Phasor-based Monitoring System Employing Real-Time Ethernet

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Summary

The purpose of this study was to produce a prototype phasor-based real-time monitoring system for small-scale power systems such as microgrids. This paper describes the architecture and performance of a monitoring system consisting of a real-time communication network, phasor measurement units, and a phasor data concentrator. For the communication network, we adopted TCnet, a real-time industrial Ethernet, which is an international standard for field-bus technology in industrial automation (IEC61784-2/61158). The prototype uses five phasor measurement units and a PC as the phasor data concentrator, linked by TCnet in the high-speed scanning mode. As a result, the scanning data was transmitted within 200 microseconds, demonstrating the real-time transmission capability of our phasor-based monitoring system using TCnet. The architecture is suitable for adoption not only in microgrids, but also in general power systems, including substation automation.

KEYWORDS

Phasor, Synchrophasor, Microgrid, Wide area monitoring system, Real-time Ethernet, TCnet, PMU, Distributed generation, Power quality

1. INTRODUCTION

The work presented here relates to a phasor-based real-time monitoring system employing real-time Ethernet. In recent years, the environment surrounding power systems has been changing due to deregulation of the power industry and the increasing adoption of distributed generation. Some small-scale power networks with renewable energy and battery storage have been proposed and developed, such as microgrids [1]. For such small-scale networks covering a limited region or site, optimal supervisory and control systems are required, as well as efficient power quality monitoring systems. In EHV transmission, wide-area monitoring systems based on synchrophasors have gradually been becoming more widespread, and various applications of phasor measurement units (PMUs) and phasor data concentrators (PDCs) have been suggested [2][3]. The concept of wide-area monitoring systems can also be useful in small-scale power networks because synchrophasors have a great potential and the configuration of the monitoring systems consisting of PMUs and a PDC has an important advantage over traditional monitoring systems.

Various methods based on synchronized phasors have been examined by other researchers, and a number of applications in wide area monitoring, protection and control have been developed in recent years. To the best of our knowledge, however, there has been little research on phasor- or synchrophasor-based real-time monitoring systems and real-time control systems with high reliability. (Here, the term "real-time" means that the phasor arrives at destination nodes within a predictive time.) Although post-event analysis and steady-state estimation for power system modeling do not need synchrophasor real-time transmission because of their accurate time tag, time-critical monitoring, such as angle/frequency monitoring, voltage stability monitoring and various protection/control functions, requires real-time transmission and reliability.

This paper describes a prototype phasor-based real-time monitoring system for small-scale power systems such as microgrids. Microgrids need control and monitoring to balance supply and demand within the microgrid and improve power quality. We present an architecture and performance results of a monitoring system consisting of a real-time communication network, phasor measurement units and a phasor data concentrator. For the communication network, we adopted TCnet, a real-time industrial Ethernet. Key requirements for such industrial automation networks include deterministic data-communication responses, openness, and low cost. TCnet has been developed to meet these needs and provides reliable control networks for industrial automation systems, such as control systems in iron and steel plants.

In the prototype monitoring system, TCnet allowed broadcasting of voltage phasors, current phasors, and equipment information at high speed and in real time to all nodes. These nodes included phasor measurement units and phasor data concentrators installed over a span of several kilometers. The prototype system had the following three distinctive features: scanning transmission and common memory, redundant communication lines, and synchrophasor.

The performance of the proposed system was evaluated in our laboratory and in the field. We have been conducting field tests in an urban apartment building that has three kinds of distributed power supply: a gas engine, photovoltaic cells, and a lead acid battery. The performance was sufficient to construct control and monitoring systems for small-scale power systems. In conclusion, our phasor-based monitoring system using TCnet was capable of real-time phasor transmission with high reliability.

In Section 2 we present the background of our study, in Sections 3 and 4, we deal with the monitoring system architecture and features, in Section 5, we discuss the performance of the prototype system, and finally, we comment on the usefulness of this study.

