DESIGN AND SIMULATION OF A SOLAR-POWERED SPLIT INVERTER AIR CONDITIONER UNIT USING SUPERCAPACITOR BANK AS AN ALTERNATIVE ENERGY STORAGE

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ABSTRACT: *This study focuses on the design and simulation of a solar-powered split inverter air conditioner unit that incorporates a supercapacitor bank as an alternative energy storage solution. The research objectives include designing the entire system, determining the appropriate size of the supercapacitor bank, simulating the system using SIMULI NK software, evaluating the life cycle cost compared to traditional lead-acid batteries and Li-ion batteries, and estimating the return on investment. To achieve these objectives, an experimental comparative research design was employed. The study involved designing and simulating a supercapacitor bank as an alternative energy storage and conducting a comprehensive comparison of three energy storage options based on various parameters such as charging and discharging rates, power and energy densities, cyclability, safety and ecology, operating temperature, cost, and maintenance. The key finding of the simulation results indicates that the discharge current of the inverter AC is high during the starting phase and gradually decreases over time. This research provides valuable insights into the potential use of supercapacitor banks as an alternative energy storage solution for solar-powered air conditioner units. The findings contribute to understanding the performance and viability of supercapacitors in comparison to traditional battery technologies. The results of the life cycle cost analysis and return on investment estimation will aid decision-makers in evaluating the economic feasibility of adopting supercapacitor-based systems.*

1. INTRODUCTION:

The Philippines has a reliable capacity of 23,410 Megawatts (MW) from its current power plants as of December in the year 2020. The Department of Energy (DOE) predicts a surge in energy demand from consumers to reach 49,287 MW by 2030. To address this, consumers are exploring alternative energy sources such as solar, wind, and hydropower. Among these, solar power is the most easily accessible and requires minimal maintenance. [1]

Continued use of fossil fuels as an energy source will worsen environmental problems due to high levels of carbon dioxide (CO_2) emissions. Therefore, there is a growing need for renewable energy sources to meet the target reduction of greenhouse gas emissions set by the Kyoto Protocol. World leaders have set a feasible goal of reducing CO_2 emissions by 2030, which encourages the use of renewable energy like biomass wind, tidal solar, geothermal, and hydroelectric power [2].

Solar energy, particularly photovoltaic (PV), has several advantages over other renewable energy sources. It has no moving parts, is quiet, requires minimal maintenance, and is entirely safe. Additionally, it can be recycled to convert sunlight directly into electricity. It can provide a clean source of energy even for those living in rural areas far from the nearest grid. PV panels can be easily installed on roofs, parking lots, and vertical facades of skyscrapers or nearby land [3].

Table 1. Materials Specifications Sheet

S/N	Description	Watts	Volts	Amps	CB	P	Conductors cu wire
1	Inverter AC	2000	12	166.67	200	2P DC	127.0 mm²
2	Controls	30	12	2.5	10	2P DC	2.0 mm²
3	Main	2000	12	169.17	200	2P DC	152.0 mm²
							2.0 mm²

There are two configurations for solar energy: grid-connected and stand-alone. Energy storage is required for standalone PV systems. due to the fluctuation of output energy generated by weather conditions and energy consumption. These systems supply steady current during the day and store excess energy in batteries for use during the night or low-sunlight days. However, the design of these systems requires a balance between dependability and affordability. As a result, alternate techniques may be necessary to address sudden changes in energy demand [4].

Supercapacitors, which are storage devices of energy that do not rely on chemical reactions, such as lead-acid and lithium-ion batteries, are known as ultracapacitors or electric double-layer capacitors [5]. They are less difficult to estimate and monitor for charging than standard batteries [6- 7]. Solar panels and windmills are examples of auxiliary power sources., and hydropower plants are used to supplement primary energy sources to accommodate load fluctuations. While SCs are currently unsuitable for primary energy storage due to their lower specific energy values, discoveries, and technologies may make them a better alternative due to their long lifespan and potential for higher specific energies at lower costs [8].

