A distributed monitoring system for photovoltaic arrays based on a two-level wireless sensor network

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Abstract. In this paper, a distributed on-line monitoring system based on a two-level wireless sensor network (WSN) is proposed for real time status monitoring of photovoltaic (PV) arrays to support the fine management and maintenance of PV power plants. The system includes the sensing nodes installed on PV modules (PVM), sensing and routing nodes installed on combiner boxes of PV sub-arrays (PVA), a sink node and a data management centre (DMC) running on a host computer. The first level WSN is implemented by the low-cost wireless transceiver nRF24L01, and it is used to achieve single hop communication between the PVM nodes and their corresponding PVA nodes. The second level WSN is realized by the CC2530 based ZigBee network for multi-hop communication among PVA nodes and the sink node. The PVM nodes are used to monitor the PVM working voltage and backplane temperature, and they send the acquired data to their PVA node via the nRF24L01 based first level WSN. The PVA nodes are used to monitor the array voltage, PV string current and environment irradiance, and they send the acquired and received data to the DMC via the ZigBee based second level WSN. The DMC is designed using the MATLAB GUIDE and MySQL database. Laboratory experiment results show that the system can effectively acquire, display, store and manage the operating and environment parameters of PVA in real time.

1. Introduction
The energy challenge and environmental problem is becoming increasingly serious all over the world. Therefore, the renewable solar energy is gradually developed and used by more and more countries [1-5]. According to the latest announcement of the National Energy Board of China, by the end of 2016, China's new PV installed capacity was 34.54 million kilowatts, the cumulative installed capacity was up to 77.42 million kilowatts and the amount of both new and cumulative installed capacity are at the first place in the world. PV arrays of PV power plants are usually installed in unattended outdoor fields such as desert, coast and on the roof [6], which are supposed to run for a long time. However, due to harsh outdoor environment, PV arrays are prone to suffer various faults [7-9]. In order to support automatic fault detection and facilitate the maintenance, it is significant to deploy distributed real-time monitoring systems for the PV arrays. The available monitoring systems for PV arrays can be classified into wired monitoring and wireless monitoring. Wired monitoring system mainly utilizes RS485 and CAN bus serial interface for local communication, and then achieves remote...
communication via the Internet [10, 1]. Due to the complicated wiring, deployment of wired monitoring systems is laboured intensive and expensive. Therefore, many wireless monitoring systems have been proposed and developed [5,6,12,13].

Wireless sensors network (WSN) has been widely used in various fields due to its high flexibility, excellent maintainability and scalability [14-19]. It also has been applied for monitoring PV power plants in real-time [2-6,18,19]. Xu and Wang applied the WSN to collect surrounding environment information and status data of PV power plant [6,19]. Papageorgas et al fuse computation and communication technologies for real-time monitoring and characterization of PV panel operational status based on wired networking combined with ZigBee [3]. Another case is that a WSN for smart monitoring of PV systems at module level is proposed, and the efficiency losses and related causes are estimated based on the acquired data [4]. In addition, Hua et al utilize the ZigBee to deliver the monitoring data of PV modules from different power stations to monitoring centre located in cloud [2]. A web-based and ZigBee-based monitoring system for grid-connected PV converter is presented by Shariff et al, in which a web-application is also developed to make the monitored data accessible via Internet [5]. An on-line distributed monitoring system based on ZigBee WSN was designed to monitor the electrical parameters and environmental parameters of PV modules in [20].

In order to achieve fine monitoring, all operating parameters of PV modules and PV strings in a PV array are expected to be monitored, including operating voltage, current, temperature and irradiance etc. However, PV arrays usually consist of a lot of PV modules, strings and sub-arrays, which will require a lot of wireless sensors leading to a high cost. Therefore, the cost of wireless sensors is an important issue. In this paper, we propose a new distributed monitoring system based on a low cost two-level WSN. The first level WSN refers to the communication between the wireless sensors on PV modules and the corresponding wireless sensors on the combiner box, which is implemented by the low cost nRF24L01 transceiver. The second level WSN refers to the communication among the wireless sensors on combiner boxes and the sink node, which is realized by the CC2530 based flexible ZigBee network. It is worth noticing that the work in this paper is based on [20] and we make further improvements. The rest of paper is organized as follows. Section 2 presents the system architecture. Section 3 introduces the design of sensing nodes installed in PV modules. The design of sensing and routing nodes deployed on combiner boxes of PV sub-arrays is described in Section 4. Section 5 demonstrates the realization of data management centre. Section 6 illustrates the system prototype and experimental results. Finally, Section 7 outlines the conclusion.

2. System architecture

2.1. System design

![Figure 1. Block diagram of the WSN based distributed monitoring system for PVA.](image)

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**Figure 1.** Block diagram of the WSN based distributed monitoring system for PVA.
As shown in figure 1, the distributed monitoring system for PV array mainly consists of a large number of PV module (PVM) sensing nodes installed in the junction box of each PVM, PV sub-array (PVA) sensing and routing nodes installed in the combiner box of each PV sub-array, a sink node connected to data management centre (DMC), and a DMC running on a local host computer.

