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Overhead Transmission Line Monitoring Equipment for Large-Scale Introduction of Renewable Energy

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In order to achieve carbon neutrality, there is a growing trend to use renewable energy as the main power source. However, with an increase in the use of renewable energy, the power system has become congested, making it difficult to connect other new power sources. To solve this problem, Japanese Connect and Manage is being developed to review conventional methods and address power system congestion. Moreover, the dynamic rating is being considered a new operational technology. To realize these concepts, a real-time monitoring system is needed to monitor the conditions of overhead transmission lines and the environment around transmission towers. This system will play an important role as renewable energy will be introduced in large quantities in the future. We have been developing an overhead transmission line monitoring system for the large-scale introduction of renewable energy. This paper introduces the features of our developed system and equipment.

Keywords: renewable energy, dynamic rating, non-firm connection, private communication network, IEC61850

1. Introduction

Renewable energy plays an important role in realizing carbon neutrality, and efforts are being made to make renewable energy the main source of power. In recent years, an increase in the use of renewable energy has congested the power system, posing a problem for the expansion of the introduction of renewable energy. In particular, it is occasionally difficult for conventional operation methods to connect other new power sources to existing power systems. To solve this problem, some countries in Europe and North America have introduced new power connection systems.(1) In Japan, a Japanese version of the "Connect and Manage" scheme is under consideration to review conventional operation methods,(2) and the introduction of a new operational technology, dynamic rating, is being considered.(3)

The Japanese Connect and Manage addresses three initiatives: rationalization of estimated power flow,*1 N-1 generation control,*2 and non-firm connection.*3 N-1 generation control and non-firm connection are applied to existing power systems to maximize their effective use by controlling the output power when their transmission capacity is exceeded. Output power is usually controlled in a systematic manner based on the planned generation quantity of the power plant and demand estimates. It is necessary to ensure that the transmission capacity is not exceeded even in the event of a sudden line failure due to a lightning strike or other cause, or a significant increase in renewable energy generation exceeding the predicted output. If the amount of introduced renewable energy increases, the power flow will fluctuate significantly according to the season and time of day, and the power system will become more complex. In such a situation, a system is desired that constantly monitors the condition of transmission lines and controls the output in coordination with the system devices.

On the other hand, dynamic rating is an operational technology that increases the transmission capacity of existing power systems by dynamically calculating the capacity of the transmission lines.

One of the factors that determine the capacity of transmission lines is their thermal capacity; therefore, they must be operated so that the conductor temperature does not exceed the permissible temperature defined for each type of transmission line. In other words, when a transmission line is in thermal equilibrium under certain weather conditions, its transmission capacity is the transmission current when the conductor temperature reaches the permissible limit.

At present, transmission capacity is based on the assumption that the weather conditions are such that the conductor temperature reaches the highest value, and is treated as a fixed value because it is calculated on the assumption that the ambient temperature, wind speed, and solar radiation are always constant. Dynamic rating is a method of dynamically calculating transmission capacity by constantly measuring the conductor temperature and the weather conditions around the transmission line, thereby making it possible to maximize the effective use of the power system by operating it at a transmission capacity reflecting the actual conditions.(4)

As described above, a system capable of monitoring the temperature/current of a transmission line, as well as the weather around a steel tower, on a real-time basis is important for the operation of N-1 generation control and non-firm connection and the introduction of dynamic rating. At Sumitomo Electric Industries, Ltd., we are developing an overhead transmission line monitoring system indispensable for the massive introduction of renewable energy.(5) This paper describes the features of the new system and system devices we have recently developed.

2. Outline and Features of Overhead Transmission Line Monitoring System

Figure 1 shows the structure of the system we have developed.

A temperature/current sensor is attached directly to the conductor of the transmission line to measure the conductor temperature and current. The measurement data are transmitted to a data aggregator wirelessly.

