Design Of A Real-Time Solar Power Monitoring And Controlling System Using Internet Of Things

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Abstract. *In this research, the system is designed to monitor parameters of residential solar power sources such as voltage, current, power capacity, power factor and energy consumption. These parameters are measured by a highly accurate PZEM circuit and the specifications are suitable for residential solar power sources. Measurement results will be sent to the main control circuit (ARM controller) via the UART communication standard to analyze and filter the necessary data. The data of that parameter will then be displayed at the system installation site using the TFT screen. After an installation period, the control circuit will send measurement parameters to the dedicated WiFi module (ESP32), the WiFi module will continue to send parameters to the cloud server for storage and monitoring. The system also builds applications that run on many operating systems, can access data, and display data in real time using IoT technology. It should be noted that the system can still operate in the event of loss or absence of WiFi signal by using Bluetooth signal. In addition, the designed system also has the function of remotely controlling on/off the solar power supply to the loads when an incident occurs, ensuring safety for the electrical system.*

Keywords

power measurement, Internet of Things (IoT), solar power monitor and control, PZEM, ESP32, ARM microcontroller.

1. Introduction

Solar power is one of the types of renewable energy sources prioritized for investment, development and use in Vietnam in particular and globally in general. Solar power systems exist in three main forms: independent solar power (off-grid system), solar power connected to the national grid (on-grid system) and combined solar power (hybrid system) [1]. Among them, on-grid systems are by far the most popular and widely used by households and companies. These systems do not require battery storage and use an inverter connected to the public grid. Any excess solar power generated is fed into the public grid and is usually paid for in a tariff (FiT) from the electricity company [2]. In addition to the basic components of the solar power system, the function of measuring and monitoring electrical parameters at the output of the system such as voltage, current, power, power factor, and electricity consumption statistics is also included, is truly necessary, it is also an effective tool to ensure timely detection and handling of incidents. There have been many studies to create system to control and monitor the quality of solar power sources via the internet in real time operating on different platforms and operating systems. Specifically, some systems are designed using Arduino and ESP8266 [3–10]. However, these systems will not be able to operate in the absence or loss of wifi signal. Some other systems are only developed and simulated using Matlab/Simpower Simulation/Labview and Webbrowser [11–17]. Systems manufactured abroad are very diverse and are all integrated into inverters, so each manufacturer will have different functions and methods of use [18–21]. This makes it difficult to monitor and control the operating solar power source, because the cost of replacing the inverter is high, not to mention compatibility with the remaining devices in the solar power source. On the other hand, the software is always updated by the manufacturer, so it is not convenient for users because it costs money and time. For systems manufactured in Vietnam, the usage environment is relatively limited. These systems focus on solar power used in factories and power farms with large capacity. The commercial price of this system often fluctuates in a large range, depending on the number of installations as well as the sales policy for each subject. In addition, these products are not capable of serving educational activities because they are commercial and copyrighted [22–26]. This research focuses on designing a system capable of monitoring, tracking and storing parameters that affect solar power quality such as voltage, current, power capacity, power factor, and energy consumption. All these parameters are continuously updated and displayed in real time. The system uses IoT technology for remote monitoring, helping to monitor multiple solar power systems at the same time without being hindered by geographical location. In order to ensure the safety of the electrical system, the designed system also has the ability to remotely control solar power on/off to supply household loads when an incident occurs.

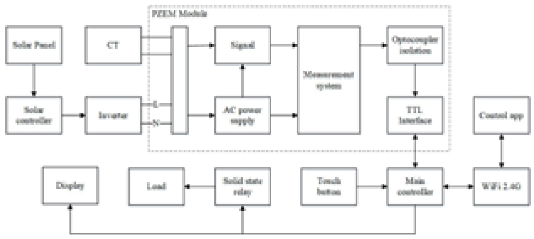

Fig. 1: Block diagram of the system.