The PVM nodes are designed to monitor the operating voltage and backplane temperature of each PVM. The monitored data are sent to the corresponding PVA nodes via the first level nRF24L01 based WSN. The PVA nodes are used to monitor the current and voltage of each PV string, environment irradiance and temperature around the combiner box of PV sub-array. In addition, the PVA nodes merge their monitored data with the one received from their PVM nodes, and then send them together to the sink node via a ZigBee based second level WSN. Because PV modules are usually connected in series to form PV strings, the current of PV modules should be equal to the current of their PV strings. Moreover, if PVM nodes acquire the operating PV module current directly, the current sensors need to be connected to the PV module, which will affect the wiring of PV modules and increase the cost of wireless sensors. Therefore, the operating current of PVM is not monitored by the PVM nodes to reduce the cost and complexity. The sink node passes the received data to the DMC via the serial port for data storage, display, and processing. Figure 2 further illustrates the distributed monitoring system involving two PV sub-arrays.

![Figure 2. Illustration of the distributed monitoring systems involving two photovoltaic sub-array.](image)

### 2.2. Wireless sensor network topology

![Figure 3. The wireless sensor networks topology of proposed system.](image)

![Figure 4. The block diagram of PVM circuit.](image)
The proposed system adopts two-level WSN for data transmission. Due to low cost and low power consumption, the first-level single hop star NRF24L01 wireless network is applied to transmit and receive the data in PV module via the Serial Peripheral Interface (SPI) communication. The second-level multi-hop mesh ZigBee wireless network is employed to deliver the PVM data, PV string data and environment parameters to DMC for further display and storage. As shown in figure 3, The PVM nodes are integrated with NRF24L01 WSN to send the PVM parameters, both NRF24L01 and ZigBee WSN are embedded in PVA nodes to receive data from PVM nodes and transmit data to sink node, respectively. The sink node delivers parameters to the DMC via serial communication.

3. Design of PVM node
The block diagram of PVM circuit is shown in figure 4. The hardware of PVM nodes consists of power management module, temperature and voltage sensors, microcontroller and wireless transmission module.

3.1. Power management module
The PVM node is powered by a battery together with the PVM. During the daytime, the PVM can generate electricity and thus it is used to power the PVM node and charge the battery as well, while the battery can maintain the basic operation of the PVM node during the night time. Since the open-circuit voltage of the PVM under Standard Test Condition (STC) is about 21.5 V which is much higher than the operating voltage of PVM node, the efficient stepping-down DC-DC voltage converter MP1584EN is used to generate the 3.3 V power supply.

3.2. Temperature and voltage sensors

The PVM nodes are designed to monitor the PVM operating voltage and module backplane temperature in real time. The low-power microcontroller MSP430G2553 which is integrated with a 10-bit resolution analog-digital converter (ADC) is used to achieve the data acquisition. The schematic diagram of the adopted voltage sensor is shown in figure 5. Since the operating voltage of PVM is usually about twenty volts but still much higher than the input range of the ADC, therefore a potentiometer implemented by two precise resistors is used to linearly scale down the voltage to fit the input range of the ADC inside the microcontroller. In this circuit, the ratio is set to be 1:10. Moreover, a capacitor is used to filter the noise, and two diodes are used to limit the output voltage between -0.7 V and 4 V. PVM usually run under the sunlight for a long time, the PVM panel temperature will be very high. Therefore, the DS18B20 temperature sensor is used. The flow chart of software design in PVM is shown in figure 5. Firstly, the MCU peripherals such as ADC, NRF24L01, and temperature sensor are initialized. Secondly, the NRF24L01 is set as receiving mode to receive the collection
signal from PVA node. Once the signal is received completely, the NRF24L01 is set as sending mode, and MCU acquire the voltage and temperature. Finally, the MCU send acquired data to PVA node via NRF24L01 network.

3.3. NRF24L01 WSN
In order to store the parameters collected by the PVM in the DMC, the system employs the low cost, low power consumption NRF24L01 wireless transceiver to deliver data, and sends the PVM’s parameter to their corresponding PVA node for the further communication. The sending and receiving flow chart of NRF24L01 wireless transceiver in proposed system is shown in figure 6. In order to ensure the synchronization of PVM acquisition nodes in time, the broadcast mechanism of NRF24L01 in this network is utilized to ensure that the PVA node receives synchronized data. Therefore, it is obvious that the sending part is set as receiving mode to receive the collect signal firstly, and the receiving part is set as sending mode to send the collect signal via the broadcast mechanism of NRF24L01.

Figure 6. The sending and receiving flow chart of NRF24L01 wireless transceiver.