2. BACKGROUND

In Japan, multiple field tests are demonstrating the technical feasibility of microgrids with a focus on incorporating renewable energy while maintaining constant grid inflows, and on providing multiple levels of power quality and reliability. A microgrid with electrical storage and gensets is expected to be capable of fully compensating for its intermittent renewable supply and presenting itself to the grid as a constant load. In order to achieve this, the microgrid energy control center communicates with and controls the distributed energy resources to balance demand and supply. As a result, imbalances can be rectified, for example, at 5-minute time-steps. Although microgrids are expected to be adopted as future power system configurations providing environmental benefits, they still need thorough economic evaluation. Information and communication technologies are useful in addressing these issues.

From around 2000, the technology called "Industrial Ethernet", designed to have real-time capabilities and high reliability, was developed to apply low-cost, high-speed Ethernet technologies to the controller networks in measurement and control systems. Furthermore, specifications which provide improved real-time features were developed and released around 2003 [4]. The system is currently called "Real-Time Ethernet" (RTE), and the IEC has published an international standard regarding the specifications of RTE in December 2007. The RTE profiles have various specifications, such as PROFINET IO, Vnet/IP, EtherCAT, TCnet, and so on.

TCnet, one of the profile families (IEC 61784-2 CPF11 / IEC 61158 Type11), is more suitable for middle-scale and high-speed applications between Factory Automation and Process Automation. Realization schemes of the real-time features of RTE and Industrial Ethernet are classified into Best-effort class, Priority control class, Token control class, and Clock synchronization class [5]. TCnet is classified as the Token control class, where each node synchronously communicates by means of token rotation scheduling in the MAC layer.

As a consequence of the technical innovation within Ethernet, it is possible to achieve a real-time feature using the Best-effort class, which communicates at a high transmission rate, buffering on a switching-hub with full-duplex transmission. However, improving the accuracy of delivery time requires certain functions, including a mechanism for synchronizing the clock time or the timing of each node on the network. Furthermore, the important feature of RTE is its ability to use standard TCP/IP communication. These features ease the realization of a monitoring system suitable for power systems because the monitoring system must have the capability to communicate time-critical information such as phasor values and control signal transmission and at the same time, low-speed communication such as message transmission (setting values, adjusting values and so on).

3. SYSTEM CONFIGURATION

Fig. 1 shows the configuration of the prototype monitoring system and a typical microgrid. The microgrid consists of several distributed energy resources (DERs) and loads interconnected through an electrical network, such as 6-kV distribution lines covering several kilometers. Moreover, the microgrid is connected to a large power grid at a single point of common coupling (PCC). The monitoring system consists of PMUs, a communication network using TCnet, a supervisory PC serving as a PDC, and a programmable logic controller (PLC) for monitoring and control. The PMUs measure the voltages and currents from the DERs and monitor load currents and voltages. These voltages and currents are converted to a phasor format at the PMUs and are then transmitted to the PDC. The PDC executes predicting processing to balance supply and demand within the microgrid, using phasors from these PMUs. The PDC also monitors power quality indices of the microgrids, such as voltage sag, frequency, active power, and reactive power. These power quality indices are computed in real time by using the phasors from the PMUs. The PLC controls each DER using the processing results of the PDC.

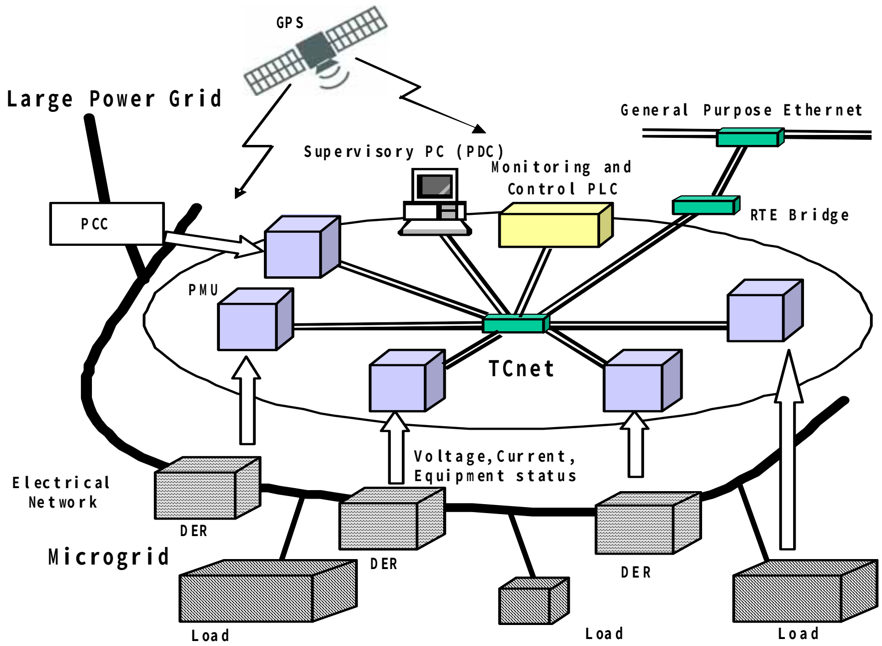

Fig. 1. System configuration.

