaching 88VDC, an inverter turns off. The inverter turns on again if the battery voltage goes up to 110VDC. In this scenario, the solar hybrid system works well and the battery life is also saved because the power from the battery can release only 60% of the total battery capacity, as shown section 2.2.1 & in Fig. 10.

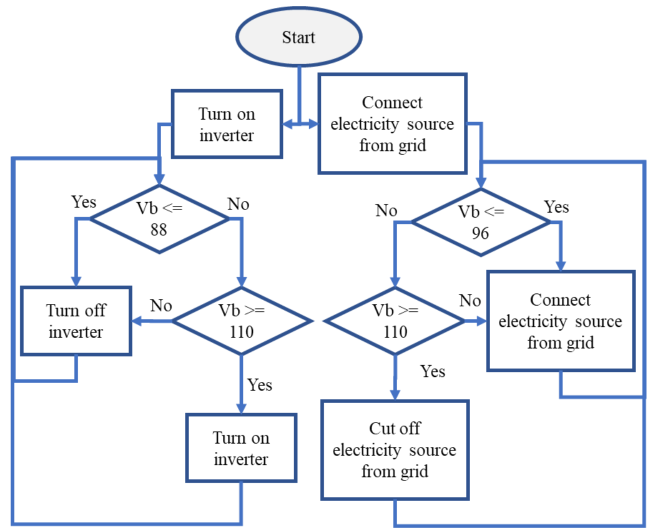

Fig. 10. Battery control procedure

In addition, the current and voltage need to be calibrated and scaled correctly. This calibration/scale method is built by the linearity theory as shown in Fig. 11.

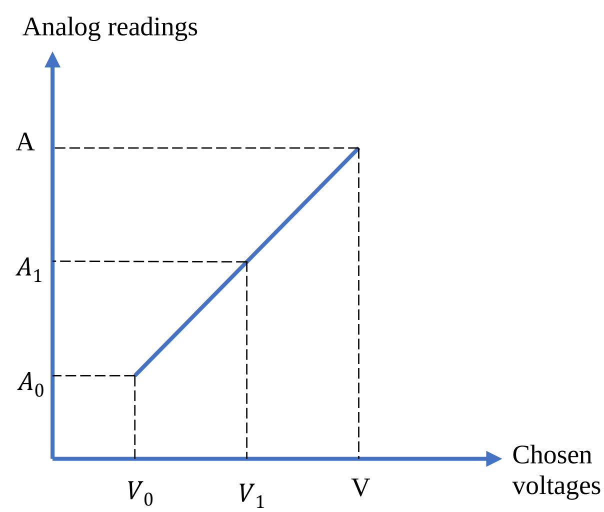

Fig. 11. Data referent record model

V_1 & V_0 are chosen voltages at different levels with different analog readings A_1 & A_0, respectively. Then, they are saved into EEPROM of the microcontroller at different addresses as the reference for computing voltage upon a new analog reading. The formulation for computing voltage is given by

$$V = \frac{(V_1 - V_0)(A - A_0)}{(A_1 - A_0)} + V_0 \qquad \text{(Eq. 8)}$$

Similarly, current can be computed by

$$I = \frac{(I_1 - I_0)(A' - A'_0)}{(A'_1 - A'_0)} + I_0 \qquad \text{(Eq. 9)}$$

where A', A'_1, and A'_0 are analog readings from the current sensors.

2.4 System deployment

After the SOGE hybrid controller has the quality checked, it is deployed to a field with a maximum load of 5.7kW and the typical load of 3kW. The Fig. 12 shows the normal operation in which the power consumption by a load is 2.1kW which draws 0.929 kW from the solar panel, 0.56 kW from the grid, and 0.611 kW from the battery. After operating for several months, the system is still working well.