2. Hardware Design

The block diagram of the system is illustrated in Fig. 1. The solar power parameter measurement block (PZEM module) is optically isolated from the remaining blocks in the system to ensure safety and stability. In addition, measured values are converted from the RS485 standard to the universal UART standard, making it easy to communicate with microcontrollers. The main processing block is assigned to an ARM microcontroller (STM32F103) with high-speed and stable processing capabilities, responsible for processing solar power parameter values received through the UART communication standard for analysis and display. The solar power parameter values will be sent to a specialized WiFi block (ESP32) for storage and monitoring according to IoT technology. System parameters need to be stored and monitored, so it is necessary to build

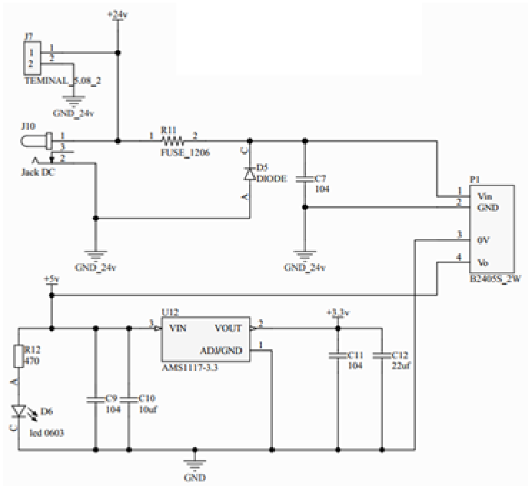

Fig. 2: Schematic diagram of the power supply block.

a server that meets the functions. The connection between the main processing block and the server requires a 2.4G WiFi communication block to ensure full implementation of the system's storage and monitoring functions. In addition, the system also needs a capacity block to control on/off the loads at the output of the solar power system, helping to promptly handle problems when problems occur. The on/off function can be performed directly at the device via touch buttons or through the application.

Fig. 3: PZEM and CT electrical parameter measurement module.

The circuit diagram of the power supply block for the entire system is shown in Fig. 2. After rectification from 220VAC to 24VDC, it will go through the DC-DC isolation module to the voltage level of 5V and 3.3V to supply to other parts in the system.

Fig. 3 shows an image of the electrical parameter measurement module (PZEM-004T) with technical specifications presented in Table 1. The circuit diagram of solar power parameter measurement block is described in Fig. 4. This is a measurement diagram using a specialized module that can fully measure the necessary parameters for monitoring as well as in accordance with household electricity consumption.

Tab. 1: The data sheet of PZEM-004T.

S/N	Function	Description
1	Voltage	Measuring range:80~260V Resolution: 0.1V Measurement accuracy: 0.5%
2	Current	Measuring range: 0~100A Starting measure current: 0.02A Resolution: 0.001A Measurement accuracy: 0.5%
3	Active power	Measuring range: 0~23kW Starting measure power: 0.4W Resolution: 0.1W Measurement accuracy: 0.5%
4	Power factor	Measuring range: 0.00~1.00 Resolution: 0.01 Measurement accuracy: 1%
5	Frequency	Measuring range: 45Hz~65Hz Resolution: 0.1Hz Measurement accuracy: 0.5%
6	Active energy	Measuring range: 0~9999.99kWh Resolution: 1Wh Measurement accuracy: 0.5%

Fig. 5 shows the circuit diagram of the main processing block. 32-bit microcontroller (STM32F103) with strong and fast processing capabilities with a processing speed of 72MHz, integrating RTC and common communication standards was applied to receive signals from the parameter measurement block. ESP32 not only has a 2.4GHz frequency suitable for common home and industrial WiFi standards, but also has a Bluetooth standard suitable for easy direct communication with smartphones. This feature is essential to serve the active function (providing SSID and PASS of WiFi at the installation location) for the system when first used. ESP32 is responsible for connecting to the WiFi network and communicating and receiving data with the SERVER via SOCKET and API.

The technical specifications of STM32F103 and ESP32 presented in Tables 2 and 3, respectively.

The circuit diagram of the capacity block is shown in Figure 6. It is responsible for controlling on/off high-capacity loads such as water pumps, ventilation fans, sun protection grids... through solid state relay (SSR).