TCnet, which is certified as international standards IEC 61784-2 CPF11 and IEC 61158 Type11, provides real-time transmission and sporadic message transmission. As shown in Fig. 2, the real-time transmission is provided by a real-time extension function located in the TCnet MAC layer to avoid frame collisions on the physical connection medium. Sporadic message transmission supports standard TCP/IP and UDP/IP protocols. By using a real-time Ethernet bridge for seamless connection between the segments of the TCnet and a general-purpose Ethernet network, various standard Ethernet devices are able to communicate with the TCnet. In the application layer, a so-called “Common Memory” is shared over the network by the time-critical applications at each node.

Each PMU, which we have been developing as a network computing terminal [6], consists of a real-time part and a network part. In the real-time part, the PMU samples analog input data, computes and transmits phasors and equipment status to the PDC in real-time. In the network part, the PMU has a network function so that it can communicate with a server, a general-purpose browser, or other PMUs and the PDC using standard Ethernet protocols, such as HTTP, SMTP and so on. The TCnet control chip interfacing each part and the transmission medium is implemented as an ASIC.

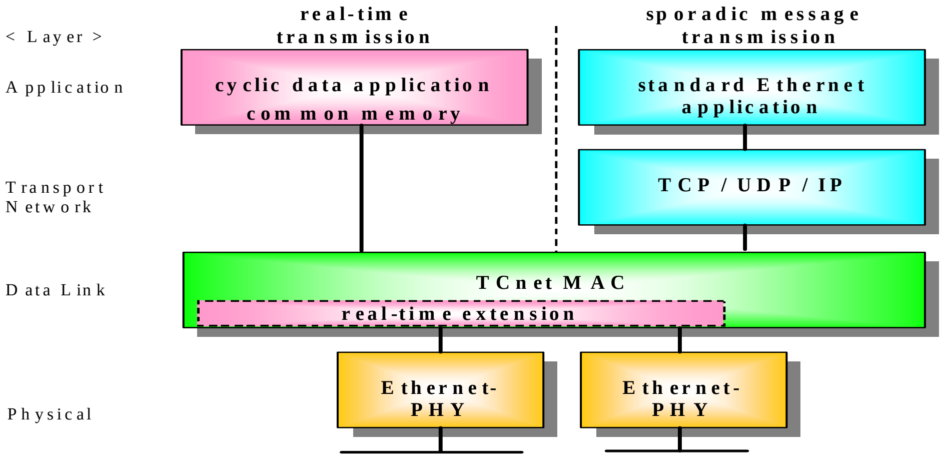

Fig. 2. Architecture of TCnet.

The supervisory PC has a TCnet communication function and a PDC function and collects phasors from the PMUs. It is an off-the-shelf PC consisting of a 2.3 GHz processor and 1 GB RAM, running Microsoft® Windows® 2003 Server.The monitoring and control PLC, having a TCnet communication function, can control the outputs of the DERs.
In the system configuration, the common memory and its management are the key functions supporting real-time operation. The common memory on the TCnet is shared logically by all TCnet nodes, that is, the PMUs, PDC, and PLC, and is physically implemented with 256 kbytes at each node. Therefore, all nodes can share real-time data via the common memory. At each node, 128 bytes of common memory is assigned as one block, and two or more blocks are used for data transmission. The PMU computes three voltage and three current phasors and transmits the computed data in a phasor or synchrophasor format, including data like CHK field in IEEE C37-118. Because phasor operations and the write timing to the common memory are not synchronized with the timing of the scan transmission, a node assigns two blocks within the common memory and writes the same data continuously to the two blocks.

