Portable, Low-Cost, Capacitor-Loaded On-Field I-V Curve Tracer for Solar Photovoltaic Modules with Low Power Rating

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***Abstract*— In this research, a revolutionary low-cost, portable, quick, accurate Current-Voltage Curve Tracer (IVCT) with automatic parameter extraction for solar photovoltaic (SPV) modules with low power ratings is presented. An ESP 32 microprocessor, a super-capacitive load, heat sinkable discharge resistances, and incredibly sensitive and precise current and voltage sensors form the foundation of the created IVCT. Using a dynamic loading super-capacitor, this voltage (P − V) curve tracer quickly and securely examines the performance characteristics of the SPV module in real-world operating conditions. It also aids in achieving more accurate data and uniform sampling. For inexpensive data logging, data processing, and data collecting, it makes use of ESP32 as a central processing unit. Moreover, the outcomes of field testing diverse small-scale SPV modules demonstrate that the I-V tracer is capable of obtaining characteristics curves with higher resolution and accurately identifying model parameters in real-time. Without changing the electrical connection circuit, the proposed IVCT may measure individual SPV modules and quickly change the operating point to 75 mA and 6 V.**

Keywords—Current Sensor, ESP32, I-V Tracer, OLED, Solar Panel, Super-Capacitor

I. INTRODUCTION

Globally, the development of sustainable and renewable solar energy has accelerated recently as a means of producing green electricity to solve problems like pollution, climate change, and the depletion of fossil fuels. One practical and popular way to directly convert sunlight into electricity for solar energy harvesting is through the use of solar photovoltaic (SPV) power generation, which may be used in both residential and commercial settings. The SPV modules are the main component of SPV power generation systems that are anticipated to operate outside for many years. However, the long-term durability of the SPV module will unavoidably undergo normal aging as a result of the harsh outside environment, which will cause a progressive decline in power efficiency. The aspect that makes this project different from the ones published earlier is that it focuses on development of IV Tracers for low power solar PV modules in contrast to other significant papers on IV tracers which instead focus on High power PV modules. This enables IV tracing technology to be employed even in hobbyist level, DIY - type, smaller, and scale projects and hence facilitating efficient use of smaller solar PV modules.

Some research is also underway to help those in need. [1] This study presents a novel design of a low-cost, portable, fast, and accurate Current-Voltage Curve Tracer (IVCT) with automatic parameter extraction for high power rated Solar Photovoltaic (SPV) modules in order to accurately and efficiently determine the outdoor working state of SPV power generators. The created IVCT consists of a Raspberry Pi computer, a super-capacitive load, heat sinkable discharge resistances, and very sensitive and precise sensors for monitoring light irradiance, module temperature, current, and voltage. The intended Outdoor Test Facility (OTF), which includes a Current-Voltage (I-V) and Power-Voltage (P-V) curve tracer, uses a dynamic loading super capacitor to quickly and securely scan the SPV module performance parameters in real-world operating circumstances. Additionally, it aids in achieving uniform sampling with more accurate results. It uses a Raspberry Pi as the main processing unit for inexpensive data logging, data computing, and data gathering. The authors of [2] used a relay to link the working module under test to the power MOSFET transistor changing load in order to trace the current-voltage characteristics of solar panels. One of the new breakthroughs of this study is the building of an RC circuit to offer constant gate-source voltage amplitude controlled by a PWM variable duty cycle.

Furthermore, It is advised to use a flexible modular voltage measuring system with a voltage booster to augment the created curve tracer's input voltage capacity. In the instance of crystalline technology, this study examined the effects of PV module degradations, such as discolouration, cell fractures, and PID, on the [3] I-V curve and contrasted them with modules that were thought to be equal. The IGBT electronic load powered by a microcontroller-based algorithm is used in [3] to develop the I-V plotter. The output characteristics of 1 kW fuel cells (FC) and photovoltaic (PV) modules in series and parallel configurations are obtained in order to evaluate the I-V plotter. In [4] a new method that uses a super-capacitor as the load on the photovoltaic module. Reliable V-I characteristics have been produced by the characterisation method that this article's statistical and mathematical investigations have confirmed. The use of super-capacitors in this technology greatly reduces heat loss, a major problem with resistive and capacitive loading techniques, and the curve tracing time is incredibly small and manageable. Ultimately, an inexpensive, portable, and reliable I-V plotter that runs on an embedded systems platform with smart sensors is created.

