String Monitoring Unit for Megawatt Solar Power Plants

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While an increasing number of megawatt solar power plants have been constructed, some of them have already been facing problems with degradation in power output due to initial failures, aging solar panels, or external factors. We have developed a string monitoring unit that uses the power line communication (PLC) technology. These units monitor individual strings of hundreds of thousands of solar panels in real time without the need for wiring additional cables. We installed the units at a megawatt solar power plant, and successfully detected irregularities in power generation by analyzing data collected from the units.

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1. Introduction

Solar power generation systems have been drawing the attention of the public, as a source of renewable energy. Moreover, in Japan, the systems began to spread rapidly in 2012 when the feed-in tariff scheme for renewable energy was replaced by the full amount purchase scheme. Since then, there has been an increase in the construction of megawatt solar power plants (output: 1 MW or more).

These solar power plants consist of a large number of solar panels. The solar panels are mainly affected by initial failures, aging solar panels, or external factors. Moreover, this results in a decrease in the power generation amount (hence, a decrease in the amount of electricity sold). It should be noted that it is quite difficult to identify the failed solar panels based solely on a decrease in the total power generation amount. This is because a megawatt solar power plant consists of thousands of solar panels, and sometimes hundreds of thousands of them.

We developed a string monitoring unit (SSMAP) that can monitor the measurement of the power generation amount for each string accurately, on a real-time basis, using a power line communication (PLC). Each string consists of about 10–20 solar panels connected in series. Furthermore, the string monitoring unit can be retrofitted easily.

This paper reports the characteristics and specifications of the string monitoring unit, and the results of the analysis of power generation data obtained by the system.

2. Overview and Characteristics of a PLC String Monitoring Unit

2-1 Monitoring by string

Figure 1 shows the configuration of a megawatt solar power plant, equipped with the string monitoring unit.

At megawatt solar power plants, strings are integrated by a combiner box, which is then connected to a power conditioning system (PCS). The electricity generated by the panels is converted to AC power by the PCS, for connection to the power distribution system.

According to a survey conducted by the National Institute of Advanced Industrial Science and Technology (AIST), about 2% of solar panels become defective within
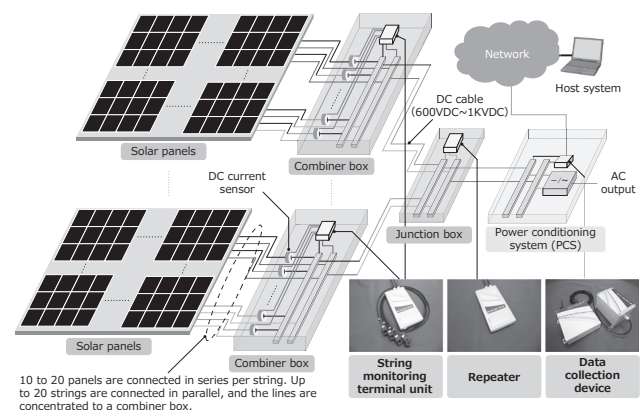

Fig. 1. Configuration of the string monitoring system

five years after the commencement of their operation.[1] To maintain stable power generation for a long period of time, defects should be identified quickly for replacement or repair.

Theoretically, a solar panel failure can be detected by monitoring the power generation amount at a PCS, combiner box, string, or panel. Regarding the monitoring at a PCS or combiner box, the failure of some solar panels gives little changes in the power generation amount, which cannot be distinguished from changes due to weather conditions. Therefore, it is difficult to detect a failure. Regarding the monitoring at a panel, the larger the scale of the megawatt solar power plant, the higher the cost required to introduce the system.

Regarding the monitoring at a string, a decrease in the power generation amount due to a solar panel failure, can be detected quickly. The unit can be introduced inexpensively, when compared with the system required for monitoring at a panel. Consequently, string monitoring is highly effective in the detection of solar panel failures.

2-2 Characteristics of a PLC string monitoring unit

Figure 2 shows the mechanism of PLC-based signal transmission.