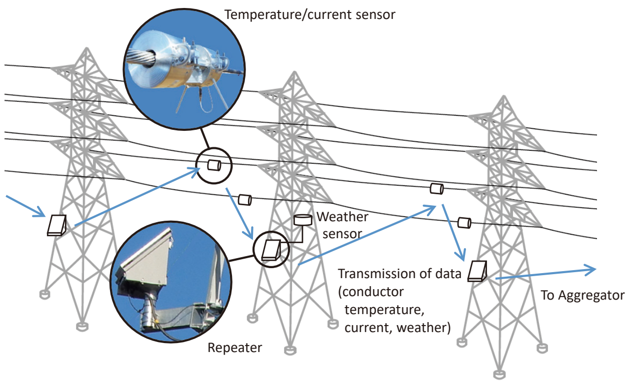

Fig. 1. Structure of Overhead Transmission Line Monitoring System (on Steel Tower Side)

A repeater is installed on one of the legs of the steel tower to relay the data sent from the temperature/current sensor. A weather sensor is also installed on the same tower to collect weather data and send them to the data aggregator.

The sensor network consisting of the temperature/current sensor, repeater, and aggregator uses a 920 MHz band radio. The specifications of the sensor network are shown in Table 1. The temperature/current sensor can also relay the data sent from other sensors or repeaters. Provided with a multi-hop communication function that performs multi-stage relay, the sensor achieves wide-area/long-distance communications.

In this system, the devices are located along the transmission line. Mesh topology is often used for multi-hop communication. As a method of enhancing communication efficiency and reducing the power consumption of the entire system, we optimized mesh topology for the linear network and constructed transmission routes using our unique technique.

Table 1. Specifications of 920 MHz Band Radio

Item	Specification
Communication system	920 MHz band specified low-power radio ARIB STD-T108 compliant
Network topology	Linear multi-hop
Maximum number of repeaters	50
Frequency band	922.5~927.7 MHz
Number of frequency channels	14
Antenna power	20 mW
Number of antennas	2
Transmission distance	1 km line of sight

The sensor network connecting the sensor and repeater to the data aggregator is a private communication network that does not use public lines. This private network makes it possible to construct networks even in mountainous areas that are outside the service areas of telecommunications carriers. This network also enables continuous operation of the system over a long period of time without being affected by the generational change of communication systems.

Data collected in the aggregator are transmitted to a cloud server or a calculation/storage server installed in the substation through OPGWs*4 or LTE, a closed network. The data are then used for the mathematical processing necessary for the calculation or estimation of allowable current. The acquired data are saved on the server and can be used for analyses and other purposes.

The firmware installed in each device can be remotely updated, making it possible to improve each device and add new functions to it as needed for maintenance and operation. This feature ensures the maintainability and availability of the system, which is required to operate stably over a long period of time.

3. Features of Each Device Comprising the System

3-1 Temperature/current sensor

The appearance and block diagram of the temperature/current sensor are shown in Photo 1 and Fig. 2, respectively. Since this sensor is directly attached to a high-voltage line conductor and must be insulated from outside, it

Photo 1. Appearance of Temperature/Current Sensor

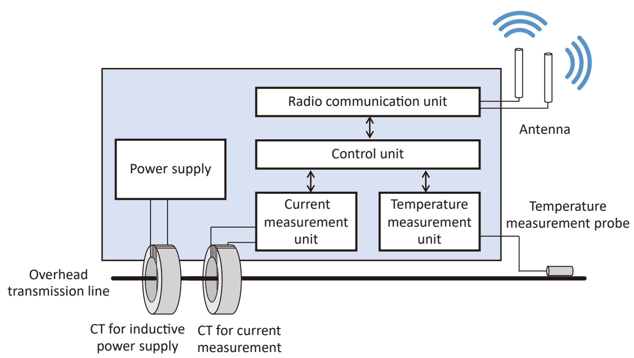

Fig. 2. Block Diagram of Temperature/Current Sensor

is difficult to supply power to the sensor from the ground. To eliminate the need for periodical power outage for battery replacement, an inductive power supply unit, which generates power from the transmission line current using electromagnetic induction, is used. The inductive power supply unit comprises a current transformer (CT) that generates inductive current from the magnetic field produced around the transmission line, and a power supply circuit that generates DC voltage from the inductive current. The temperature/current sensor further comprises a CT for current measurement, a current measurement unit that calculates the current, the temperature measurement probe to be attached to the transmission line conductor, a temperature measurement unit that calculates the surface temperature of the conductor, a communication unit for data transfer, and a control unit that collectively controls these devices.