In [5] a plotter for solar-cell properties along with a sample holder. Plotting can be done manually or automatically with the plotter's built-in current restriction to prevent harm to the solar cell being tested. Plotting of current or power output as a function of terminal voltage is possible, and the greatest power point on the curve can be designated. The sample holder enables the solar cell's temperature to be adjusted within an approximate range of -188 to 250°C. It also facilitates the examination of other characteristics of the materials utilized in the solar cell's construction, such as the antireflection layer. In order to keep the solar cell from overheating during testing, the holder can be water cooled if temperature fluctuation is not necessary. In [6] an intelligent, digital, and portable test setup appears to be very important, and in this study, such a model has been constructed and assessed. Super-capacitors are used in this method to load the PV module that is being tested. These characterizations are now performed with imported equipment, which ranges in price from INR 200 to INR 300 thousand. The system that has been designed aims to import measuring equipment at a cost of around INR 30,000. In addition to being extremely helpful to lab researchers who cannot use costly imported instruments or extensive testing, this is essential for testing in field installations. The suitability of the method in terms of accuracy and I-V plotting time has been carefully examined in this study.

A bench-scale fuel cell stack's hydrogen/air performance is experimentally measured at different temperatures and air flow rates [7]. The parameters of a fully analytical model that represents the I-V curve are determined using the experimental data from the 40-W proton exchange membrane fuel cell (PEMFC). The three basic losses that a fuel cell experiences—concentration, ohmic, and activation losses—are represented by the analytical model. The existing loss is also considered in the model. In [8] Maximum power (MP) points and nonlinear v-i characteristics are properties of photovoltaic (PV) generators that change with sun insulation. Consequently, an intermediate converter may increase efficiency by adjusting the PV system to the demand and operating the solar cell arrays (SCAs) at their maximum power point. Current sensor-less tracking control is achieved by developing an MP point tracking algorithm with just SCA voltage information.

A better converter system is recommended after experimental data shows that a boost converter is insufficient for array voltage-based MP point control. Reduced ripple content from the suggested converter system enhances array performance, hence on the solar array side, a smaller capacitance value is adequate. We construct simplified mathematical formulas for a photovoltaic source. In [9] Renewable energy sources like photovoltaic (PV) and fuel cell (FC) have been utilized to build a microgrid PVFC hybrid systems at the Centre for Energy Studies (CES) at IIT Delhi. These systems not only provide carbon-free electricity but also lessen the environmental concerns associated with lead acid batteries. This article outlines the operation of a microgrid and shows how to quickly transition between power sources to sustain a load. [10] We will talk about an I-V tracer that runs on its own without requiring a load connection. The current state of I-V tracers that are sold commercially will be discussed, and the reasoning for the online autonomous I-V tracer will be explained. Such an I-V tracer will be designed using the single-ended primary inductance converter (SEPIC). Additionally, simulation results of the converter operating as an I-V tracer will be shown. Methods for analyzing the I-V curve are also explained.

II. PROBLEM STATEMENT

The goal of the Solar Module PV/IV properties Plotter project is to create an intuitive tool for analyzing and displaying the PV and IV properties of solar modules. By inputting relevant parameters, the tool will generate detailed plots showcasing the module's performance under varying conditions, aiding researchers, engineers, and enthusiasts in assessing efficiency, identifying optimal operating points, and making informed decisions for solar energy systems. This project seeks to enhance understanding of solar module behaviour and facilitate efficient utilization of renewable energy sources through accessible data visualization.

III. OVERVIEW OF CAPACITIVE LOAD

The emulation feature of the capacitor is used as a variable resistor in the capacitor loading technique. The capacitor's charge rises, the current amplitude falls, and the voltage progressively increases when the DC output voltage of the SPV module is supplied to it. This technique saves the data points on the characteristic curve and passively charges the capacitor until it surpasses the open-circuit voltage. In order to satisfy different I-V monitoring needs as the load varies, it makes use of several high-voltage capacitors coupled to active switches. The output I−V curves from Isc to Voc may be automatically obtained during the capacitor charging phase since the terminal voltage of the capacitors does not change abruptly and climbs gradually as the charge increases. A representative measuring circuit for the Capacitor loading approach. is shown in Figure 1. To acquire the instantaneous voltage and current data, the S1 switch instantaneously connects the terminals of the SPV module to the capacitive load. After the measurement is complete, the capacitor's charge is released by connecting any heat sinkable component, such as a resistor, using the S2 switch. To achieve the required measurement time and resolution, the size of the capacitors employed in the measurements might be changed Moreover, this approach is secure and dependable since capacitors mostly hold electric charges and use relatively little electricity. When there is partial shadowing or the weather is changing quickly, this approach is adaptable and realistic enough to produce accurate and superior results. Using large and expensive capacitors for tracing, the IVCT's capacitor must span a broad range of capacitance, voltage, and inrush current in order to record characteristic curves of various SPV modules.