The string data measured at a combiner box is transmitted via a PLC that uses an existing DC cable (600 VDC–1kVDC) as a communication line. Thus, a new
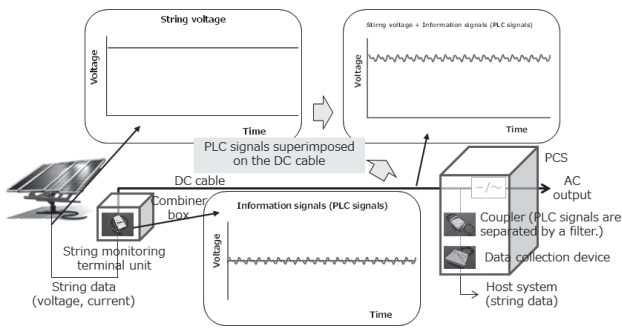
Fig. 2. Mechanism of PLC-based signal transmission

communication line is not required, resulting in a low initial cost.

A kHz-band PLC technology was adopted for the string monitoring unit, because it is used for smart meter system[2], and is applicable both indoors and outdoors; it is also resistant to the noise generated by PCSs, thus ensuring stable communication.

A string monitoring terminal unit is installed inside a combiner box or near a combiner box, in order to measure the currents and voltages of the strings. The data measured by a string monitoring terminal unit is transmitted by PLC to a data collection device (installed near DC input of the PCS), and then to a host system via the Internet. The electricity generated by the solar panels is supplied to the terminal unit, eliminating the need for an additional power line for the terminal unit. The string monitoring unit can be easily retrofit to existing megawatt solar power plants in operation, by using clamp type DC current sensors.

3. Specifications of the PLC-based String Monitoring Unit

3-1 Data collection device

The main specifications of the data collection device are shown in Table 1.

The data collection device is installed in a PCS enclo-

Table 1. Main specifications of the data collection device

Item		Specifications
Communication interface to a host system		Ethernet (100BASE-TX)
Communication protocol to a host system	Modbus	Operates as a Modbus slave to provide data based on a sequence from a host system
	HTTP/HTTPs	Transmits the obtained data to a host system using HTTP or HTTPS
Number of string monitoring terminal units supported		Up to 30 units per data collection device
Power consumption		3 W or less
Dimensions		Main unit: W 150 × D 150 × H 43 mm Coupler: W 102 × D 152 × H 82 mm (excluding protrusions)
Installation location		In the PCS enclosure, etc.

sure, to enable a PLC connection with up to 30 string monitoring terminal units. The data collected by the terminal units can be transmitted to a host system via Modbus (an industry standard). The data can also be transmitted using HTTP or HTTPS, which are typical protocols for web server communication.

To collect the string data using PLCs, the network IDs and individual IDs must be set to the terminal units. To ensure operational convenience, we built mechanism to simultaneously set the IDs to all the terminal units (installed in the combiner boxes), via PLCs from the data collection device. By so doing, the need to set the IDs to terminal units separately was eliminated.

3-2 String monitoring terminal units

The main specifications of the string monitoring terminal units are shown in Table 2.

Table 2. Main specifications of a string monitoring terminal unit

Item		Specifications
Monitoring items	String voltage	1ch up to 1,000 V, accuracy ± 5% (1,000 V, 25°C)
	String current	20 ch ± 15 A, accuracy ± 5% (15 A, 25°C)
	Digital signal	1 ch (input)
Measurement cycle		Every minute
Current sensor		Clamp type or Through type with hall element
Power consumption		20 W or less
Dimensions	Main unit	W 35 × D 117 × H 223 mm (excluding protrusions)
	Sensor	Clamp type: W 26 × D 27 × H 38 mm Through type: W 29 × D 46 × H 24 mm (excluding protrusions for both types)
Installation location		In the combiner box (IP44 or more), etc.

The string monitoring terminal units are powered by electricity generated from the solar panels. We made arrangements to achieve operation using a voltage lower than the PCS start-up voltage, in order to cope with significant voltage changes and ensure stable system operation. Given the increasing use of 20 string combiner boxes in recent years, we made arrangements to measure the currents of up to 20 strings. We also reduced the width to 35 mm, and the overall volume by 40% (compared with our conventional product). This allowed the terminal units to be easily retrofit to the small combiner boxes at existing power stations in operation.