The touch button block with the central element is IC TTP223 uses SMD components based on capacitance changes designed to replace the traditional direct

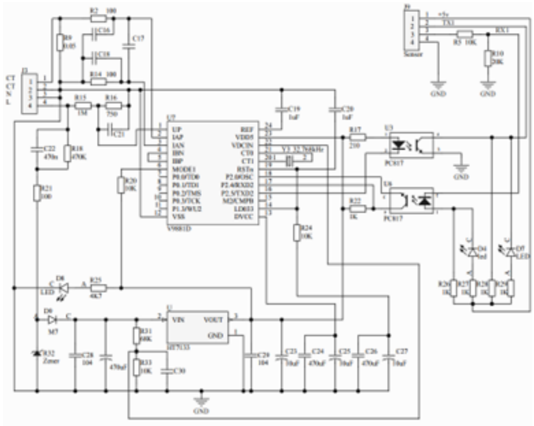

Fig. 4: Schematic diagram of solar power parameter measurement block.

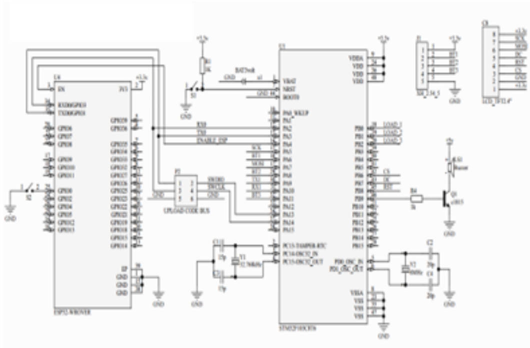

Fig. 5: Schematic diagram of the processing block, WiFi communication and TFT display.

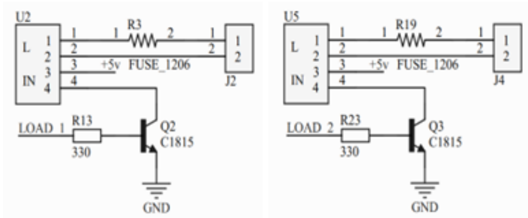

Fig. 6: Schematic diagram of the capacity block.

push button shown in Fig. 7. Their advantages are low power consumption and wide operating voltage range.

3. Firmware Setup

The algorithm flow chart for programming two important circuits in the system, the WiFi circuit and the main control circuit, is illustrated in Fig. 8 and Fig. 9, respectively. From these flow charts, programming the system is easily done using specialized programming languages. Fig. 8 shows the operation of the main control circuit, which uses the STM32F103 microcontroller to receive and process data from the solar power parameter measurement circuit. First, the mi-

Tab. 2: The data sheet of STM32F103.

S/N	Function	Description
1	Arm®32-bit Cortex®-M3 CPU core	72 MHz maximum frequency, 1.25 DMIPS/MHz (Dhrystone 2.1) performance at 0 wait state memory access Single-cycle multiplication and hardware division
2	Memories	64 or 128 Kbytes of Flash memory 20 Kbytes of SRAM
3	Communication interfaces	Up to two I2C interfaces Up to three USARTs (ISO 7816 interface, LIN, IrDA capability, modem control) Up to two SPIs (18 Mbit/s) CAN interface (2.0B Active) USB 2.0 full-speed interface
4	Clock, reset and supply management	2.0 to 3.6 V application supply and I/Os POR, PDR, and programmable voltage detector (PVD) 4 to 16 MHz crystal oscillator Internal 8 MHz factory-trimmed RC Internal 40 kHz RC PLL for CPU clock 32 kHz oscillator for RTC with calibration
5	Timer	Three 16-bit timers, each with up to 4 IC/OC/PWM or pulse counter and quadrature (incremental) encoder input 16-bit, motor control PWM timer with dead-time generation and emergency stop Two watchdog timers (independent and window) SysTick timer 24-bit down-counter
6	Up to 80 fast I/O ports	26/37/51/80 I/Os
7	Debug mode	Serial wire debug (SWD) and JTAG interfaces

Tab. 3: The data sheet of ESP32.