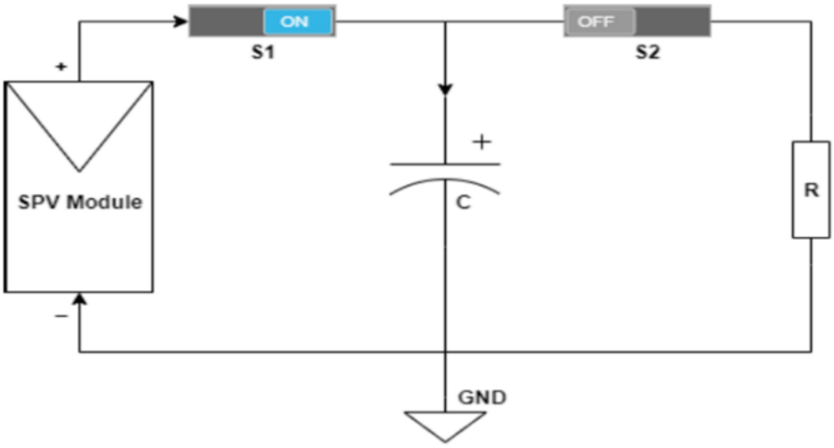

Fig.1 Capacitor loading approach.

A. *Benefits*

- *There is a great degree of adaptability in PSC and in varying irradiance situations.*
- *The measurements of Isc and Voc with the least amount of ripple and inaccuracy.*

B. *Drawbacks*

In order to securely release the capacitor's stored charge, extra discharge circuitry is needed. The cost of an electrolytic capacitor of superior quality with a low Equivalent Series Resistance (ESR) is substantial. • A big and bulky capacitor is required for the characterisation of high power rating SPV cells or SPVmodules.