Table 2 shows the main specifications of the temperature/current sensor.

Table 2. Main Specifications of Temperature/Current Sensor

Item		Specification
Power supply unit	Operating transmission line current range	50 ~ 1,200 A (Type1) 150 ~ 3,200 A (Type2)
Current measurement unit	Measurement range	50 ~ 1,200 A (Type1) 150 ~ 3,200 A (Type2)
	Target measurement accuracy	±3%
Conductor temperature measurement unit	Measurement range	-20 ~ +120°C (Type1) -20 ~ +180°C (Type2)
	Target measurement accuracy	±2°C
Communication interface		920 MHz band radio
Dimensions		W180 × H180 × D314 mm (excluding protruding portions)
Weight		Approx. 11 kg

As described above, the power necessary to operate the temperature/current sensor is generated by electromagnetic induction from the magnetic field produced around the transmission line. The operating transmission line current range of the power supply unit is divided into Type 1 (50 - 1,200 A) and Type 2 (150 - 3,200 A), depending on the characteristics of the CT for the inductive power source. It is necessary for each use of the sensor to consider the size and location of the power source and load connected to the power system. Type 1 is mainly intended for use in power systems using ACSR*[5] conductors, while Type 2 is for power systems using TACSR*[6] conductors. The measurement range of the current measurement unit is basically equal to the Type 1 or Type 2 range.

If the current flowing through the transmission line decreases to below its lower limit, the power produced by electromagnetic induction will decrease. To avoid starting up in this state, the temperature/current sensor is provided with a usable power monitoring function and controls the startup depending on the power monitored, thereby enhancing the operational stability of the sensor and thus the entire system.

Measuring the current is important in order to grasp the actual current when dynamic rating, N-1 generation control, and non-firm connection are applied, as well as to verify the validity and improve the accuracy of the calculated allowable current and conductor temperature. In addition, the increase in renewable energy connected to the power system has increased the number of branches and made it more complex. Reverse current flow from renewable energy sources to the power system is added to forward current flow from the power plant to the loads. Since the output power of some renewable energy sources fluctuates significantly, it is difficult to know the current flowing in the middle section of the power system. Installing a temperature/current sensor in such a power system makes it possible to dynamically grasp the transmission current.

The conductor temperature is measured directly by placing a temperature measurement probe in close contact with the transmission line, with importance attached to accuracy and responsiveness. With regard to responsiveness, it is especially important to be able to follow a temperature rise due to a sudden change in the transmission current, such as when a single line failure occurs in N-1 generation control.

Since the temperature/current sensor is attached directly to the conductor of the transmission line, protection against fault current and corona discharge countermeasure are needed. As for the fault current, protection devices are installed in the input terminal of each CT.

High-voltage lines occasionally cause a corona discharge*[7] to occur from the surface of the conductors. The corona discharge may last for several hours depending on the weather conditions. The temperature/current sensor ensures stable operation even when corona discharges occur. In addition, reducing the electric potential gradient*[8] by making the casing cylindrical makes it difficult for the sensor itself to cause corona discharges.

3-2 Repeater

The appearance and main specifications of the repeater are shown in Photo 2 and Table 3, respectively.

Photo 2. Appearance of Repeater

Table 3. Main Specifications of Repeater

Item	Specification
Power supply unit	Solar panel: 12 V-15.5 W × 1 piece
	Battery: 12 V-38 Ah × 1 unit
Communication interface	920 MHz band radio
	GNSS
External interface	Serial (for weather sensor)
Dimensions	W350 × H500 × D365 mm (excluding protruding portions)
Weight	Approx. 30 kg

The repeater is installed on one of the legs of the steel tower and is independently powered by a solar panel or battery.