4. Design of PVA node
Figure 7 shows the block diagram of PV string circuit. The hardware of PVA nodes consists of power management module, voltage sensors, current sensors, temperature sensors and irradiance sensors, microcontroller and two wireless transmission module.

4.1. Power management module
The PVA node is powered by electricity, the electricity voltage can be employed for sub-array voltage collection and gradually reduced to the required working voltage via the different power stepping-down DC-DC voltage converter. The LM7805 chip is used to generate the 5 V power supply for current sensors and irradiance sensors. And the LM1084IS-3.3 chip is applied to generate the 3.3 V power supply for microcontroller, NRF24L01 wireless transceiver and ZigBee wireless transmission module. During the conversion, several capacitors are used to filter the noise.
4.2. PV string parameters acquisition

The PVA nodes are designed to real-time monitor the PV string operating voltage, operating current, irradiance, environment temperature in combiner box. The low-power microcontroller MSP430F149 which is integrated with a 12-bit resolution analog-digital converter (ADC) is applied to achieve the data acquisition. PVA nodes adopt the isolated Hall voltage sensor LV25-P and Hall current sensor HBC06LSP for PV string operating voltage and operating current acquisition. Because the PVA consists of three strings in parallel, the system only designs a string voltage acquisition and five strings current acquisition, the extra two strings current acquisition, one of them is used to measure the irradiance, the other is applied for expansion in the future. DS18B20 temperature sensor is also applied to collect the working temperature of combiner box. Due to the linear relationship between short-circuit current and irradiance, and temperature has little influence on the irradiance which can be neglected, so the PVA nodes obtain the irradiance by measuring a PVM’s short-circuit current. The flow chart of software design in PVA is shown in figure 8. Firstly, the MCU peripherals such as ADC, NRF24L01, and temperature sensor are initialized. Secondly, the NRF24L01 is set as sending mode to send the collection signal to PVM node. Once the signal is sent completely, the NRF24L01 is set as receiving mode, and MCU acquire the voltage, current, irradiance and temperature. Finally, the MCU merges received data with acquired data and sends to sink node through ZigBee network.

5. Design of the DMC software

The DMC running on a host computer is designed by Matlab GUIDE, and the DMC includes the serial communication, parameters displaying, curve plot and data storage. The data uploaded from PVA nodes is received via CC2530 based ZigBee module, and is stored in MySQL database. Meanwhile, the PV data such as temperature, irradiance, voltage and current etc. is displayed and plotted in the interface. The flow chart of the DMC is shown in figure 9, and figure 10 shows the interface of DMC.

Figure 7. The block diagram of PV string circuit.  
Figure 8. The flow chart of software design in PVA.

Figure 9. The flow chart of DMC.
6. System prototype and experimental results
In order to verify that the designed system can run normally, the laboratory PV array on the 6th floor is selected as the laboratory object, which consists of three PV strings in parallel and each string consists of six PVM in series. The open-circuit voltage of the single PV module under STC is about 21.5 V and the short-circuit current is about 6.03 A under STC.

The test procedure is as follows. Firstly, the PVM nodes are installed in the junction box of the PVM and also powered by the PVM. The PVA node is deployed in the PV combiner box, the node collects real-time data per second. Secondly, the data collected by PVM nodes and PVA node are transmitted to the sink node via two-level WSN. Finally, the sink node sends the received data to DMC via the serial port to store and display. The physical pictures of the PVM and PVA node are shown in figures 11 and 12, respectively. The real-time parameters of PVM and PV strings are illustrated in figures 13 and 14, respectively. The part of real-time PV data stored in database is shown in figure 15. During the parameter acquisition, the selected PV array collects and transmits the parameters in different irradiance.
Compared the collected data by the proposed system with the data collected by multimeter, thermometer and illuminometer, they are mostly similar to each other. Several tests show that the data is normal and reliable in the distance between the fifth floor and the sixth floor in the laboratory. When the communication distance of the node is increased (such as > 100 m), a small amount of packet loss occurs. The distance between the PVM in the PVA and the different types of nodes will not exceed the packet loss distance generally, so it doesn’t affect the normal operation of the proposed monitoring system.
7. Conclusions
A distributed monitoring system for PVA based on NRF24L01 and ZigBee two-level WSN is proposed in this paper. The proposed system consists of the sensing nodes installed on PVM, sensing and routing nodes installed on combiner boxes, data management centre running on a host computer. Firstly, PVM nodes collect the parameters of PVM and transmit them to PVA node via the first level single hop nRF24L01 WSN. Secondly, PVA nodes receive the data from PVM nodes and collect the parameters of PV strings, then merge all data to the sink node via multi-hop ZigBee WSN. Finally, the sink node sends the data to the DMC via serial communication. The laboratory experiment results demonstrate that the proposed system can effectively collect, display, store and manage the working status and environment parameters of PV array real-time.

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