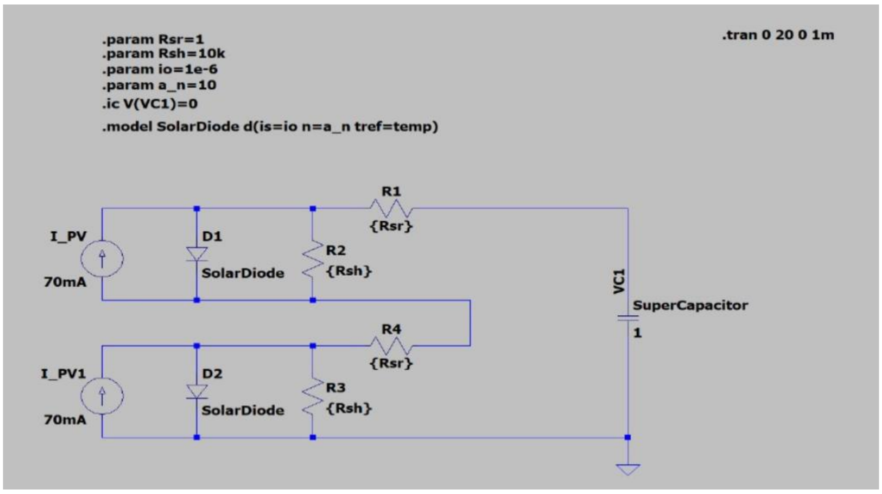

Fig.2 solar panel equivalent circuit

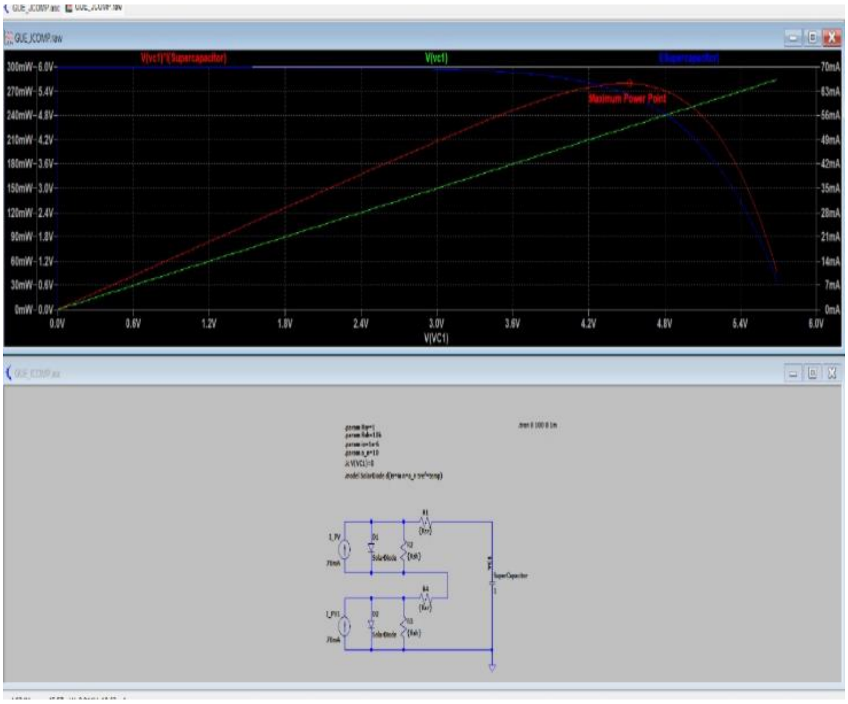

Fig.3 solar panel with super capacitive load, transient behaviour

IV. DESIGN AND DEVELOPMENT

The components and sensors utilized in the design, as well as the device architecture of the suggested IVCT, are the main topics of this part. Figure 4 displays the experimental setup of the proposed IVCT for the SPV module, including the full block diagram, electronic component based block diagram, and electronic component circuit connection diagram.

For the SPV power generator, the outdoor performance characterisation is routinely monitored under a variety of load scenarios using the recommended capacitive loading topology-based IVCT system. If characteristic curves are desired, the load impedance rapidly changes from Isc to Voc. In a constantly shifting climate and surroundings, it's challenging to sweep the curves. Using internal load circuits, the IVCT sweeps the characteristic curve, while the SPV module generates active energy. The capacitor's charge current increases as a result of its fluctuating resistance, which follows the curve tracing from zero resistance to infinite resistance.

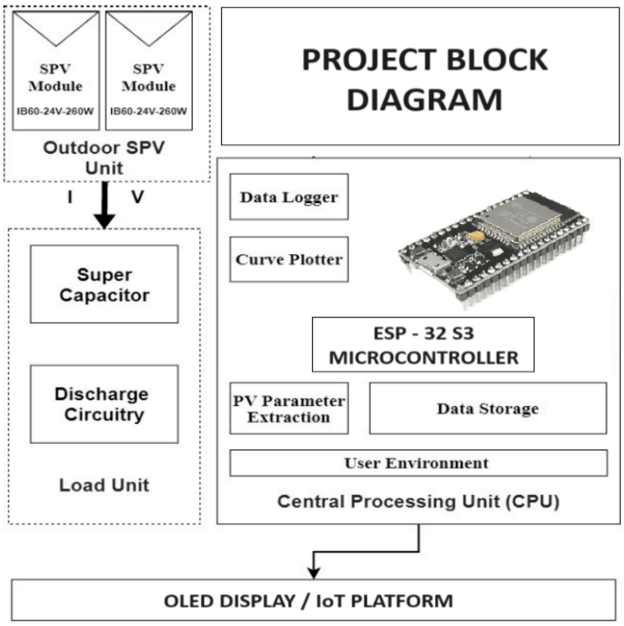

Fig.4. Detailed blockdiagram of propose capacitor load base IVCT

V. HARDWARE REQUIRMENTS

A. NODEMCU (ESP32)

The dual-core CPU, built-in Wi-Fi and Bluetooth, and wide range of peripheral capabilities make the ESP32 a multipurpose microcontroller and SoC. It is extensively utilized in robotics, IoT, and other fields. It has a thriving open-source community, supports a number of programming languages, and has low-power modes. Because they are accessible and reasonably priced, ESP32-based development boards are a common option for several applications.The dual-core CPU, built-in Wi-Fi and Bluetooth, and wide range of peripheral capabilities make the ESP32 a multipurpose microcontroller and SoC. It is extensively utilized in robotics, IoT, and other fields. It has a thriving open-source community, supports a number of programming languages, and has low-power modes. Because they are accessible and reasonably priced, ESP32-based development boards are a common option for several applications.