A multifunctional weather sensor is used to measure the local weather around the steel tower, which is important for dynamic rating. This sensor can measure wind direction, wind speed, ambient temperature, solar radiation, rainfall, and so on. The repeater transmits the data collected by the weather sensor to the aggregator wirelessly.

Since the repeater comprises a GNSS*[9] receiver, it can acquire and use time information and other pieces of information.

3-3 Aggregator

The flow of sensor data is shown in Fig. 3. The aggregator transmits the data sent from the temperature/current sensor and local weather data sent from the repeater to a calculation/data storage server. A highly secure network that transmits the data to the server without using public lines can also be built by using LTE or connecting the aggregator to an OPGW network or other closed network with a media converter (MC).

The calculation/data storage server calculates the allowable current in dynamic rating from the sensor data. Figure 4 shows the flow of allowable current calculation by the calculation/data storage server. The weather forecast data distributed by weather providers are separated by specific distance intervals and are averaged for each area. Therefore it often differs from the weather of the area where the observation target is located. The newly developed system compares the forecast data with the field measurement data transmitted by the repeater from the weather sensor installed on the steel tower, and feeds the difference back to the forecast data for correction. The predicted allowable current based on corrected weather forecast data is verified using the actual allowable current calculated from field measurement data and repeating this makes it possible to optimize the correction.

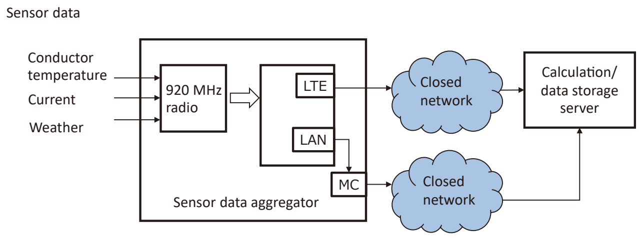

Fig. 3. Block Diagram of Aggregator

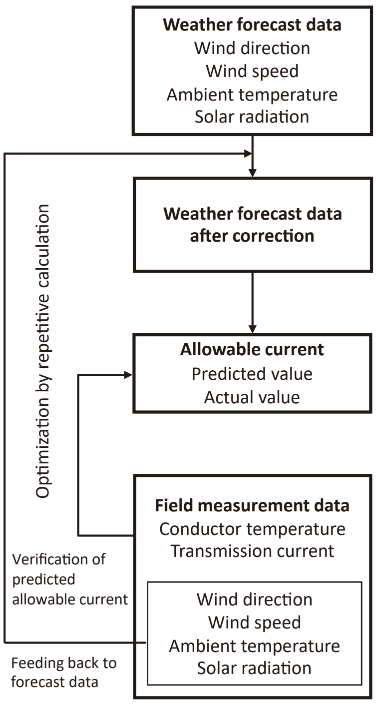

Fig. 4. Calculation of Allowable Current

4. Performance Evaluation

The developed devices and system were evaluated in-house mainly for basic performance, and then the system was installed in an overhead transmission facility of a power transmission and distribution business operator for demonstration tests. This chapter describes the evaluation items and results.

4-1 Performance evaluation for temperature/current sensors

Figure 5 shows the evaluation results for the accuracy of the current measurement unit. The accuracy of the Type 1 unit was 1% or less until the current reached 1,200 A, while that of the Type 2 unit was 2% or less until the current reached 3,200 A. As a result, it was confirmed that both the Type 1 and Type 2 units achieve the target accuracy.