S/N	Function	Description
1	Wi-Fi certification	Wi-Fi Alliance
2	Bluetooth certification	BQB
3	Wi-Fi 2.4G	802.11 b/g/n (802.11n up to 150 Mbps)
4	Bluetooth	Bluetooth v4.2 BR/EDR and Bluetooth LE specification
5	Module interfaces	SD card, UART, SPI, SDIO, I2C, LED PWM, Motor PWM, I2S, IR, pulse counter, GPIO, capacitive touch sensor, ADC, DAC
6	Integrated crystal	40 MHz crystal
7	Integrated SPI flash	4 MB
8	Operating voltage/Power supply	3.0 V 3.6 V
9	Operating current	Average: 80 mA

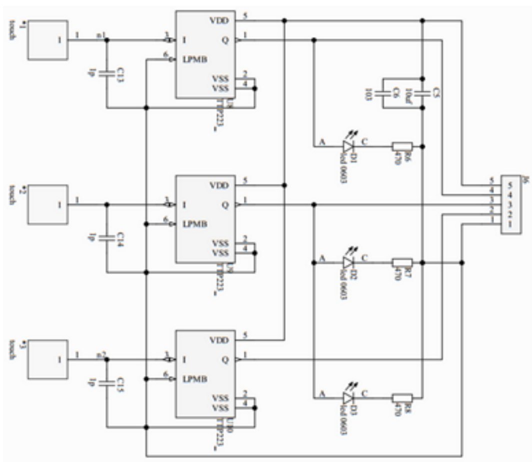

Fig. 7: Schematic diagram of touch button block.

crocontroller initializes functions, ready for displaying and transmitting data through the necessary communication standards. Then, the microcontroller will send a data request from the measurement circuit via the UART standard and wait until it receives the necessary data. The data will then be displayed at the device using the TFT screen. The microcontroller also checks the setting time to save data. If the setting time is enough, it will send data via WiFi circuit to transfer to the server. In addition to checking data reception from the parameter measurement circuit, the control circuit also checks data reception from the WiFi circuit when the user uses the application to control SSRs on/off. This can also be done through touch buttons on the device, these buttons can select the output to be controlled and change the SSR's on/off status.

Fig. 8: Flowchart for processing data from the measuring circuit of the main control circuit.

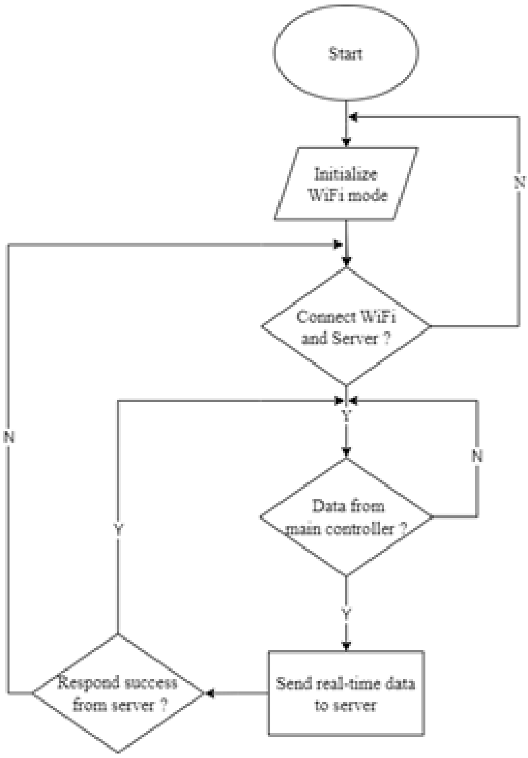

Fig. 9: Flowchart processes data and sends it to the server of the WiFi module.