3-3 How to install a string monitoring system

Figure 3 shows the configuration of the string monitoring system in (a) a low-voltage system and (b) a high-voltage system. At the most basic level, a string monitoring terminal unit is installed in a combiner box, and a data collection device is installed in a PCS.

It should be noted that the low-voltage and high-voltage systems require different repeater installation configurations, due to the difference in the line concentration configuration from a combiner box to a PCS. In low-voltage systems, a junction box is installed between a PCS

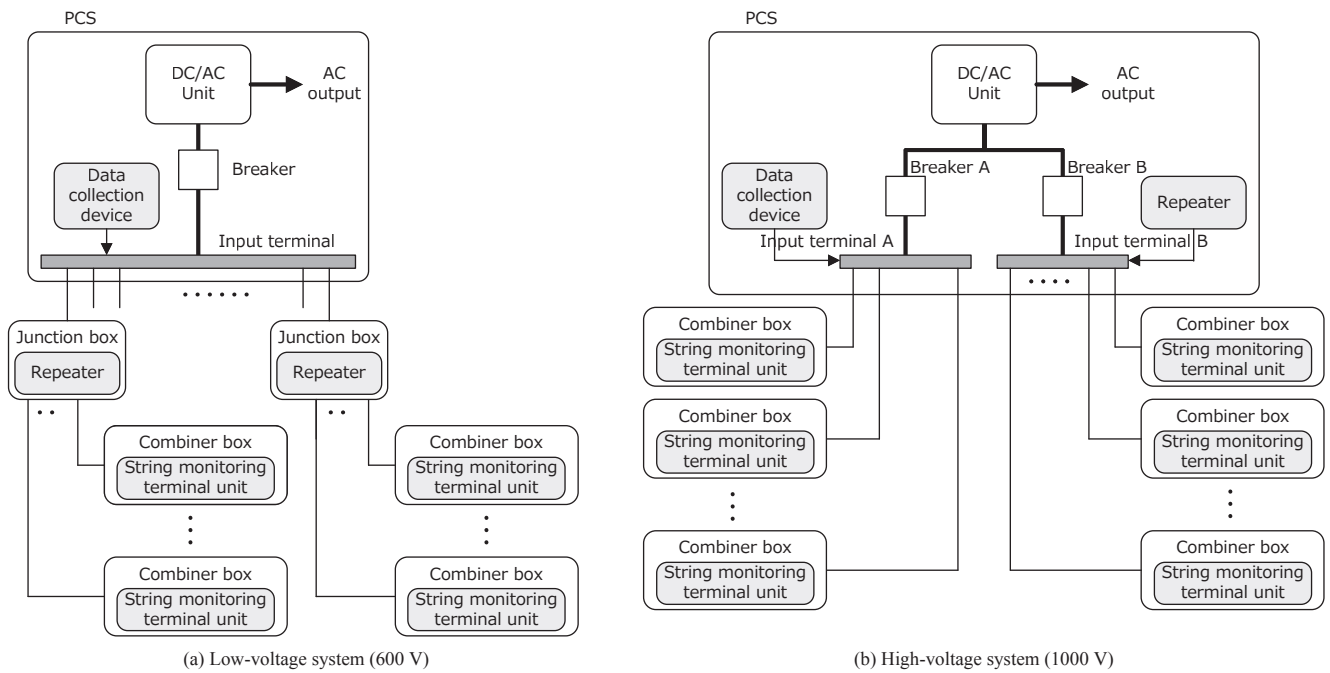(a) Low-voltage system (600 V)

(b) High-voltage system (1000 V)

Fig. 3. Installation configuration of string monitoring systems (high and low-voltage systems)

and a combiner box in many cases; and the input terminals in the PCS are integrated into a single unit. Moreover, in high-voltage systems, no junction box is installed between a PCS and a combiner box; and the PCS has multiple input terminals. The PLC signals from a string monitoring terminal unit (which is directly connected to input terminal B) are attenuated when they pass through the DC/AC conversion unit of the PCS. Furthermore, because different PCSs generate different levels of noise, the data can be collected stably using a PLC, by installing a repeater in a junction box or PCS input terminal B.