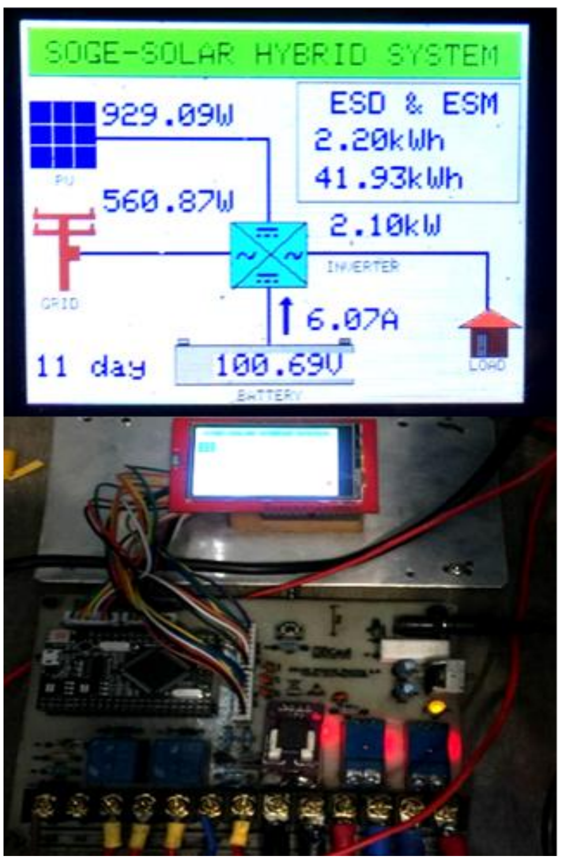

Fig.12. LCD screen installation

3. RESULTS AND DISCUSSION

As a result, the performances of the SOGE controller are working well when conditions of discission-making when it should connect or disconnect the AC source and turn on or off the inverter based on battery voltage level, lightning detection, day and night detection as shown in Fig. 12. Therefore, this SOGE hybrid inverter can supply sufficient energy to the load. However, in the beginning, the energy records of each branch are not accurate if it compares to the measurement by using the multimeter as shown in Table 5. These errors exist because of the current calibration range. The maximum current calibration is 6A that is the maximum current from the DC power supply but the board is used with the normal current of 22A. It has a wide range so it can also make a wide error.

Table 5 Load power error before update

Power Display (kW)	Current (A)	Battery Voltage (V)	Power computed (kW)	Error (kW)	Error (%)
2.97	21.37	98.4	2.10	0.86	27%
3.07	22.34	98.4	2.19	0.87	28%
3.11	23.5	98.4	2.31	0.79	26%
3.11	22.75	98.4	2.23	0.87	28%
3.19	22.84	98.4	2.24	0.94	30%

After the errors are found, the SOGE controller board has reuploaded the program including the filter of error. So, the error can be eliminated as shown in Table 6. In another special case, the errors can be reduced by regulating the high specific load while it is doing the current calibration.

Table 6 Load power error after update

Power Display (kW)	Current (A)	Battery Voltage (V)	Power computed (kW)	Error (kW)	Error (%)
1.15	11	100	1.1	0.05	4%
1.14	11	101	1.1	0.02	2%
1.10	10	104	1.04	0.06	5%
1.12	10.5	102	1.07	0.04	4%
1.37	13	102	1.32	0.04	3%

3.1 Comparison between old system and new system

After the old solar hybrid system is replaced, the user is satisfied with its performance. Between these systems, they have two sources that are solar and grid source, and load 5.7k that are similar. Otherwise, they have many things different as shown in Table 7.

Table 7 The different parts of old and new system

Old System	New System
Solar on-grid design	Solar hybrid design
Solar power = 1.14kW	Solar power = 3.12kW
Grid power = 5kW	Grid power = 3kW
No battery and no charger	24 batteries, charger 50A
On-grid inverter 5kW attached with controller	Self-design hybrid inverter 5kW and controller
Provide insufficient power	Provide sufficient power

5. CONCLUSIONS

To sum up, four main points are described in terms of the SOGE hybrid controller. They are the controller diagram, hardware, software, and the deployment of this controller into the field. This controller can measure all the parameters needed and manage the power of this hybrid system well. It is an autonomous system that the load consumes the power mostly from the existing power of solar with minor power compensation from the grid if it has not gotten enough power from solar alone. This power is done by the SOGE controller. Since the SOGE controller of the system has been built in-house, it is flexible for function customization on the system parameters and it can also control the input power sources and output power source. Therefore, the output power of this system is sufficient to use for their users.

In the future, the solar hybrid controller will be designed based on load by regulating the duty cycle of voltage from the AC source to get the desired voltage which is used as the battery voltage reference so that the battery will be controlled at this voltage level. Furthermore, this system will be also designed to integrate IoT system. Therefore, all the data from this system can be easily collected over network and internet.

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