The operation of the WiFi circuit using the ESP32 chip is based on the flow chart of Fig. 9. After applying power supply, the WiFi circuit will initialize the appropriate operating mode (station mode) and connection method to the Internet (combined socket and http). Then, the WiFi circuit will connect to the WiFi Access Points in the household, thereby connecting to the system's server. When ready, the WiFi circuit will check whether there is data coming from the main circuit or not. If so, it will receive and send data to the system server. This data will be saved and provided to applications to display in real time and wait for a successful response from the server. In addition, the WiFi

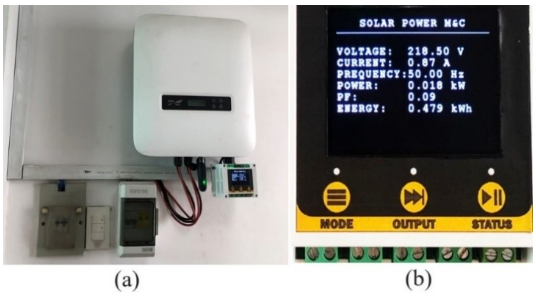

Fig. 10: (a) installed system model. (b) display and control side of the system model.

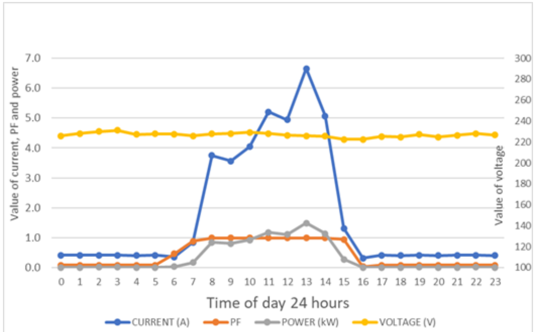

Fig. 11: Measured parameters of the solar power source during the day with the lowest generating capacity.

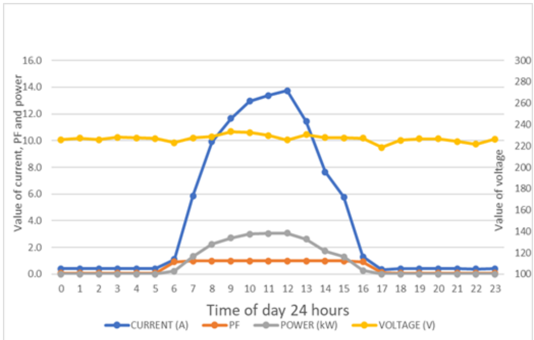

Fig. 12: Measured parameters of the solar power source during the day with the highest generating capacity.

circuit also has the function of receiving data from the server to send to the main control circuit to turn on/off the corresponding SSR controlled on the application.

4. Results and Discussions

After design and construction are completed, the system is installed and operated at a specific address in Ho Chi Minh city – Viet Nam with a rooftop solar power system connected to the national grid (on-grid) system with a nominal capacity of 4,680.00 Wp as shown in Fig. 10. The system measures solar power parameters and displays the measured values in real time on the TFT screen, those values are updated every 1 second. In addition, the device also has touch keys that

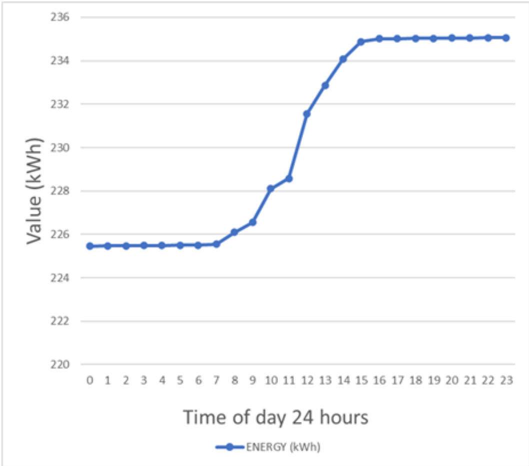

Fig. 13: Energy is generated from solar power during the day.