4. OUTLINE OF THE KEY TECHNOLOGIES

Microgrids require monitoring and control to balance supply and demand and to improve their power quality.The prototype system adopts the following key technologies to meet these requirements.
1) Real-Time Data Transmission and Common Memory
As shown in Fig. 3, the data to be transmitted are ordered based on four priority levels: high-speed, medium-speed, and low-speed cyclic data are transmitted using a real-time transmission mode, and sporadic message data are transmitted using a non-real-time transmission mode. The scheduling mechanism in the data link layer follows a token passing protocol. At the start of the high-speed transmission period, a SYN (SYNchronize) frame is broadcasted to all nodes. After the SYN frame, each node holding a transmission right can send its data within a preset time which depends on the system configuration. The high-speed transmission period is the period at which SYN frames are broadcast, and the medium-speed or low-speed transmission period is a multiple of this period. The sporadic message transmission used by standard Ethernet applications has no adverse effect on the real-time transmission capabilities.
The transmission period for each real-time transmission priority level is configurable. It is necessary to satisfy equation (1) in consideration of the number of nodes, the total scan data volume, and the margin for the sporadic message transmission:

$$T_H > (T_{SYN} + T_{SCAN} + T_{MAC} + T_{DELAY}) / (1 - R_{margin})$$
$$T_{SCAN} = T_{Frame} \times (N_H + N_M / T_M + N_L / T_L) \qquad \text{.............................(1)}$$

where:
TH, TM, TL: High-speed, medium-speed, low-speed transmission periods;
TSYN: transmission time of the control frames;
TSCAN: total scan time in a high-speed transmission period;
TMAC: MAC control time of TCnet control chip;
TDELAY: total transmission delay between nodes;
Rmargin: margin rate for the sporadic message transmission, 0.25 (25%) or more;
TFrame: transmission time of frame data;
NH, NM, NL: number of blocks for high-speed, medium-speed, and low-speed transmission.

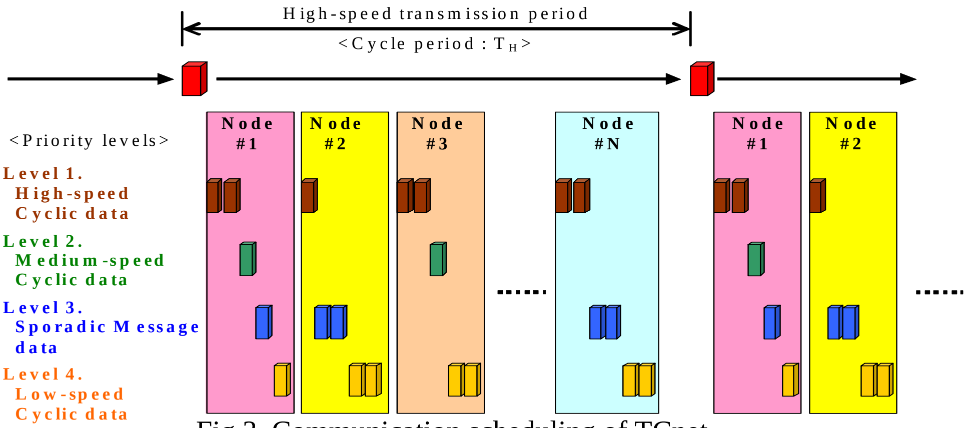

Fig.3. Communication scheduling of TCnet.

Fig. 4 shows the concept of real-time transmission with the common memory. The common memory is divided into two or more blocks, which are dedicated areas for each node, according to the size of the memory. The data for each block are transmitted from a publish node to the member nodes using scan transmission, which means constant-cycle broadcasting within each transmission period, allowing the block data to be quickly refreshed. With this configuration, all nodes hold the data with temporal and spatial coherence within the common memory. Thus, the application program in each node has easy access to all data within the memory. Because the application software only writes and reads the data to be refreshed within the common memory and does not need to consider the scan transmission process, real-time transmission can be achieved with a lower specification processor, and the cost of developing the monitoring system can be reduced. Moreover, from the point of view of effective bandwidth utilization for networking, it is useful that time-critical data like the synchrophasors can be transmitted using the real-time transmission mode when non-time-critical data, like the configuration frames specified in IEEE C37-118, are transmitted using the sporadic message transmission mode.