2. MATERIALS AND METHODS

The two main activities of this study which experimental comparative research design were to design and simulate a supercapacitor bank as an alternative energy storage and to compare the three-energy storage in terms of their charging and discharging rates as well as their power and energy densities, cyclability, safety and ecology, operating temperature, cost, and maintenance [9-11].

The supercapacitors used in this model will be connected in parallel connection to maximize the available supercapacitors. The supercapacitors are in module form, which comprises 200 pieces of 12V, 500F individual supercapacitors. Preliminary set-ups were done to determine the best connection in terms of the charging time and the discharging time [12-21].

Table 2. Load Schedule

Description of Material	Specification	Quantity
Solar Panel	450W	8 PV
Supercap Bank	100000F, 12V	8 pcs
Charge Controller		1 pc
Control Box	Pre-assembled control box	1 set

In each set-up, a different connection of supercapacitors, the total capacitance was computed using the formula:

CT=Cind*n/m Equation 1.1

where:

CT = total capacitance in Farads, F

Cind= rated capacitance of individual supercapacitors in Farads, F

n = number of groups in parallel, unit-less

m = number of units connected in series, unit-less VT = Vind * m Equation 1.2

where:

time will be recorded for both charging and discharging of each set-up.

2.1. Software Design

The microcontroller used to switch the relays will be programmed with the Arduino IDE v.1.6.5.0, Arduino. cc and the global Arduino community have created, tested, and supported an open project.

2.2. Simulation and Verification

Simulink, an open-source circuit assembly flatform online, was used to simulate and validate the charging, discharging, and sensor circuitry [4]. Simulink has a built-in programming platform, similar to the Arduino IDE, and the circuitry was simulated and programmed simultaneously using an online application.

2.3. Charging/Discharging Time

To compare the charging and discharging rates of the three energy storage systems. Each energy storage was charged using PV modules with corresponding charge controllers, and the supercapacitor was charged using the designed charging circuit. Similarly, the Li-ion and Lead-Acid batteries do not require a charge controller or a discharging circuit, unlike the supercapacitor. The charging and discharging times were both recorded using the data logger system.

Data for the energy density, power density, cyclability, safety ecology, operating temperature, cost, and maintenance of SC, Li-ion, and LA batteries, on the other hand, were derived solely from their specification sheets and other works of literature.

VT = rated voltage in volts, V

m = number of units connected in series, unit-less While the energy capacity of a capacitor and supercapacitor is different from how a battery is computed, and it goes this way:

E = 0.5 * CT * (VT)2 Equation 1.3

where:

E = energy capacity of supercapacitor in Joules, J or W-s

CT = total capacitance in Farads, F VT = rated voltage in volts, V

For 2 tons Split-type AC (2000W),

E = 2000W x 8 hours x 3600s = 5.76x107 J

5.76x107 J = 0.5 CT (12V)2 CT = 800000 F

Cin= 100000 Farad 12V (based on availability in the market-Alibaba)

n=800000F/100000F = 8 individual supercapacitors connected in parallel

The supercapacitor connected to become a module will be charged at 90% of their maximum rated voltage to avoid overvoltage and will be discharged using a 2kW Inverter Split-type Air conditioner. The start voltage, end voltage and

2.4. Solar Panel Design Computations

The proposed specifications and requirements are 12 VDC, 450 Wp PV module

2.4.1. Power Consumptions Computations

Inverter AC: 2000 W, 8 hours Control Circuit: 30 W, 12 hours Therefore,

Total Load = [2000W(8h) + 30W(12h)] = 16.36 kW-hr/day Equation 1.4

2.4.2. AC Photovoltaic Module

PEC (2017) Article 6.90.1.2 is defined as a tracker, the entire, environmentally friendly equipment is made up of solar cells, optics, an inverter, and other parts and is intended to produce vac electricity when exposed to sunlight.Panel, PEC(2017) Article 6.90.1.1.