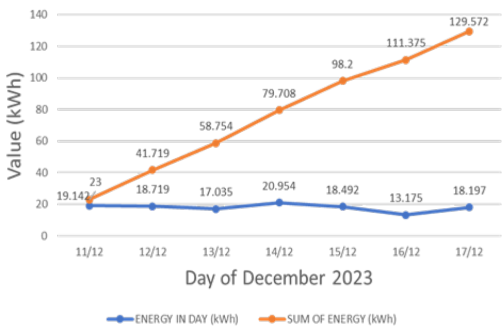

Fig. 14: Energy is generated from solar power for one week.

can control on/off loads using solar power. Measured parameters can be monitored at the TFT screen or via smartphone. The system will send measured parameters to the server every 5 minutes, and the time saved on the server is unlimited. Smartphone applications can easily review the day's parameters in the form of graphs or data storage files.

Fig. 11 and Fig. 12 show the results of displaying the parameters of the solar power source according to the day with the lowest and highest power generation capacity, respectively, during a period of 1 month of system test operation.

These charts show that solar power begins to provide energy at about 6:00 a.m. when the new daylight begins and ends at about 4:00 p.m. when the sun gradually fades. For the day with the lowest solar radiation intensity, the highest recorded output power was about 1.5kW at 13:00, while for the day with the highest solar radiation intensity, the highest recorded output power was recorded is about 3.3kW at 12:00. Current and power parameters also reach high values between 11:00 and 13:00.

The output voltage parameters of the solar power source recorded in two cases are relatively stable, with

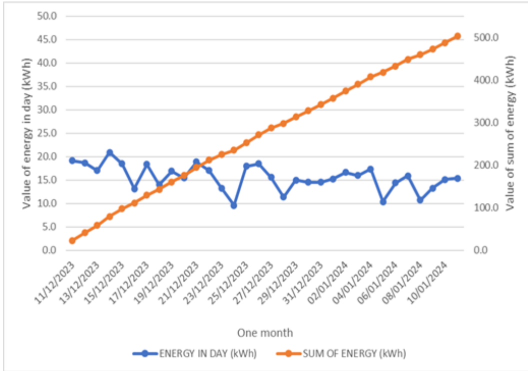

Fig. 15: Energy is generated from solar power for one month.

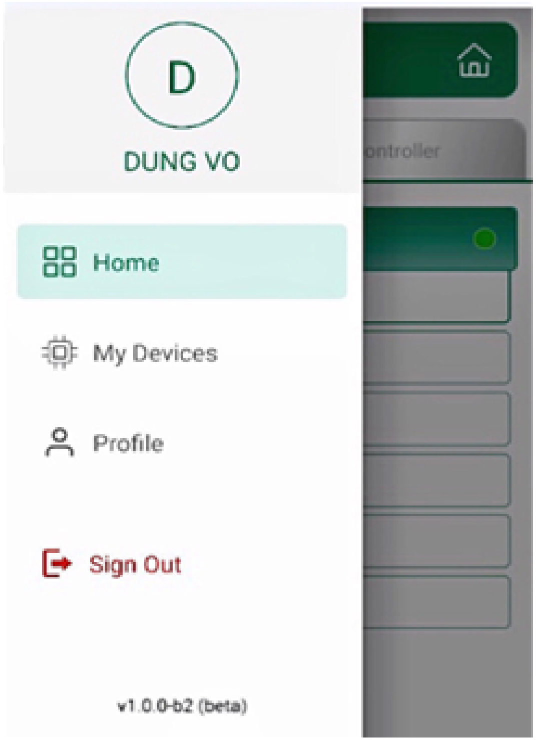

Fig. 16: App interface on smartphones (iOS & Android).

little change during a day. This result is completely consistent and reliable because the system is installed in a place where solar power is connected to the national grid. The results shown in Fig. 11 and Fig. 12 are used to evaluate the stability of solar power sources.

Fig. 13 shows the energy output generated on a random day. Based on these values, it is easy to see the truly effective energy value during the period from 7:00 a.m. to 3:00 p.m.