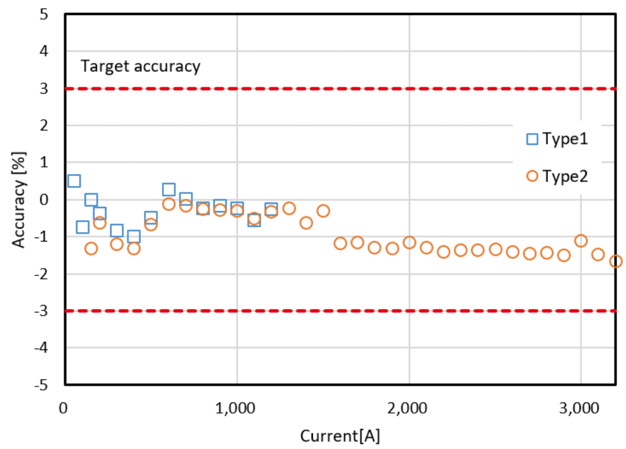

Fig. 5. Accuracy of Current Measurement Unit

Figure 6 shows the evaluation results for the responsiveness of the temperature/current sensors in conductor temperature measurement. This evaluation was conducted on the supposition of output fluctuation in N-1 generation control and renewable energy generation. In the evaluation, a current of 840 A was passed through the transmission line until its temperature remained constant. Then the current was instantly increased to 1,160 A to measure the change in conductor temperature. Figure 6 shows the measurement results and compares them with the calculation results.

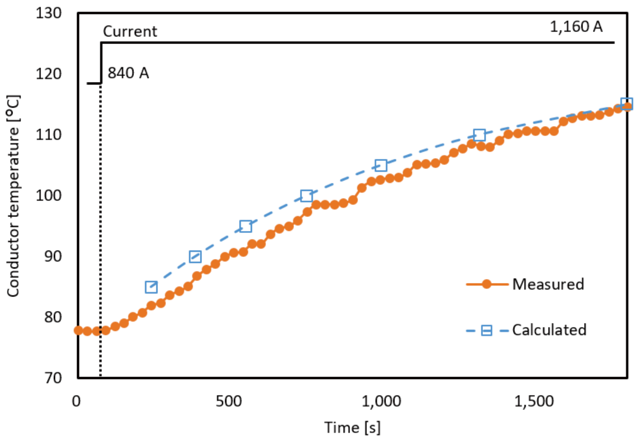

Fig. 6. Responsiveness of Temperature Measurement Unit

The conductor temperatures used for the comparison were calculated from the equation shown in Reference (6) for the relationship between conductor temperature change and time under transient conditions. An emissivity of 0.9, ambient temperature of 27°C, solar radiation of 0 W/m^2, and wind speed of 0 m/s were used as the calculation conditions. The measured temperatures were virtually equal to the calculated values, verifying that both the responsiveness and accuracy are acceptable.

4-2 Communication performance evaluation

Figure 7 shows the in-house evaluation results for the distance characteristic of the received signal strength of the temperature/current sensor. Even when the distance between sensors was 1 km, their received strength had a sufficient margin. This verified that communications between sensors can be made over a distance of 2 to 3 km in a real environment. It was also confirmed that the sensor ensures stable communications even when the number of devices comprising a network is 10 or more.

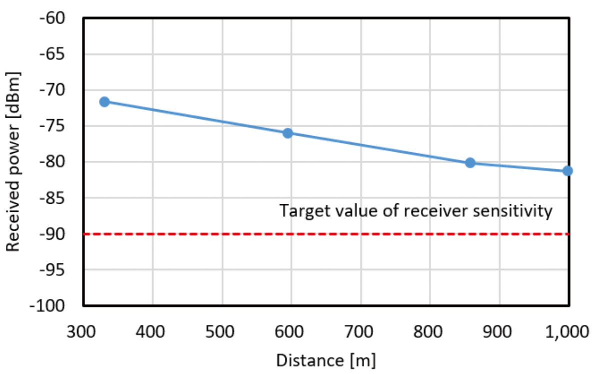

Fig. 7. Distance Characteristic of the Received Signal Strength of Temperature/Current Sensor

4-3 Dynamic rating

Figure 8 shows, as an example of the calculation of allowable currents in dynamic rating, the allowable current predicted from weather forecast data, the actual allowable current calculated from field-measured weather data, and the allowable current calculated based on conventional severest conditions. The weather forecast data were corrected as shown in Fig. 4. The accuracy of the predicted allowable current is important for power system operation, and during most hours this current is needed to be calculated so that it will not exceed the actual allowable current. In the demonstration test, the capacity increased by approximately 30% and the predicted allowable current was confirmed to be generally smaller than the actual allowable current with a probability of 95% or more.