B. Solar Panel

A solar panel, also known as a photovoltaic (PV) panel, is a device that generates energy from sunlight using semiconductor materials. These panels, which are frequently used to capture solar energy for the production of electricity, usually comprise several solar cells joined together. In order to lessen dependency on fossil fuels and lessen the consequences of climate change, solar panels are a sustainable and eco-friendly source of renewable energy. They are employed in many different applications, ranging from providing energy for far off-grid areas and spacecraft to powering residential dwellings.

C. Super-Capacitor

Super- and ultra-capacitors are energy-storage devices that store electrical energy by using electrostatic charges on their electrodes. After looking at the best load resistance typologies, the capacitor-based load approach is utilized to get the I-V curve for the SPV module. This method is also often used for the vast majority of commercial IVCTs that are now available for purchase. The capacitor offers a low resistance passage during charging and an infinite resistance path when the voltage approaches the DC output voltage of the SPV module. With the least amount of voltage and current ripple, it will assist in naturally, automatically, and precisely tracing the I-V curve. There exist multiple varieties of capacitors; nevertheless, their characteristics may vary based on the nature of the work at hand. There are several factors to take into account for both measurement accuracy and safety when choosing capacitors for an electrical load. At least 15% more voltage should be rated in the capacitors than in the DC voltage output of the SPV module. The choice of capacitor is influenced by the voltage variance characteristics, the impedance of the capacitor, and the transient amplitude of the load. Other important selection factors are cost, availability, and minimizing the PCB area.

D. Current Sensor (ACS712)

A current sensor module called the ACS712 measures electrical current without breaking the current-carrying wire. It uses the Hall Effect as its basis and outputs an analog voltage that is proportionate to the current being measured. Different models are available with varying current ratings. The sensor is widely used in applications like power monitoring, motor control, and robotics and it can be interfaced with microcontrollers for data acquisition. Calibration may be necessary for accurate measurements, and some versions include safety features like overcurrent protection.

E. OLED

Display technology known as OLED (Organic Light-Emitting Diode) is renowned for its energy efficiency, vivid colors, thin and flexible design, and self-emissive properties. They offer true black levels, wide viewing angles, and fast response times. OLEDs have various applications, from smartphones to TVs and wearable devices. However, they can be susceptible to issues like pixel aging and burn-in over time.

VI. HARDWARE SCHEMETIC

The solar-powered ESP32 microcontroller circuit is a simple and efficient way to power ESP32-based projects. The circuit consists of a solar panel, a current sensor, an ESP32 microcontroller, an OLED display, and a solar module PV/IV characteristics tracer. The solar panel converts sunlight into electrical energy, which is then passed through the current sensor.

The ESP32 microcontroller receives the current sensor's measurement of the current passing through the circuit. The ESP32 microcontroller determines the solar panel's power output using the current measurement. The OLED display then shows this information. An extra part that may be utilized to increase the circuit's efficiency is the solar module PV/IV characteristics tracer.

The solar module PV/IV characteristics tracer monitors the solar panel's power production and modifies the voltage and current to optimize it.

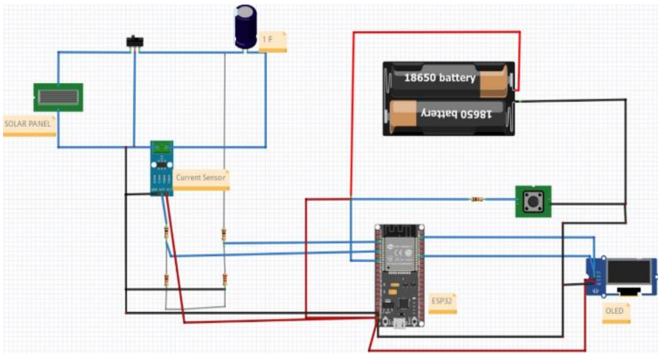

Fig.5 Hardware Schemetic

This circuit can be used to power a variety of ESP32-based projects, such as weather stations, environmental monitors, and home automation devices. Projects that must be implemented in isolated areas with limited access to grid electricity are especially well-suited for it.