Fig. 14 shows the solar power output generated in one week. With the nominal capacity of the solar power source being 4.68kW, the average energy generated in a day ranges from 18-19 kWh, the maximum and minimum values are approximately 21kWh and 13kWh, respectively. Based on this result, users can evaluate the

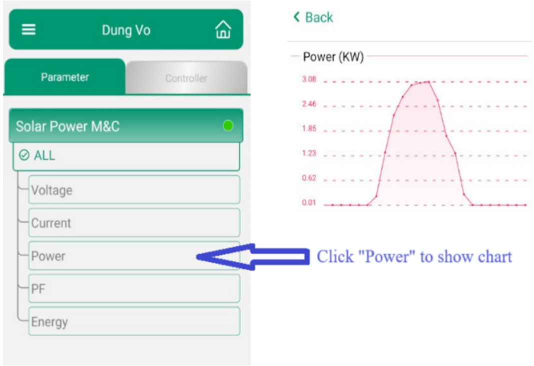

Fig. 17: The function to view measurement parameters and graphs on the application.

effectiveness of solar power installation with high accuracy.

Fig. 15 shows the energy of solar power generated in one month. From these data, it can be seen that the energy generated from solar power is relatively stable. Although there are special days of low and high energy generation, the overall number of stable days is the majority and the difference in value is not too much. From the result, users can evaluate the quality of solar power sources.

Fig. 16 shows the interface of the smartphone application. Based on the system's requirements, the application is designed with the following functions: Main function (Home) - management of monitoring measured solar power parameters (Parameter Tab and Controller Tab); Device management (My Devices) - will control how many devices are connected to the system, the device's operating status as well as the device's technical parameters; Device user information (Profile) - to be able to record and communicate, it also contains a number of utilities for users.

By clicking the Home button, then selecting the Parameter Tab, the interface will display the measurement parameters as shown in the Fig. 17. Users just need to click on the parameter to view, the data will be displayed in graph form, this is very convenient for monitoring.

5. Conclusions

In this research, the system for controlling and monitoring the parameters of solar power sources has been completely built. The system has been deployed in households with solar power installed. System parameters are updated in real time and stored safely, securely and unlimitedly on the server, making daily and monthly monitoring extremely simple and easy. From that result, users can easily evaluate the performance and stability of solar power sources, detect and promptly handle problems that occur, and then plan the maintenance to ensure solar power operates optimally. The system operates stably for a long time, results are reliable and meets user expectations. The results of the system research meet the purpose of accessing technology, and especially can be used as a teaching and training model for students in engineering and technology fields.

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Author Contributions

T.T.T. developed the ideas, wrote draft, tested the system, and supervised the project. L.T.T. performed the hardware design. T.H.K supported firmware setup. All authors contributed to the final version of the manuscript.

References

[1] `https://givasolar-jinko.vn`.

[2] `https://solare.vn/blogs/news/cac-he-thong-nang-luong-mat-troi-hien-nay`.

[3] SRILAKSHMI, M.. A Study of Solar Power Monitoring System Using Internet of Things (IoT). *International Journal of Innovative Science and Research Technology*. 2021, vol. 6, no. 5. ISSN: 2456-2165.

[4] KOMKRIT C., K. MEEKUL. Design of an IoT Energy Monitoring System. In: 16th International Conference on ICT and Knowledge Engineering. 2018. DOI: 10.1109/ICTKE.2018.8612412.

[5] MAISAGALLA G., T C. PRAKASH, N V. RAMAKRISHNA, B. P. YADAV. IoT Based Solar Power Monitoring System. In *IOP Conference Series: Materials Science and Engineering*. 2020. DOI 10.1088/1757-899X/981/3/032037.

[6] DINESH K. S., A. BRAHMIN. A Review on Solar Monitoring System. *International Research Journal of Engineering and Technology*. 2021. vol 8, no. 1. ISSN: 2395-0056

[7] BABU, R. L. R., RAMBABU, D., NAIDU, A. R., PRASAD, R. D., KRISHNA, G. P.. IoT enabled solar power monitoring system. *International*

Journal of Engineering & Technology. 2018, vol. 7, no. 3. DOI: 10.14419/ijet.v7i3.12.16172.