Model No.	ZPM 435 ph72	ZPM 440 ph72	ZPM 445 ph72	ZPM 450 ph72	ZPM 455 ph72
Warranty					
Product Warranty	12 Years				
Power Warranty	25 Years of 80% Output Power				
Electrical Data at STC					
Maximum Power (Pmax)	435 Wp	440 Wp	445 Wp	450 Wp	455 Wp
Voltage at Maximum Power (Vmpp)	33.76 V	33.91 V	34.06 V	34.21 V	34.36 V
Current at Maximum Power (Impp)	12.89 A	12.98 A	13.07 A	13.16 A	13.25 A
Open Circuit Voltage (Voc)	40.8 V	40.95 V	41.1 V	41.25 V	41.4 V
Short Circuit Current (Isc)	13.34 A	13.41 A	13.52 A	13.62 A	13.72 A
Panel Efficiency	20.09 %	20.33 %	20.56 %	20.79 %	21.02 %
	Standard Test Conditions (STC): air mass AM 1.5, irradiance 1000W/m², cell temperature 25°C				

Figure 1. Solar Panel Data Sheet

A

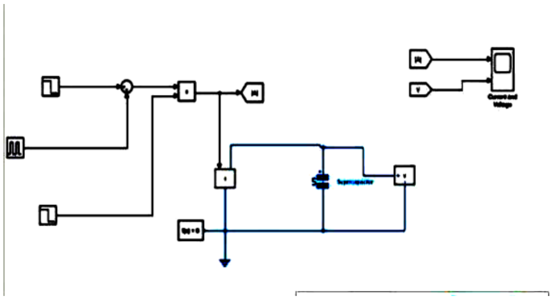

Figure 2. Supercapacitor bank of a solar-powered air-conditioning system Simulink Model

collection of modules mechanically fastened together, wired, and designed to provide a field installable unit.

Total PV Panels = 16360 X 1.2(for system loss) = 16.432 kW-hr/day Equation 1.5

Size of PV panel = Total Wp of PV panel capacity required = Total PV Panels/average sun hours of region or area

Total Wp = 16432/4.75 = 3459.37 Wp Equation 1.6

Total Panel energy required = 3459.37/450(as per module used) Equation 1.7

= 7.69 PV or 8 PV @ 450Wp

2.4.3. Charge Controller Computations

The controller size computation is based on the total short-circuit current of the solar panel.

2.4.4. PV Panel Connections (8 pieces -450 W PV panel) Series-parallel connection, two panels in series connection that will make four sets of series connection and then the parallel connection of the four sets of series connection.

Controller Size= panel short circuit * number of parallel connections * safety margin Equation 1.8

= (11.36 * 4) + 25 % = 56.8 A or use 60 A, 0-150 volts DC, 7000 watts charge controller

Charge Controller Sizing: 200% of Wp Eq. 1.9

Total Wp = 16432/4.75 = 3459.37 Wp 3459.37 * 200 % = 6918.74 Watts

2.4.5. Sizing of Conductors and Overcurrent Devices

Circuit connections and electrostatic discharge equipment must always be dimensioned to carry a minimum of 125 % of the maximum currents calculated. PEC allows for the rating or setting of overcurrent devices. Because the photovoltaic source circuit current will be used in the design, the short circuit current shall be the sum of the parallel module-rated short-circuit currents multiplied by 125%.

Calculation of estimated load:

1 x 2000 watts + 30 watts = 2030 watts

For maximum expected current load:

2030/12 = 169.17 ampere

The size of the conductor wire from the charged controller to the main circuit breaker should be 152 mm2, and the over-current protection should utilize a 200-ampere 2-pole DC circuit breaker [3].

