Design of an Integrated Photovoltaic and Thermal Monitoring System Using ForceControl Configuration Software

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Abstract. Integrated solar photovoltaic and thermal (PV/T) systems utilize the heat produced during photovoltaic power generation to heat water, which can then be used for heating and domestic water supply purposes. At the same time, the water is used to cool the solar panel, thereby enhancing the efficiency of power generation and consequently improving the overall utilization of solar energy. To realize real-time monitoring and display of the temperature and power generation of the integrated PV/T system, we designed a monitoring system based on a ForceControl configuration system. In this paper, we provide details of the construction of the system, including the establishment of the physical integrated PV/T system, the temperature data acquisition system, and the electric data acquisition system, as well as the design of a monitoring interface based on the ForceControl configuration software. Within this study, the system was also constructed and verified. The results indicated that the system can display parameters including temperature of the PV module rear panel, temperature of the water tank, and power generation in real time. Furthermore, its characteristics, including friendly interface, intuitive display, and high precision all make it an appropriate tool for monitoring integrated PV/T systems.

Introduction

Challenging realities, including energy supply crises, environmental pollution, and fog and haze have all prompted governments to accelerate adjustments to energy structures and to develop and utilize clean and renewable energy. Solar energy, as one of these clean and renewable energy sources, can be utilized mainly via photothermal and photovoltaic technologies, where solar energy is converted into heat or electricity. However, existing systems utilizing solar energy tend to be simple, where photothermal and photovoltaic systems are implemented separately. These systems often exhibit low overall utilization efficiency, making them incapable of fully utilizing solar energy [1]. Currently, the efficiency of commercial photovoltaic systems is usually lower than 20%. In addition, photovoltaic cells are significantly affected by temperature. Moreover, the output power of photovoltaic cells is reduced by approximately 0.4% to 0.5% for every 1 °C increase [2]. To overcome these issues, researchers have developed an integrated solar photovoltaic and thermal (PV/T) system, which utilizes the heat produced during photovoltaic power generation to heat water that can be used for heating and domestic water supply purposes. At the same time, the water is used to cool the solar panel, thereby enhancing the efficiency of power generation and consequently improving the overall utilization of solar energy [3-5]. In this study, we designed an integrated PV/T monitoring system, which can monitor and display temperature and power generation data in real time.

PV/T Module Structure

The structure of a PV/T module suitable for use in the Jiangsu Province is shown in Figure 1. The system is a combination of a photovoltaic module and a solar heat collector, fabricated by installing the collector and a pipeline system to the back of the photovoltaic module. The major components include the solar photovoltaic module, the heat collector tube, and inlet and outlet pipelines. The heat collector, made of aluminum alloy (which has a heat transfer coefficient of 226 W/MK), was
placed on the TPT (abbreviation of Tedlar/PET/Tedlar) of the module. To reduce the thermal resistance between the photovoltaic module and the collector, a layer of thermal silicon grease was added between them. The photovoltaic module is a polycrystalline-silicon-type electric module, the major technical parameters of which are listed in Table 1.

![Figure 1. PV/T module structure.](image)

Table 1. PV/T module parameters.

| Parameter                                | Value  |
|------------------------------------------|--------|
| Maximum power (Pmax)                     | 300 W  |
| Working current at maximum power point (Imp) | 8.28 A |
| Working voltage at maximum power point (Vm) | 36.2 V |
| Short circuit current (Isc)              | 8.77 A |
| Open circuit current (Voc)               | 45.4 V |
| Module efficiency                        | 16.3%  |

Establishment of an Integrated PV/T Monitoring System

A monitoring system is generally composed of three parts: a data acquisition unit, a data transmission unit, and a monitoring and display unit [6]. Data acquisition was achieved mainly through temperature sensors and smart electronic watt-hour meters, while monitoring and display was achieved by ForceControl configuration software.

Establishment of the Physical System

The construction of the physical system is shown in Figure 2. To facilitate comparison, a PV/T module and an ordinary PV/module were placed side by side, both with an azimuth angle of 180⁰ south and an inclination angle of 30⁰, so that the two modules would receive the same amount of solar radiation. As presented in Figure 2, the PV/T module is on the left, and the ordinary PV module is on the right.

![Figure 2. Establishment of the Physical system.](image)

The pipeline system of the PV/T module is shown in Figure 3. The hot-water port of the module is connected to the top of the insulated water tank, whilst the cold-water port is connected to the bottom. During operation of the system, thermal energy from the rear panel of the photovoltaic module heats the water in the pipeline via the heat collector. The heated water subsequently flows up through the pipeline and enters the insulated water tank, whereas the colder water in the tank
flows through the pipeline and enters the cold-water port as replenishment. This continuous cycle keeps heating the water, thereby providing a hot water supply. In addition, the heat on the rear panel is absorbed by the circulating water, which reduces its temperature and therefore improves the power generation efficiency of the module.