Table 3 shows the specifications of a PLC-based string monitoring system.

The frequency band that is used for a low-frequency PLC (applicable both indoors and outdoors) was used in compliance with the Radio law. To improve the robustness against noise, a spread spectrum system was adopted. There are two selectable data transmission speeds, depending on the noise condition.

Table 3. Specifications of a PLC-based string monitoring unit

Item	Details
Frequency range used	120-400 kHz
Communication speed	1.25 kbit/s, 5.0 kbit/s (subject to change depending on the modulation mode)
Modulation	Spread spectrum

4. Results of Introducing a String Monitoring System, a Case Study, and Monitoring Data

4-1 Results of introducing a string monitoring system

Our string monitoring system has been employed at about 30 power stations with capacities that range from 1-15 MW (about 150 MW in total).

A string monitoring terminal unit is installed in the free space inside a combiner box (see Fig. 4). A clamp type current sensor is installed on each string in the combiner box. Repeaters are installed in the junction boxes or PCS input terminals, to ensure stable communication.

A data collection device is installed in the free space inside the PCS enclosure, etc. (see Photo 1). After the installation, the string data is collected from the terminals every minute.
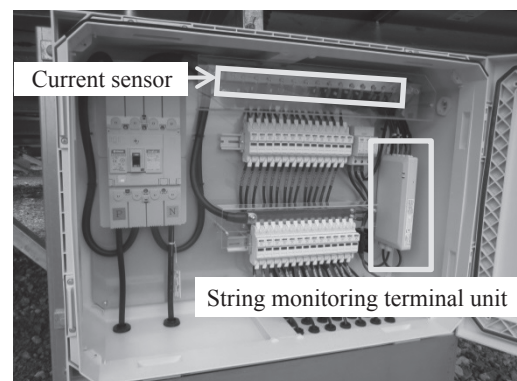

Fig. 4. String monitoring terminal unit installation status

PCS enclosure (on the left), installation status in the PCS (on the right)

Photo 1. Data collection device installation status

4-2 A case study and monitoring data

Table 4 and Photo 2 show a 1 MW solar power station where our string monitoring system was introduced.

Table 4. Configuration of a 1 MW solar power plant

Item	Configuration details
Generation power	1 MW
PCS	500 kW x 2
Number of junction box	4
Number of combiner box	32
Number of strings	314

Photo 2. Overview of a 1 MW solar power plant

We verified the operational status of the monitoring system and solar power plant, using the string data during the 13-month period from January 2015 to January 2016.

Figure 5 (a) shows the changes in the power generation amount of 10 strings measured at a combiner box on April 22, 2015. It was confirmed that all 10 strings generated electricity at almost the same level. Figure 5 (b) shows the power generation amount of the strings at the same combiner box, measured on December 18, 2015 (about seven months later). The power generation amount of one string was found to have decreased. Based on an on-site survey, no external factors (e.g. shade of trees and fouling) affecting this string were found. It is likely that a problem occurred.