Determining the size of the conductor of the Inverter DC and control circuit:

a. Inverter AC – 1: 2000/12 = 166.67 Amperes

The size of the conductor wire should be 127mm2, and the over current protection should utilize a 200 ampere 2-pole DC circuit breaker.

b. Control Circuit: 30/12 = 2.5 Amperes

The minimum size of the conductor wire should be 2.0 mm2, and the over-current protection should utilize a 10 amperes 2-pole DC circuit breaker.

2.4.6. Determining the size of the conductor and over-current protection device of the PV panel.

PV Panel connection (8 pieces -450 W PV panel):

Series-parallel connection, two panels in series connection that will make four sets of series connection and then the parallel connection of the four sets of series connection.

total = ((panel short circuit current * no. of parallel connection)

+ safety margin) * 125%)) = ((11.36 * 4) + 25 %) * (1.25))

= 71 Amperes

The size of the conductor wire should be 10 mm2, and the over-current protection should utilize an 80-ampere 2-pole DC circuit breaker.

Determining the size of the conductor and over-current protection device of the battery bank. The size of the battery bank conductor will be 25 mm2 and over the current protection device of 80 amperes.

3. RESULTS AND DISCUSSIONS

The following figures below show the results of the simulation testing that has been conducted by the researcher to identify the voltage, current, period, and efficiency of the super capacitor bank of a solar-powered air-conditioning system.

Figure 2 shows the Simulink model of the super capacitor bank of a solar-powered AC system. For the researcher to conduct his simulation testing he must first determine and place the sensors in their designated positions [4]. By placing the sensors in their proper place, the Simulink can now determine and simulate the charge and discharge of current and voltage of the super capacitor bank of a solar-powered AC system.

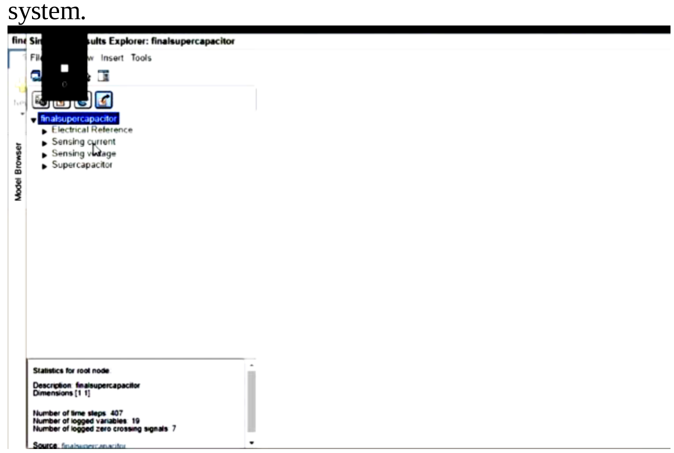

Figure 3. Simulink Simulation Result Explorer for the Supercapacitor Bank

The figure above shows the beginning of the compilation of the Simulink model for the supercapacitor bank of the solar-powered air-conditioning system. It is shown in Figure 3 that the compilation and run time of the Simulink model of the supercapacitor bank is at 4,000 seconds equivalent to 1 hour, 6 minutes, and 6 seconds.

After the compilation of the supercapacitor bank Simulink model, the simulation result explorer of the MATLAB

Simulink will show the simulation testing results for the current sensing and voltage sensing of the proposed system which is shown in Figure 4.