Figure 3. Establishment of the pipeline system for the PV/T module.

Establishment of the Temperature Data Acquisition System

Selection of Temperature Measurement Points. To compare the temperature variations and the water temperatures of the two modules, a total of six temperature measurement points were set, including two points at one quarter and three quarters of the rear panel of the PV/T module, a point at one quarter of the rear panel of the ordinary PV module, two points at the top and the middle of the water tank, and a point to measure the ambient temperature.

Selection of a Temperature Sensor. There are multiple methods available for measuring temperature in an industrial environment. Common temperature sensors include resistance-type, thermocouple-type, and PN-junction-type sensors, although most high-precision measurements adopt the standard platinum-resistance temperature sensors \[7\]. In this study, we selected the PT100 temperature sensor, a meter that converts the temperature into a standardized output signal that can be transferred. These sensors are mainly used for the measurement and control of temperature parameters during industrial processes, and have a temperature acquisition range of \(-200 \text{ to } +850 \degree\)C. They have several advantages, including high precision, superior stability, exceptional interchangeability, corrosion resistance, a broad measurement range, and convenience in use \[8\].

Connection of the Temperature Data Acquisition System. For the temperature data acquisition module, we adopted the SSEEWE SRND-CM-PT acquisition model, the major parameters of which are listed in Table 2. Using the RS232/485 MODBUS RTU standard communication protocol, this model can network with the configuration software, and is therefore widely used in digital signal acquisition and control of industrial devices. The connection diagram between the temperature acquisition module and the PT100 temperature sensor is shown in Figure 4. Platinum-resistance based temperature measurements have three types of connections: two-wire, three-wire, or four-wire. Despite its simplicity and convenience, the two-wire connection is substantially affected by the trace resistance; this is not so much a problem for three-wire connections. Therefore, in this study, we adopted the three-wire connection method by connecting one end of a wire to the internal end of the thermal resistor, and the other end to two other wires.

Table 2. Parameters of the SRND-CM-PT data acquisition module.

| Parameter                                      | Value                          |
|-----------------------------------------------|--------------------------------|
| Temperature input channel                     | 6                              |
| Temperature measurement range                 | -200\degree C to +600\degree C |
| Resolution                                    | 0.1\degree C                   |
| Product dimension                             | 125×73×42                      |
| External power supply                         | DC12-24 V                      |
| Working temperature range                     | -10\degree C to +60\degree C   |
| Sensor                                        | Supports two-wire/three-wire PT100 |
| Installation method                           | Standard DIN guide-rail installation |
Figure 4. Connection between the temperature data acquisition module and a PT100 sensor.

Establishment of the Electric Data Acquisition System

For the monitoring system to collect and display the electric parameters such as voltage, current, and power (electric energy), it is necessary to first collect data on the relevant physical quantities, including the voltage and current of the system.

Establishment of the Electric System. The establishment of the electrical system, which consists of a DC/AC inverter, a data transfer unit (DTU), a watt-hour meter, an over-voltage and under-voltage protector, is shown in Figure 5. The 36 V DC power generated by the PV module is converted into 220 V AC power via the microinverter, which is then incorporated into the public power grid. The over-voltage and under-voltage protector automatically powers off and resets the system upon over-voltage or under-voltage, thereby protecting the system.

Figure 5. Establishment of the electric system.

Selection of the Inverter. Because of the parameters of the photovoltaic module, including power and working voltage\textsuperscript{[10]}, we selected (2x) MI-250 microinverters manufactured by Hoymiles Converter Technology Co., Ltd. as they can be matched to 200–310 W photovoltaic modules. The parameters of the inverter are listed in Table 3. In the microinverter system, each photovoltaic cell component was equipped with an independent maximum power point tracking (MPPT) controller, which greatly improved the utilization of the photovoltaic cells. Consequently, power generation was maximized, i.e., the microinverter system can generate more power than traditional systems\textsuperscript{[11]}.  