[8] SUBHASRI, G., JEYALAKSHMI, C. A Study of IoT based solar panel tracking system. *Advances in Computational Sciences and Technology*. 2018, vol. 11, no. 7 . ISSN 0973-6107

[9] KATYARMAL, M., WALKUNDE, S., SAKHARE, A., RAWANDALE, M. U. Solar power monitoring system using IoT. *International Research Journal of Engineering and Technology (IRJET)*. 2018, vol. 5, no. 3. ISSN: 2395-0056

[10] KANDIMALLA, J., KISHORE, D. R. Web Based Monitoring of Solar Power Plant Using Open Source IOT Platform Thingspeak and Arduino. *International Journal for Modern Trends in Science and Technology*. 2017. vol. 3, no. 4. ISSN: 2455-3778

[11] BIPIN K., K. SINHA. Tracking of Sun for Solar Panels and Real-Time Monitoring Using LabVIEW. Journal of Automation and Control Engineering. 2013, vol. 1 no. 4. DOI: 10.12720/joace.1.4.312-315.

[12] SOHAM A., D. SAHA, A. DAS, J. JANA, HIRANMAYSAHA. An IoT Based Smart Solar Photovoltaic Remote Monitoring and Control unit. *IEEE International Conference on Control, Instrumentation, Energy & Communication (CIEC)*. 2016, pp.432-436. DOI: 10.1109/CIEC.2016.7513793.

[13] RENATA I. S. PEREIRA, IVONNE M. DUPONT, PAULO C. M. CARVALHO, SANDRO C. S. JUCA. IoT Embedded Linux System based on Raspberry Pi applied to Real-Time Cloud Monitoring of a decentralized Photovoltaic plant. *International Journal of Measurement*. 2018. Vol. 114. Doi: 10.1016/j.measurement.2017.09.033

[14] AISSACHOUDER, S. SILVESTRE, B. TAGHEZOUIT, ENGINKARATEPE. Monitoring, modeling and simulation of PV systems using LabVIEW. *International Journal of Solar energy Elsevier*. 2012, Vol. 1, pp.337-349. DOI: 10.1016/j.solener.2012.09.016.

[15] HAIDER-E-K., A. A. KHUWAJA, A. SATTAR. Solar Power Remote Monitoring and Controlling Using Arduino, Labview and Web browser. *IEEE International Conference on Power Generation System and Renewable Energy Technologies*. 2015. pp.1-4. DOI: 10.1109/PGSRET.2015.7312240.

[16] KANGKANAHAZARIKAA, P. K. CHOUDHURY. Automatic monitoring of solar photovoltaic (SPV) module. *Science direct proceedings*. 2017. Vol. 4, pp.12606-12609. DOI: DOI: 10.1016/j.matpr.2017.10.069.

[17] RAJALINGAM S., MALATHI V. "HEM algorithm-based smart controller for home power management system. *International Journal of Energy and Buildings ELSEVIER*. 2016. Vol.131, pp. 184-192. DOI: 10.1016/j.enbuild.2016.09.026.

[18] `https://www.rasuni.com/collections/sma-sunny-tripower-x/products/sma-sunny-tripower-x-25`.

[19] Datasheet of Sunny Tripower X powered by ennexOS, *SMA Solar Technology AG*, 2023.

[20] `https://www.sma.de/en/products/apps-software/sma-energy-app#c373`.

[21] `https://1m29l9z267.k.topthink.com/@solarmansmart-web_en/jichugongneng.html`.

[22] `https://atpro.com.vn/he-thong-giam-sat-nang-luong-mat-troi/`

[23] `https://thinhtamphat.com/San-pham/He-thong-giam-sat-nang-luong-mat-troi.html`

[24] `https://onfac.net/scada-cho-he-thong-dien-nang-luong-mat-troi/`

[25] `https://ats.com.vn/vi/pv-ppc/`

[26] `https://onfac.net/phan-mem-giam-sat-pin-nang-luong-mat-troi/`

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