Figure 5 shows the results of the simulation testing done after an hour, 6 minutes, and 6 seconds for the Super capacitor bank of the solar-powered air conditioning system's charge and discharges. The upward movement of the signal wave (which is colored blue) for the charge of

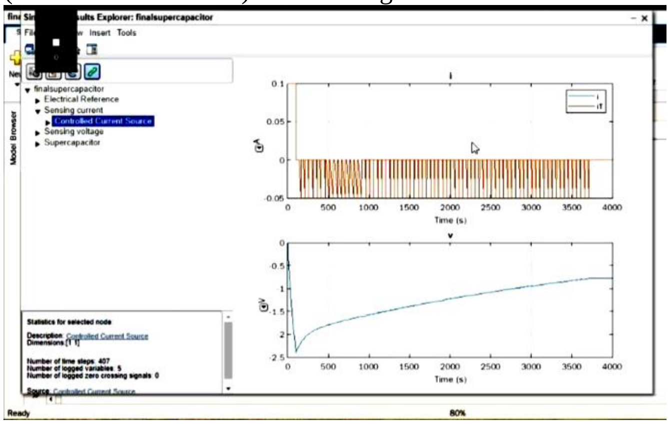

Figure 4. Charge and Discharge Simulation Testing Result of the Super capacitor Bank

the super capacitor bank indicates that the energy harvested from the cells of the solar panels is properly charged and deposited into the super capacitor bank. The charging of the supercapacitor bank happens when the AC unit is on/off but

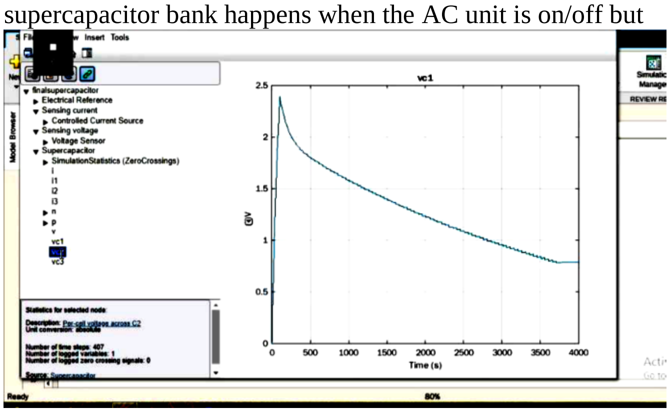

Figure 5. Charge and Discharge Simulation Testing Result of the Super capacitor Bank

is still plugged on.

The downward movement of the signal wave (which is colored red) indicates the discharge of the voltage and current of the super capacitor bank. The discharge happens when the user of the air-conditioning system is using the AC unit.

Figure 6 displays the outcomes for the super capacitor bank charge and discharge peak. The figure above is the combined results of the entry and exit of voltage in the super capacitor bank of the air-conditioning system. The

peak of the voltage is seen when the super capacitor bank is fully charged from the energy harvested by the solar panels. The usage of the stored

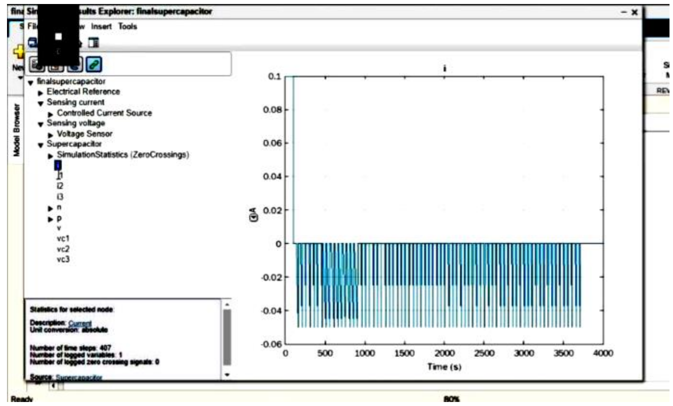

Figure 6. Charge and Discharge Simulation Testing Result of the Super capacitor Bank

energy when used is seen as the downward motion of the signal wave, indicating that the AC unit is currently in use.

Figure 7 depicts the current charge and full capacity peak of a solar-powered air-conditioning system's super capacitor bank. The photo depicts the super capacitor's current supply while it is charging and has reached its maximum energy storage capacity. When the capacitor is fully charged, the current automatically decreases, negating the requirement for a full-charge sensing circuit. (Buchmann, I., 2017). The figure above also depicts the current's idle position when the AC unit is not in use.