Table 3. Parameters of the MI-250 microinverter.

| Input Parameter               | Output Parameter         |
|------------------------------|--------------------------|
| Maximum input voltage 60 VDC | Rated output voltage 230 V AC |
| Input voltage range 16-60 V DC | Rated operating frequency 50 HZ |
| MPPT voltage range 27-48 V DC | Output power factor >0.99 |
| Maximum input current 10 A DC | Rated output current 1.08 A AC |
| Maximum input short circuit current 15 A DC | Rated output power 250 W |
| Working temperature range -40 ~ +65°C | Protection grade IP67 |

Selection of the DTU. In this study, we adopted the DTU-MI-GPRS DTU manufactured by Hoymiles Converter Technology Co., Ltd. to match to the inverter. The DTU collects the operation
data of the microinverter wirelessly, and transfers it to the Hoymiles monitoring platform via Ethernet. It utilizes a dual-antenna design, with one of the antenna communicating with the microinverter at 2.4G RF to collect its operation data, and the other communicating with the remote monitoring platform via either a SIM card or the Ethernet using the General Packet Radio Service (GPRS) standard. Users can view the operation condition of the photovoltaic power generation system through a webpage or mobile app.

**Selection of the Watt-hour Meter.** For the acquisition of electric parameters, we adopted the Chint DDSU666 single-phase electronic watt-hour meter. The working principle of the meter is as follows: the measured instantaneous voltage \( u \) and current \( i \) are respectively processed in a voltage sampler and a current sampler to convert them into weak electric signals proportional to the measurements, which were then sent to the multipoint control unit (MCU) \(^{[12]}\). The MCU subsequently calculates the signals in the sampling circuit and converts them individually into electric energy, power, power factor, as well as other electric parameters, which are then displayed by the display circuit. Meanwhile, the data were saved in the storage circuit, and can be exchanged with other communication devices through the communication circuit provided the device conforms to the system’s interface and protocol.

**Design of the Monitoring Interface**

The configuration software is an important medium that provides worker information during industrial production processes. Common types of configuration software include WinCC, Kingview, ForceControl, and MCGS. The three-dimensional ForceControl software is one of the earliest configuration software developed in China. Its main advantage is that it is based on the three-layer structure of a real distributed real-time database, thereby offering a privileged overall structure as well as a fast speed. Consequently, we adopted the ForceControl configuration software in our monitoring interface design.

**I/O Devices and Communication Connections**

The ForceControl software requires configuration of the I/O drive devices to allow the exchange of data with them through database variables \(^{[13]}\). In the pop-up “Device Configuration” dialog box, the first step is to insert the device name and device address, followed by selecting and setting the serial port, and finishing the configuration using the default parameters. In this study, both the DTU and the watt-hour meter adopted the RS485 communication protocol, and selected the standard Modbus (RTU serial port) protocol.

**Database Configuration**

New analog I/O points must be created for the temperature acquisition module, the settings of which should align with the addresses of the attached I/O devices and the corresponding registers, as shown in Table 4. Because the data sent from the temperature acquisition module to the PC is 10× the actual temperature, calculation points were established to divide the raw data by 10. For data that required a report query, automatic saving was established in the Historical Parameters tab. Similarly, the watt-hour meter also needs to communicate and exchange data with the configuration software. The corresponding parameter settings of the communication addresses are listed in Table 5.

| Address | Bit   | Read/Write | Instructions            | Data range (one decimal place) |
|---------|-------|------------|-------------------------|-------------------------------|
| 4x0000  | 16BIT | R          | Temperature of the 0th channel | -2000 ~ +6000                  |
| 4x0001  | 16BIT | R          | Temperature of the 1st channel | -2000 ~ +6000                  |
| 4x0002  | 16BIT | R          | Temperature of the 2nd channel | -2000 ~ +6000                  |
| 4x0003  | 16BIT | R          | Temperature of the 3rd channel | -2000 ~ +6000                  |
| 4x0004  | 16BIT | R          | Temperature of the 4th channel | -2000 ~ +6000                  |
| 4x0005  | 16BIT | R          | Temperature of the 5th channel | -2000 ~ +6000                  |
Table 5. Parameter settings of the communication addresses of the watt-hour meter.

| Parameter address | Parameter code | Parameter description                          | Data type | Data length (Word) | Read/Write property |
|-------------------|----------------|-----------------------------------------------|-----------|--------------------|---------------------|
| 2000H             | U              | Phase A voltage                                | float     | 2                  | R/W                 |
| 2002H             | I              | Phase A current                                | float     | 2                  | R/W                 |
| 2004H             | P              | Instantaneous total active power               | float     | 2                  | R/W                 |
| 2006H             | Q              | Instantaneous total reactive power             | float     | 2                  | R/W                 |
| 2008H             | S              | Instantaneous total apparent power             | float     | 2                  | R/W                 |
| 200AH             | PF             | Total power factor                             | float     | 2                  | R/W                 |
| 200CH             | RESERVED       | Reserved                                       | float     | 2                  | R/W                 |
| 200EH             | Freq           | Grid frequency                                 | float     | 2                  | R/W                 |
| 2010H             | RESERVED       | Reserved                                       | long      | 2                  | R/W                 |
| 4000H             | Ep             | Total active electric energy                   | float     | 2                  | R/W                 |

Secondary-side electric quantity data

Display Interface

To create an intuitive superior visual experience, we designed a real-time display interface, as shown in Figure 6. The interface displays the positions of the water module and the water tank, the installation positions of each PT100 and its real-time parameters, and the electric connection of the entire system. In addition, it can perform real-time communication with the watt-hour meter, thereby providing all functions required by real-time data monitoring and display.