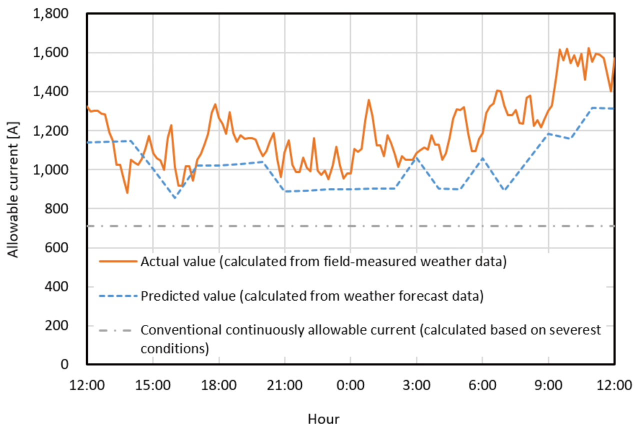

Fig. 8. Comparison of Allowable Current

4-4 Test for interconnection with IED

The use of aggregated sensor data is not limited to the calculation of allowable currents in dynamic rating. Our aggregator also supports IEC61850, which has become popular in recent years as an international standard protocol for automating the operation of electric power facilities. Using IEC61850 GOOSE,*10 we conducted a test for interconnectivity between our aggregator and an IED,*11 which supports this protocol. As a result, it was confirmed that two-way communications can be made between both devices.(7) Effective use of sensor data will enable IEDs and the facility control systems to which they are connected to achieve more advanced control than before.

5. Future Prospects

There are various issues such as the aging of overhead transmission facilities and a shortage of maintenance personnel, in addition to power system congestion associated with an increase in renewable energy as described above.(8)

Our overhead transmission line monitoring system uses a repeater and a weather sensor to acquire weather data around the steel tower. Using a variety of other sensors and devices, this system can also acquire environmental data other than weather data. Acquisition and accumulation of data over a long period of time and their analysis can improve the maintenance and preservation efficiency of power transmission facilities.

6. Conclusions

In this paper, we have discussed the features of the overhead transmission line monitoring system we have recently developed. Carbon neutrality and the introduction of a large amount of renewable energy to achieve carbon neutrality are becoming a worldwide trend. As the environment surrounding energy changes, the use of sensing technology, IoT, and AI technology become increasingly important in the operation of power systems. Under these circumstances, we will address the need for the implementation of dynamic rating and various other technologies.

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Technical Terms

*1 Rationalization of estimated power flow: The maximum power flow to be used as the reserve capacity calculation condition has traditionally been assumed based on the condition that maximizes the power flow. The rationalization of estimated power flow is the act of expanding the reserve capacity by assuming the power flow under more actual conditions.

*2 N-1 generation control: Many transmission systems consist of two channels to reserve some capacity on each channel for accidental failures of one of the channels. N-1 generation control is a method of expanding transmission capacity. A power supply controller is installed to instantly control the output in the event of a failure and thus to use ordinarily the capacity reserved for an emergency.

*3 Non-firm connection: A method of making full use of the transmission capacity of power systems by transmitting the power from renewable energy sources when the power systems have a reserve capacity, while controlling the output when the power systems' capacity is used up.

*4 OPGW: An abbreviation for composite fiber optical overhead ground wire.

*5 ACSR: An abbreviation for aluminum conductor steel reinforced.

*6 TACSR: An abbreviation for thermal-resistant aluminum alloy conductor steel reinforced.

*7 Corona discharge: An aerial discharge phenomenon that occurs mainly during rainfall from the tip of a waterdrop adhering to the surface of a transmission line.

*8 Electric potential gradient: The slope of electric potential directed outward from a transmission line.

*9 GNSS: An abbreviation for global navigation satellite system.

*10 GOOSE: An abbreviation for generic object-oriented substation events, one of the communication systems defined by the IEC61850 standard.

*11 IED: An abbreviation for an intelligent electronic device, a protection controller for multi-functional and programmable power system equipment.

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