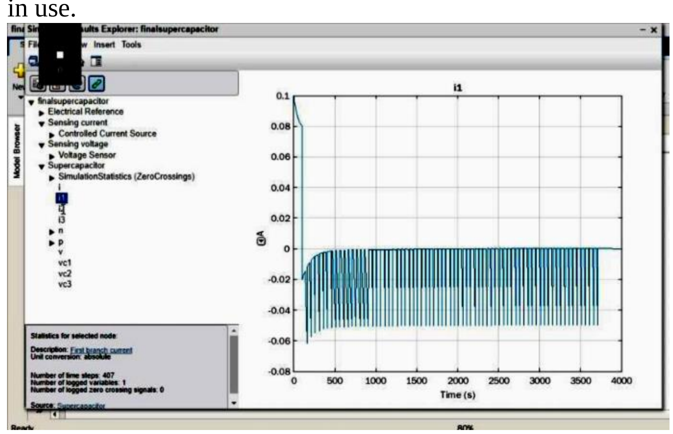

Figure 7. Charge and Discharge Simulation Testing Result of the Super capacitor Bank

Figure 8 represents the discharge current of the supercapacitor when the AC unit is turned on. The flow of discharge is determined by the individual's use of the air-conditioning system. The primary stage of opening the AC unit, represented by the wave graph in the diagram above, is the release of current.

Figure 9 depicts the scope block of the super capacitor for the solar-powered air-conditioning system. The scope block displays the compiled results of the super capacitor system simulation analysis from MATLAB Simulink.

The scope block's purpose is to demonstrate and compare that the results from the scope block are similar to the simulation results explorer. Ensure that the results of both tests are consistent with one another.

The block that is used to measure the efficiency in the super capacitor bank of a The RMS block is a solar-powered air-conditioning system. Figure 10 shows the compiling process