Design of Bar Chart for Electric Energy

The electric energy statistics of the watt-hour meter accumulate continuously. To count and display the power generation at a certain hour, we designed specific program actions in the global script.

Figure 6. Real-time display interface.

Figure 7 demonstrates the programing logic structure, which shows the logic behind the creation of the power generation bar chart at each hour. When assigning values to multiple intermediate variables, they were designed to exhibit different meanings at different times, thereby allowing the presentation of different data.

Figure 7. Programming logic behind the creation of the power generation bar chart.
When initiating the program, write:

```plaintext
one_dianNeng_pr = dianneng.PV;// assign the value of watt-hour meter 1 to the intermediate variable one_dianNeng_pr
two_dianNeng_pr = dianneng2.PV;// assign the value of watt-hour meter 2 to the intermediate variable one_dianNeng_pr
```

Due to changes in sunlight intensity, we only counted the power generation at each hour from 08:00 to 16:00. During the execution of the program cycle, write:

```plaintext
IF  $Minute ==00 && $Second == 00  THEN// assign values to the historical values at each integral hour
    one_dianNeng_pr = dianneng.PV;
    two_dianNeng_pr = dianneng2.PV;
ENDIF
IF  $Hour ==8 && $Minute <= 59 && $Second == 59  THEN// prior to each integral hour, calculate the power generation in the current hour by subtracting the historical value by the current value
    h8 =   dianneng.PV   - one_dianNeng_pr;
    8h =   dianneng2.PV   - two_dianNeng_pr;
ENDIF
IF  $Hour ==9 && $Minute <= 59 && $Second == 59  THEN
    h9 =   dianneng.PV   - one_dianNeng_pr;
    9h =   dianneng2.PV   - two_dianNeng_pr;
ENDIF
IF  $Hour ==10 && $Minute <= 59 && $Second == 59  THEN
    h10 =  dianneng.PV   - one_dianNeng_pr;
    10h =  dianneng2.PV   - two_dianNeng_pr;
ENDIF
IF  $Hour ==11 && $Minute <= 59 && $Second == 59  THEN
    h11 =  dianneng.PV   - one_dianNeng_pr;
    11h =  dianneng2.PV   - two_dianNeng_pr;
ENDIF
IF  $Hour ==12 && $Minute <= 59 && $Second == 59  THEN
    h12 =  dianneng.PV   - one_dianNeng_pr;
    12h =  dianneng2.PV   - two_dianNeng_pr;
ENDIF
IF  $Hour ==13 && $Minute <= 59 && $Second == 59  THEN
    h13 =  dianneng.PV   - one_dianNeng_pr;
    13h =  dianneng2.PV   - two_dianNeng_pr;
ENDIF
IF  $Hour ==14 && $Minute <= 59 && $Second == 59  THEN
    h14 =  dianneng.PV   - one_dianNeng_pr;
    14h =  dianneng2.PV   - two_dianNeng_pr;
ENDIF
IF  $Hour ==15 && $Minute <= 59 && $Second == 59  THEN
    h15 =  dianneng.PV   - one_dianNeng_pr;
    15h =  dianneng2.PV   - two_dianNeng_pr;
ENDIF
```

Figure 8 shows the bar chart of the power generation from the photovoltaic system between 08:00 and 16:00 on a certain day. The system with the water module generated more power per hour than the system without.
Temperature Curve and Report Query

To enable the query and export of the historical data, we designed the temperature curve and report query functions. Figure 9 shows the temperature curves between 09:00 and 15:00 on a certain day, and Figure 10 shows the expert report at 12:07 on a certain day. The rear panel temperature of the photovoltaic system with the water module was significantly lower than that of the system without.

Conclusion

In this study, we experimentally verified that the monitoring system we designed (based on the ForceControl configuration software) could collect multiple parameters of the integrated PV/T system. These parameters included the rear panel temperature of the photovoltaic module, ambient temperature, water tank temperature, as well as the output voltage, current, power and electric energy from the inverter. These parameters are then displayed on the monitoring interface. This system offers distinctive advantages, including a user-friendly interface, intuitive display, high precision, and low cost.

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