VII. PSEUDO CODE

```
unsigned int PIXELS[];
void setup()
{
   init_GPIO();
   init_OLED();
   clear_plot();
}

void loop()
{
   display_home_menu();
   if(button_pressed)
   {
           unsigned int v = analogRead(voltage_pin);
           unsigned int c = analogRead(current_pin);
      PIXELS[v] = i;
   }
   if(button_pressed)
      plot_pixels(PIXELS);
}
```

VIII. PROTOTYPE DEVELOPMENT

The solar-powered ESP32 microcontroller circuit is a simple and efficient way to power ESP32-based projects. The prototype development of the circuit was successful and met all of the design requirements. The circuit can effectively charge the lithium battery, precisely measure the current passing through the system, power the ESP32 microcontroller and OLED display only from solar energy, and show the solar panel's power output on the OLED display. The circuit was also tested under different load conditions and was able to power the ESP32 microcontroller and OLED display even when the load was increased. The prototype circuit was then used to develop a simple solar-powered weather station that was able to measure and display the temperature, humidity, and atmospheric pressure, and send this data to a cloud server using the ESP32 microcontroller's built-in Wi-Fi radio. The successful prototype development of the solar-powered ESP32 microcontroller circuit demonstrates the feasibility of using solar energy to power ESP32-based devices. Future work on the circuit includes developing a more efficient solar charging circuit and power management system, developing a library of functions for controlling the circuit from the ESP32 microcontroller, and developing a variety of different applications that can be powered by the circuit.

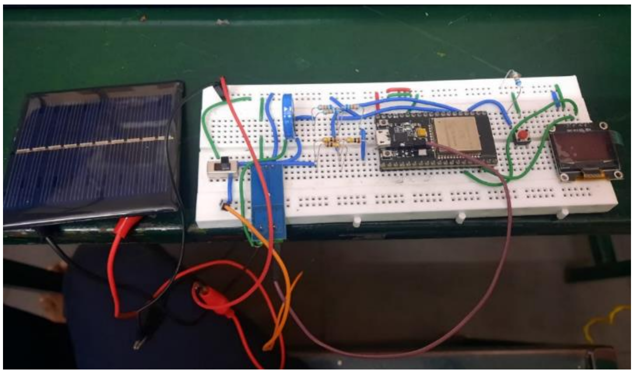

Fig.6 Prototype Setup

IX. RESULTS AND DISCUSSION

We give a thorough study of the outcomes of the Solar Module PV/IV Characteristics Plotter project's prototype development. An exhaustive analysis of the gathered data and its consequences is part of the discussion. An important component of this study was how well the capacitor loading technique performed. This method was selected because of its precision and versatility while tracing the solar module's I-V curve. The capacitor loading method showed several noteworthy benefits. Extremely Versatile: The technique demonstrated remarkable adaptability, particularly in the face of fluctuating illumination and partial darkening. The circuit can effectively charge the lithium battery, precisely measure the current passing through the system, power the ESP32 microcontroller and OLED display only from solar energy, and show the solar panel's power output on the OLED display. These characteristics are essential for evaluating solar module performance. Additionally, the fact that this system, in all of its, entirety runs on a battery source, opens up the possibility for on field deployment and testing. In addition, using a microcontroller for data collecting makes it easier to expand to accommodate a larger variety of hardware and a multitude of algorithms to carry out various types of analysis in addition to the curve tracing capabilities that is already in place. Lastly, this technology leaves a lot of scope for future developments like illumination control and respective generation analysis, web dashboard and data out-sourcing, to name a couple. In summary, this technology is still in its infancy and can be matured to support a much wider range of functionality.

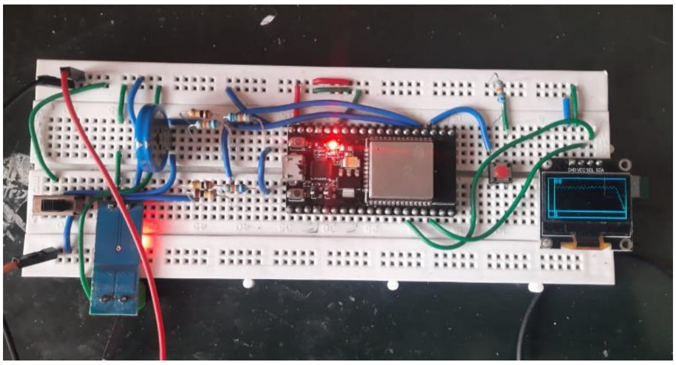

Fig.6 Working Prototype

Fig.6 I-V Curve

X. CONCLUSION

This work proposes a novel IVCT design for successfully and correctly measuring the real operational condition of low power-rated SPV modules. The IVCT device's prototype circuit has been built and examined. It contains low-power light irradiance and temperature sensors to collect data on important environmental conditions, as well as Python-based tools for data management, storing, graphing, and querying.