The power generation amounts of several strings were

(a) April 22, 2015

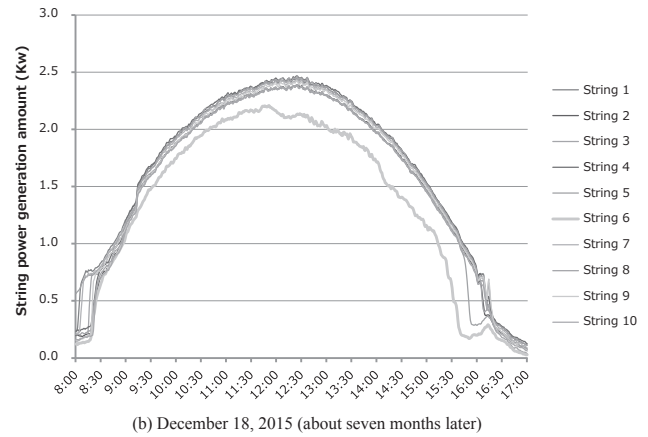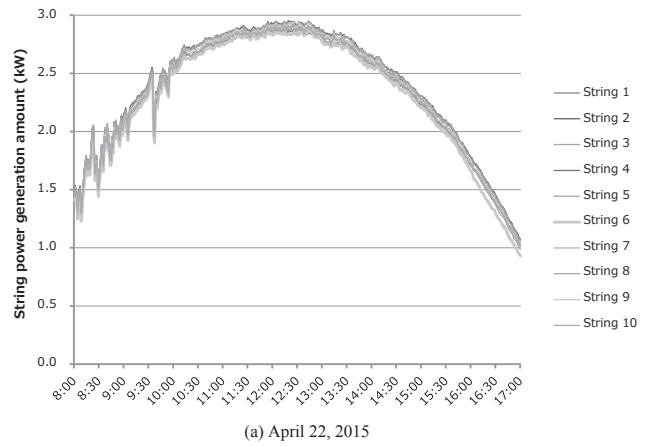(b) December 18, 2015 (about seven months later)

Fig. 5. Changes in the power generation amount of the strings during the day

found to be lower than that of others, in the morning and evening (see Fig. 6). An on-site survey of the solar panels of these strings found that the solar panels were slightly covered by the shade of trees (see Photo 3). It should be noted that the string monitoring unit can detect a decrease in the power generation amount due to solar panels being slightly covered by the small shade of trees.
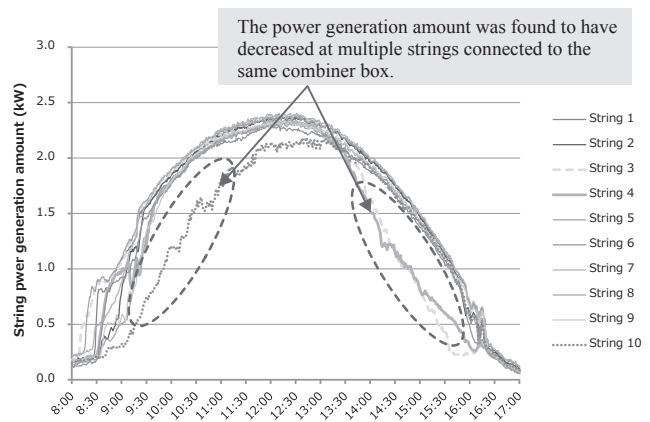

Fig. 6. Changes in the power generation amount of the strings during the day
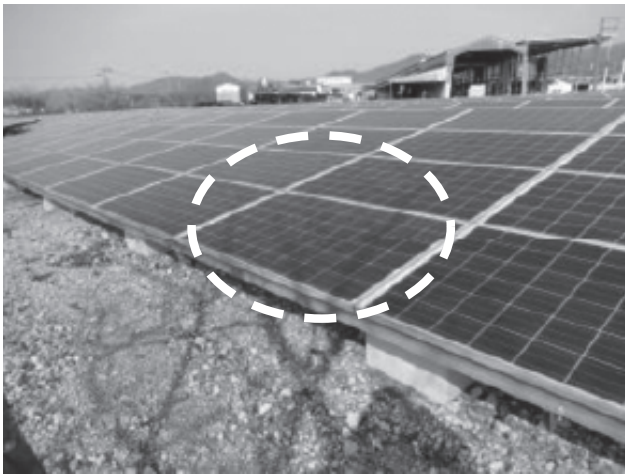
Photo 3. Shade of trees on panels

Next, we used the string data to compare the power generation amount monitored at a combiner box (the total string data in a combiner box), with the power generation amount monitored at a string.

The bar chart in Fig. 7 shows the total power generation amount at a combiner box, normalized with respect to the mean value of the power generation amount at all the combiner boxes connected to the same PCS, in the time series.

The line chart in Fig. 7 shows the power generation amount at each string connected to a combiner box, normalized with respect to the mean value of the power generation amount at all the strings connected to the same PCS, in the time series. The monthly value was calculated based on the value on the day in the month when the daily power generation amount was highest.