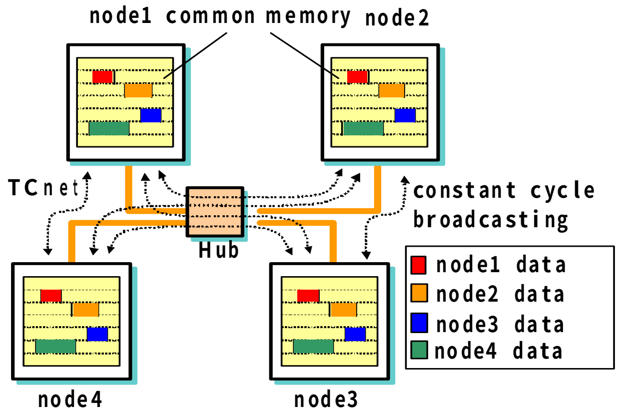

Fig. 4. The concept of real-time transmission with a common memory.

2) Redundancy Communication Channel

TCnet is able to handle redundant transmission mediums (Medium-A and Medium-B) in parallel. As shown in Fig. 5, the TCnet control chip transmits a frame to both mediums and receives a frame from either Medium-A or Medium-B. The TCnet control chip monitors the status of each medium and refreshes the common memory with the frame from one of the healthy media. Therefore, the application software does not need to deal with this task. When a communication failure occurs on one of the mediums, transmission continues on the healthy medium by switching to the healthy channel without interruption, under the control of the TCnet control chip. This means that the recovery time of TCnet is effectively zero. Such redundancy is important in monitoring and control systems for power systems in order to ensure high reliability and reduce the operating and maintenance costs.

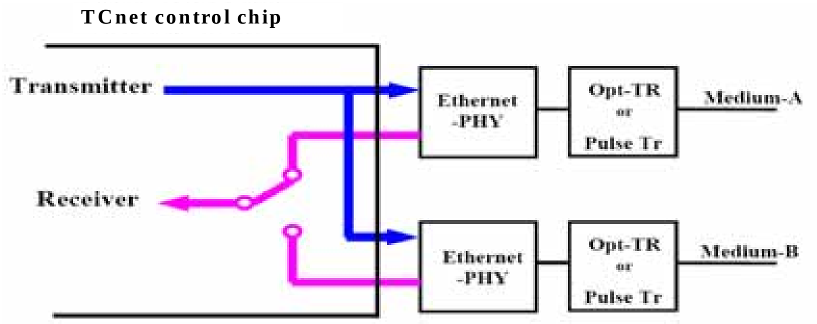

Fig. 5. Redundant transmission mediums of TCnet.

3) Synchrophasor

Because TCnet is not of the clock synchronization class in the Industrial Ethernet family, it is important to check the time tag included in the synchrophasor data block from each PMU at the PDC. The PMU outputs the voltage and the current phasor to TCnet in the form of a synchrophasor block. The momentary synchrophasor phase angle relative to the cosine function of the UTC (Coordinated Universal Time) timing is obtained by using the 1PPS (1 pulse per second) signal output from the GPS receiver. In the prototype system, the PDC, that is, the supervisory PC, collected the voltage and current phasors from each PMU using the real-time transmission mode and calculated the active and reactive power of the DERs and loads. Because the transmission timing of TCnet is not synchronized with the GPS clock and the synchrophasor calculating software of the PMU cannot control the transmission timing the supervisory PC was used to check the time tag of each synchrophasor block. If no synchrophasor blocks had the same time tag, the PC application would again check the next block received to obtain the synchrophasor data with the correct time tag. In the future, when the transmission timing of the TCnet synchronizes with a precise clock and the TCnet control chip provides a time tag and sampling signal, it will not be necessary to connect the GPS receiver to each PMU and the supervisory PC can easily collect synchrophasors without performing a check on the time tag..

Not all applications for power systems have precise time requirements of less than 1 μs. Timing accuracy requirements vary by application, typically from seconds to microseconds. Our proposed TCnet system provides options, namely synchrophasors with high-accuracy timing or phasors with middle-accuracy timing, ranging from sub-milliseconds to milliseconds. That is to say, when considering the tradeoff between cost and accuracy, users can implement a phasor-based monitoring system with middle-accuracy without using GPS, while ensuring real-time transmission. Even in this case, the use of phasors allows the PDC applications software to be quickly developed and easily maintained. As a result, various protection and control applications based on phasors can be flexibly developed because the network is capable of real-time phasor transmission and high reliability.