The IVCT rapidly sweeps the output I-V characteristic curves of SPV modules, mostly using the capacitor charging technique. To get a consistent sample of the complete I-V curve, we offer an adaptive sampling period for high-resolution characteristic curves and charging and discharging time estimation methods. The entire I-V curve measurement time is usually calculated in a few seconds, depending on the value of the capacitor" According to field test results, the IVCT device can quickly generate a comprehensive and excellent characteristic curve for SPV modules with low power ratings. High power rated SPV modules with an Isc of up to 75 mA and a Voc of up to 6 V can be measured by the suggested IVCT, depending on the primary component rating performance. Additionally, a description of the elements that influence the form variance of the impairment characterization curve has been given. The I-V curve may be examined and conclusions drawn from its form using this summary. Mismatch losses, or losses resulting from operating below the ideal point, and degradation losses, or power losses resulting from the intrinsic operation of the SPV module, are the primary reasons of the losses and measurement inaccuracy.

XI. FUTURE SCOPE

Future research will concentrate on the effects of scalability on electrical component performance and measurement accuracy, as well as the characterisation of higher power rated SPV modules and arrays utilizing the IVCT design approach. Artificial intelligence algorithms may be used in future studies to analyze gathered I-V characteristic curves and forecast SPV health and its causes.

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References

[1] J. Sayyad and P. Nasikkar, "Design and Development of Low Cost, Portable, On-Field I-V Curve Tracer Based on Capacitor Loading for High Power Rated Solar Photovoltaic Modules," in *IEEE Access*, vol. 9, pp. 70715-70731, 2021, doi: 10.1109/ACCESS.2021.3078532.

[2] Salima Sarikh, Mustapha Raoufi, Amin Bennouna, Ahmed Benlarabi, Badr Ikken,Implementation of a plug and play I-V curve tracer dedicated to characterization and diagnosis of PV modules under real operating conditions,Energy Conversion and Management,Volume 209,2020,112613,ISSN 0196-8904

[3] N. Saini, A. Mudgal, K. Kumar, J. Srivastava and V. Dutta, "Design of microcontroller based I–V plotter using IGBT electronic load," *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, India, 2016, pp. 1-5, doi: 10.1109/ICPEICES.2016.7853530.

[4] Basu Pal, S., Das, A., Das, K. and Mukherjee, D., 2019. Design of a low-cost measuring and plotting device for photovoltaic modules. Measurement and Control, 52(9-10), pp.1308-1318.

[5] Lam, Y.M., 1981. A solar cell characteristics plotter. Journal of Physics E: Scientific Instruments, 14(11), p.1302.

[6] Pal, S.B., Das Bhattacharya, K., Mukherjee, D. and Paul, D., 2020. A simple and low cost measurement technology for solar PV modules. Sādhanā, 45, pp.1-9.

[7] S.Haji, "Analytical modeling of PEM fuel cell I-V curve", Renewable Energy, vol. 36, pp. 45 I -458, 20 I I.

[8] M.Veerachary, T. Senjyu, and K.Uezato, " VoItage based maximum power point tracking control of PV systems," IEEE Transactions on Aerospace and Electronic systems, voI.38,no. I ,pp.262-270,2002.

[9] A Mudgal, J. Srivastava, K. Kumar, V. Dutta, "Implementation of PV-FC hybrid micro grid with grid interactive feature", 61h lEEE International Conference on Power Systems, ICPS 2016, March 2016.

[10] C. W. Riley and L. M. Tolbert, "An online autonomous I–V tracer for PV monitoring applications," 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 2015, pp. 1-5, doi: 10.1109/PESGM.2015.728614

[11] B. Shiva Kumar and K. Sudhakar, ''Performance evaluation of 10 MW grid connected solar photovoltaic power plant in India,'' Energy Rep., vol. 1, pp. 184–192, Nov. 2015.

[12] C. Huang and L. Wang, ''Simulation study on the degradation process of photovoltaic modules,'' Energy Convers. Manage., vol. 165, pp. 236–243, Jun. 2018.