In the bar chart that shows the comparison by combiner boxes, the power generation amount ratio is almost equivalent to the mean value (power generation amount ratio ≈ 1.0). In the line chart that shows the comparison by strings, the power generation amount ratio of a single string is far below the mean value. That is, string monitoring can detect a slight decrease in the power generation amount, which cannot be detected with the monitoring of combiner boxes.
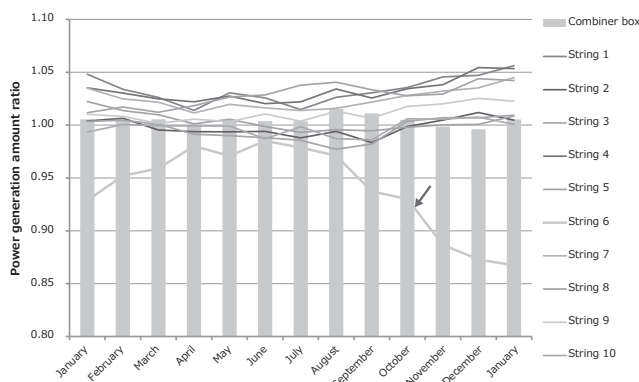
Table 5 shows the analysis results of the power generation amount (with respect to time slots), of strings at which a decrease in the power generation amount was detected in January 2015, June 2015, and January 2016.

In the three time slots (8:00-10:00, 10:00-14:00, 14:00-17:00), we compared the mean power generation amount of 314 strings in total, with the power generation amounts of the respective strings. We calculated the rate of strings with power generation amounts that were lower than the mean power generation amount by 10% or more (314 strings in total, on the left side of the Table 5). Moreover, we also calculated the mean decrease rate of the power generation amounts, of strings that experienced a decrease in power generation (on the right side of Table 5).

Table 5. Decrease in the string power generation amount

Period	Rate of strings whose power generation amount decreased 10% or more (314 strings in total)				Mean decrease rate of the power generation amount of strings whose power generation decreased (indicated on the left)			
	8:00–10:00	10:00–14:00	14:00–17:00	8:00–17:00	8:00–10:00	10:00–14:00	14:00–17:00	8:00–17:00
January 2015	11.8%	2.2%	6.1%	2.9%	22.0%	26.0%	19.0%	22.0%
June 2015	4.5%	1.3%	3.2%	2.2%	16.0%	22.0%	33.0%	25.0%
January 2016	15.0%	2.5%	9.6%	4.5%	26.0%	28.0%	22.0%	22.0%

The data enabled the analysis discussed below. The maintainability can be improved by the implementation of the string monitoring unit.

(1) The power generation amount in many strings decreased by 10% or more from the mean power generation amount of the 314 strings in total. This occurred more readily in the time slots of 8:00-10:00 and 14:00-17:00, than in the time slot of 10:00-14:00. Moreover, it is attributed to the influence of the shade of trees, etc. in the morning and evening.

(2) We calculated the decrease rate of strings whose power generation amount decreased by 10% or more and the mean power generation decrease rate. We compared the results in January 2015 with those in January 2016. The table shows that both rates increased. Although the influence of shade remains relatively the same, both rates increased in the same month in the following year. The power generation amount is considered to have decreased for some reason.

4. Conclusion

A string monitoring unit can detect a slight decrease in the power generation amount, prior to the occurrence of a significant decrease. This makes it possible to detect a failure quickly. In Japan, the amount of solar power plants equipped with the proposed system is still low. Therefore, a decrease in the power generation amount discussed above is likely to be overlooked, resulting in a loss of electricity sales.

Fig. 7. Mean power generation amount ratio for strings and combiner boxes

A PLC-based string monitoring unit does not require a new communication line or power line, and can be easily retrofit to existing power plants in operation. It is therefore considered an effective means to check and maintain the soundness of power plants, and to reduce the loss of electricity sales. Moreover, it is expected to be sold in markets outside Japan, where string monitoring units have been widely introduced.

- SSMAP is a trademark or registered trademark of Sumitomo Electric Industries, Ltd.
- Modbus is a trademark or registered trademark of Schneider Electric USA Inc.

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