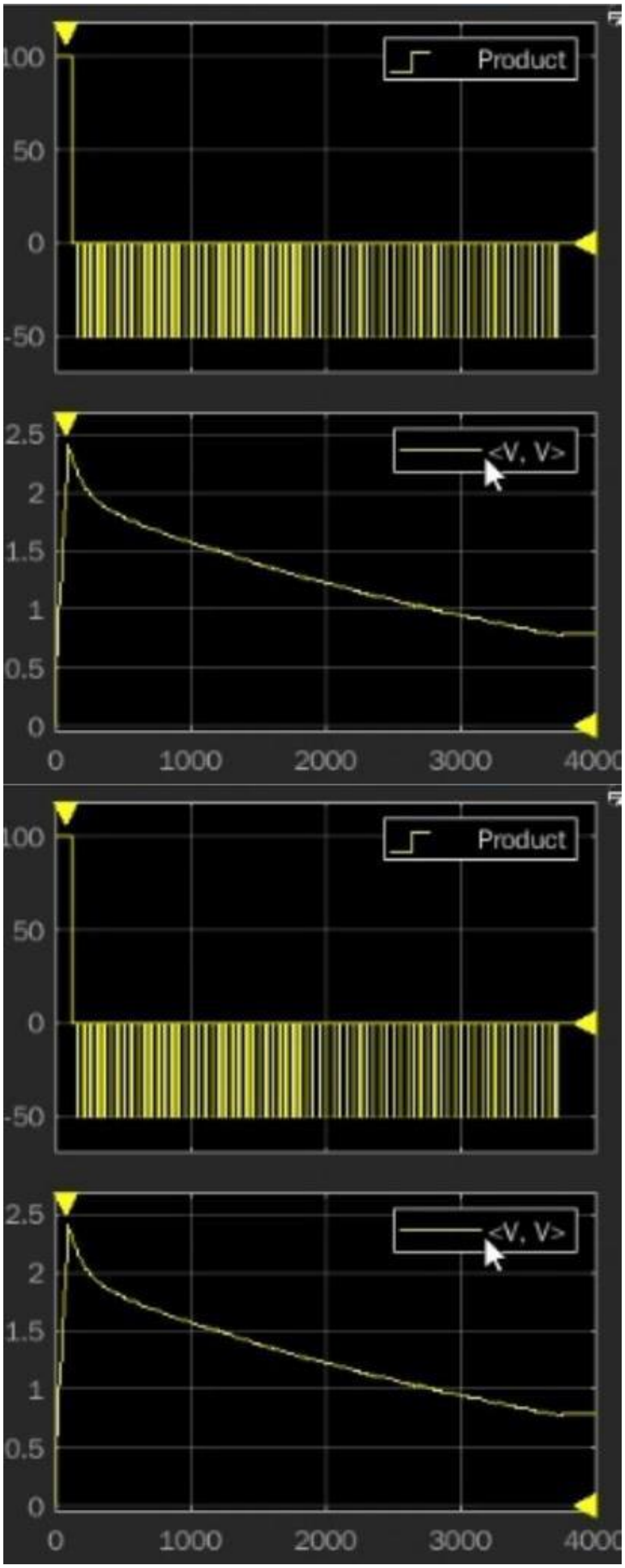

Figure 8. Super capacitor Scope Block

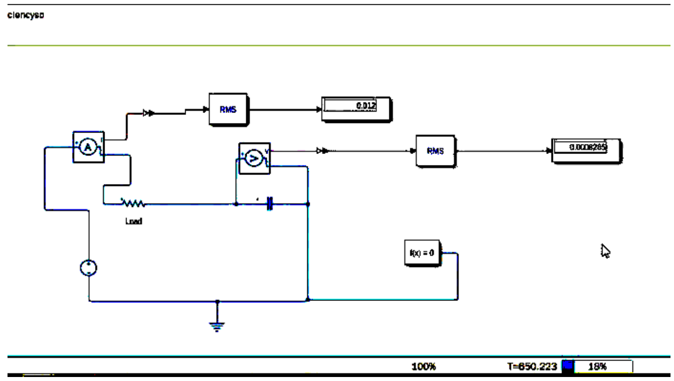

Figure 9. Testing Efficiency of the Super Capacitor Bank

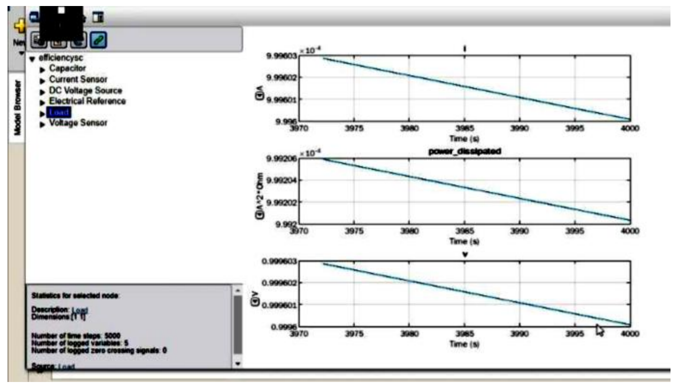

Figure 10. Power Dissipation Results of the Testing Efficiency of the Super Capacitor Bank

4. CONCLUSIONS

Based on the results presented in the previous section, this research yields the following conclusions:

1. The researcher was able to simulate a Solar PV system using a Supercapacitor as a battery bank and supplying a load of 2kW Inverter Air Conditioner in Simulink. The system is expected to be a stand-alone system wherein only the DC Circuit is involved. The system will not be using AC Voltage and the simulation results suggest that the design is efficient.
2. Simulation results show that during the starting phase of the inverter AC, the discharge current is high and will gradually be lower and at almost the same value as time passes by.