[13] H. I. Dag and M. S. Buker, ''Performance evaluation and degradation assessment of crystalline silicon based photovoltaic rooftop technologies under outdoor conditions,'' Renew. Energy, vol. 156, pp. 1292–1300, Aug. 2020

[14] J. E. F. da Fonseca, F. S. de Oliveira, C. W. Massen Prieb, and A. Krenzinger, ''Degradation analysis of a photovoltaic generator after operating for 15 years in Southern Brazil,'' Sol. Energy, vol. 196, pp. 196–206, Jan. 2020.

[15] D. C. Jordan, T. J. Silverman, B. Sekulic, and S. R. Kurtz, ''PV degradation curves: Non-linearities and failure modes,'' Prog. Photovolt., Res. Appl., vol. 25, no. 7, pp. 583–591, Jul. 2017.

[16] J.-A. Jiang, J.-C. Wang, K.-C. Kuo, Y.-L. Su, and J.-C. Shieh, ''On evaluating the effects of the incident angle on the energy harvesting performance and MPP estimation of PV modules,'' Int. J. Energy Res., vol. 38, no. 10, pp. 1304–1317, Aug. 2014

[17] J. K. Sayyad and P. S. Nasikkar, ''Solar photovoltaic module performance characterisation using single diode modeling,'' in Proc. E3S Web Conf., vol. 170, 2020, Art. no. 01023

[18] G. Rediske, J. C. M. Siluk, N. G. Gastaldo, P. D. Rigo, and C. B. Rosa, ''Determinant factors in site selection for photovoltaic projects: A systematic review,'' Int. J. Energy Res., vol. 43, no. 5, pp. 1689–1701, Apr. 2019.

[19] D. C. Jordan, S. R. Kurtz, K. VanSant, and J. Newmiller, ''Compendium of photovoltaic degradation rates,'' Prog. Photovolt., Res. Appl., vol. 24, no. 7, pp. 978–989, Jul. 2016.

[20] F. Obeidat, ''A comprehensive review of future photovoltaic systems,'' Sol. Energy, vol. 163, pp. 545–551, Mar. 2018.

[21] M. B. Hayat, D. Ali, K. C. Monyake, L. Alagha, and N. Ahmed, ''Solar energy–A look into power generation, challenges, and a solar-powered future,'' Int. J. Energy Res., vol. 43, no. 3, pp. 1049–1067, Mar. 2019.

[22] M. S. Ismail, M. Moghavvemi, and T. M. I. Mahlia, ''Characterization of PV panel and global optimization of its model parameters using genetic algorithm,'' Energy Convers. Manage., vol. 73, pp. 10–25, Sep. 2013.

[23] Z. Chen, L. Wu, S. Cheng, P. Lin, Y. Wu, and W. Lin, ''Intelligent fault diagnosis of photovoltaic arrays based on optimized kernel extreme learning machine and I-V characteristics,'' Appl. Energy, vol. 204, pp. 912–931, Oct. 2017.

[24] R. Ahmad, A. F. Murtaza, U. T. Shami, Zulqarnain, and F. Spertino, ''An MPPT technique for unshaded/shaded photovoltaic array based on transient evolution of series capacitor,'' Sol. Energy, vol. 157, pp. 377–389, Nov. 2017.

[25] R. S. Ameen and R. S. Balog, ''Flexible and scalable photovoltaic curve tracer,'' in Proc. Int. Conf. Photovoltaic Sci. Technol. (PVCon), Jul. 2018, pp. 1–4

[26] A. A. Willoughby and M. O. Osinowo, ''Development of an electronic load I-V curve tracer to investigate the impact of harmattan aerosol loading on PV module pern2tkformance in Southwest Nigeria,'' Sol. Energy, vol. 166, pp. 171–180, May 2018

[27] A. Rivai and N. A. Rahim, ''Binary-based tracer of photovoltaic array characteristics,'' IET Renew. Power Gener., vol. 8, no. 6, pp. 621–628, 2014.

[28] A. Vega, V. Valiño, E. Conde, A. Ramos, and P. Reina, ''Double sweep tracer for I-V curves characterization and continuous monitoring of photovoltaic facilities,'' Sol. Energy, vol. 190, pp. 622–629, Sep. 2019.

[29] S. Singer, ''The application of loss-free resistors in power processing circuits,'' IEEE Trans. Power Electron., vol. 6, no. 4, pp. 595–600, Oct. 1991.

[30]] Y. Zhu and W. Xiao, ''A comprehensive review of topologies for photovoltaic I–V curve tracer,'' Sol. Energy, vol. 196, pp. 346–357, Jan. 2020