5. PERFORMANCE RESULTS

In the laboratory, we first measured the transmission time between the PMU and the PDC on TCnet. The experimental PMU transmitted three voltage and three current phasors when the size of the transmission data was 256 bytes, corresponding to two blocks in the common memory. With the high-speed transmission mode (T_H = 1 ms), the measured transmission time was less than 180 μs. Second, with two or more PMUs, the transmission time increased by about 15 μs for each PMU added to the network. Third, with the medium-speed transmission mode (T_M = 5 ms), we measured the accuracy of the transmission period. The time period was kept at 4.75 ms, equal to 95% of the setting value of T_M = 5 ms. The remaining 5% was a margin provided for a large volume of traffic in sporadic message transmission. Actually, the sporadic message transmission for the supervisory PC to obtain setting data and event log files whose size was 1MB from these PMUs had no adverse effect on the accuracy of high-speed transmission period. Finally, from the results, we designed a prototype system with a maximum of 64 PMUs to operate in the real-time transmission mode.

In field tests have been conducted since 2007, we measured the electric power supply and demand in an apartment building located in an urban area. The apartment building was equipped with a gas engine generator, photovoltaic cells, and a lead acid battery. The electric power from these devices and the electric power received from the utility company was supplied to loads such as each homes, elevators, and water supply pumps. Installed each of the five PMUs in these DERs, an inverter, and the PCC, we measured the balance of the power supply and demand and the power quality within the microgrid. Fig. 6 shows an example of the active and reactive power measurement at one of the DERs. This measured data on TCnet and the system status are usually gathered by a remote monitoring PC via the Internet and the real-time bridge.

Using the measurement results, the microgrid was controlled at five-minute intervals to balance power supply and demand so that their difference was less than ±0.5 percent of planned demand value, to keep the voltage at the connection point between the microgrid and power system constant. It was confirmed that the real-time data transmission by the TCnet enabled highly accurate measurement and control, at the set transmission cycle, even though a large quantity of messages flowed in the background.

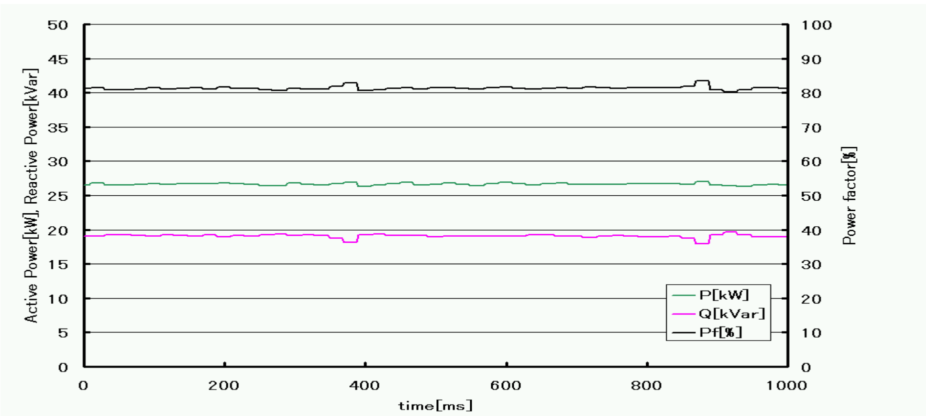

Fig.6. Example measurement results.

6. CONCLUTIONS

We have introduced a phasor-based monitoring system employing real-time Ethernet and evaluated its performance. In the prototype monitoring system for a microgrid, TCnet, one of the family of real-time Ethernet profiles, allowed broadcasting of voltage and current phasors, and equipment information at high speed (less than 5 ms) and in a predictive time to all nodes. Synchrophasors at all nodes using a GPS receiver were easily shared within the monitoring system. The time-deterministic transmitted synchrophasors that we present will enable the practical realization of various protection and control applications, not only in small-scale power system monitoring for balancing supply and demand, but also in flexible protection and control schemes whose software configuration can be easily changed according to user requirements.

7. ACKNOWLEDGEMENT

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