5. RECOMMENDATION

This research has the following recommendations:

1. It is highly recommended by the researcher that the whole study and design will be evaluated by the technical person who is a subject matter expert in Solar Energy systems. Enhancement of the design will be considered.
2. It is also recommended by the researcher to assemble and fabricate the proposed prototype to test the functionality of the design study.
3. The circuit's design will be reevaluated to ensure the safety and accuracy of the whole system.

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6. REFERENCES

[1]. Yellow alerts: A sign of worse things to come? (n.d.). Philstar.com. Retrieved December 7, 2023, from https://www.philstar.com/headlines/2016/09/13/1623383/yellow-alerts-sign-worse-things-come

[2]. Keller, H. (n.d.). 30 Years of Passive Infrared Motion Detectors -a Technology Review. Retrieved February 15, 2023, from https://www.silverlight.ch/pdf/2000-05_irs2paper_Hans_j_Keller.pdf

[3]. U.S. Department of Energy. (n.d.). The history of solar. https://www1.eere.energy.gov/solar/pdfs/solar_timeline.pdf

[4]. A Luque, & Hegedus, S. (2011). Handbook of photovoltaic science and engineering. Wiley.

[5] Supercapacitor Information – Battery University. (2019). Batteryuniversity.com. https://batteryuniversity.com/learn/article/whats_the_role_of_the_super capacitor

[6] Lead-based Batteries Information – Battery University. (2018breaker).Batteryuniversity.com. https://batteryuniversity.com/learn/article/lead_based_batteries

[7] Battery versus Supercapacitor. (2017, September 8).

[8] Photovoltaic Solar Cells. (n.d.). Retrieved from alternative energy tutorials: https://www.alternative-energy- tutorials.com

[9] art . design . research . projects by scott mitchell. (n.d.). Www.openobject.org. Retrieved December 7, 2023, from http://www.openobject.org/physicalprogramming/images/c/cd/sensor

[10] cibex - IT EDV Tirol - Netzwerk, Security, Software, Web Tirol, Wörgl, Telfs. (n.d.). Retrieved December 7, 2023, from http://www.bluesky-energy.eu/en/2018/08/02/cost-comparison-of-battery-storage/

[11] Balicat et al. (2017). Light Intensity Controlled Solar Street Lighting System.

[12] PIR Motion Sensor. (n.d.). https://cdn- learn.adafruit.com/downloads/pdf/pir-passive-infrared- proximity-motion-sensor.pdf

[13] KEYES 5V Relay Module. (n.d.). https://roboticafacil.es/datasheets/ky-019.pdf

[14] Maxwell Technologies, I. (n.d.). Battery University. Retrieved from https://batteryuniversity.com/learn/article/whats_the_role_of_the_super capacitor

[15] Mehul Oswal et al. (2010/5/7). A Comparative Study of Lithium-Ion Batteries.

[16] (PDF) Comparison of lead-acid and lithium ion batteries for stationary storage in off-grid energy systems. (n.d.). Www.researchgate.net. https://doi.org/10.1049/cp.2016.1287

[17] Miniature circuit breaker Application guide. (n.d.). Retrieved December 6, 2023, from https://pim.galco.com/Manufacturer/ABB%20Control/TechDocument/Application%20Information/abb_mcb_app.pdf

[8] Singh, O., & Sisodia, T. S. (2017, August 1). Solar LED street light system with automatic scheme. IEEE Xplore. https://doi.org/10.1109/ICECDS.2017.8390094

[19] Tecate Group – Ultra capacitors, Capacitors, and Custom Assemblies. (n.d.). Www.tecategroup.com. Retrieved December 7, 2023, from https://www.tecategroup.com/

[20] Ulit et al. (2018). Design, Fabrication, and Testing of Lithium Ion Battery Solar Street Light.

[21] Battery University. (2010, September 26). BU-201: How does the Lead Acid Battery Work? Battery University. https://batteryuniversity.com/article/bu-201-how-does-the-lead-acid-battery-work