This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2019.2940668, IEEE Transactions on Industry Applications

Design of an Industrial IoT-Based Monitoring System for Power Substations

Long Zhao, Student Member, IEEE
Igor Matsuo, Student Member, IEEE
Yuhao Zhou*, Student Member, IEEE
Wei-Jen Lee, Fellow, IEEE
University of Texas at Arlington, 701 S Nedderman Dr, Arlington, TX 76019, USA
long.zhao@mavs.uta.edu, matsuoigor@gmail.com, yuhao.zhou@mavs.uta.edu*, wlee@uta.edu

***Abstract* -- The Internet of Things (IoT) concept allows objects to share data through wired or wireless connections for communication purposes. The Industrial Internet of Things (IIoT) is an extended concept of IoT that refers to an integration of data acquisition, communication, and processing on a real-time network. Currently, IIoT has been involved with the development of smart grids in many applications. As the operation of power systems is extremely time-critical, low-latency communication needs to be considered for most control and monitoring applications. Real-time capability of IoT is considered as a key feature for monitoring and control applications of power systems. Therefore, system operators can use the real-time monitoring system to provide better decisions for both technical and financial-related matters. In this paper, a high-speed IIoT-based monitoring system with recording functions is developed and implemented for a power system substation. Due to the high reliability and processing speed of FPGAs, an FPGA-embedded controller is adopted in this system. The IoT platform also provides remote visualization for system operators in real time. This paper mainly aims to provide a practical application that was implemented and tested in a real power substation. The system incorporates the features of an IoT platform with the needs of high-speed real-time applications while using a single high-resolution time source as the reference for both steady-state and transient conditions.**

***Index Terms*-- Field-programmable gate arrays, Internet of Things (IoT), Industrial Internet of Things (IIoT), Remote Monitoring, Real-time systems, Smart grids.**

I. INTRODUCTION

Internet of things (IoT) was first proposed in 1999 by Kevin Ashton, and it has been applied in different areas such as health, agriculture, traffic, and power grids [1-4]. The purpose of IoT is to use networks to build connections among objects while reducing time and location limitations [5]. The Industrial Internet of Things (IIoT) has been applied in various industrial areas. IIoT can be understood as an embedded system using a real-time network to promote the operation of manufacturing processes [6]. In this case, the real-time system is defined as "the system in which the correctness of the system does not depend only on the logical results of computation but also on the time at which the results are produced. It has to perform critical tasks on a priority basis keeping the context switching time minimum. [6]". Due to the real-time capability of the IoT, many monitoring and control systems have adopted IoT in various fields. In paper [1], an electrocardiogram (ECG) remote monitoring system has been proposed with the IoT platform. The purpose of this system is to monitor long-term health conditions for patients at the residential level. This IoT-based wearable ECG monitoring system provides accurate ECG signals with lower power consumptions. Paper [2] introduces an IoT solution for online monitoring of anesthetics in human serum. The electrochemical approach and simultaneous detection have been discussed in the paper. By using the IoT platform, the patients' measured parameters could be monitored by the medical doctor in real-time with mobile devices. Paper [3] shows an IoT-based long-term wearable device to monitor the mental wellbeing. Multiple signals are collected and analyzed with the IoT platform. Paper [7] presents a WSN platform for IoT environmental monitoring applications, and the applications requirements and the exploration of possible solutions are discussed. In paper [8], an IIoT-based condition monitoring system is developed for a large-scale and continuous device. In this development, the new technology has been seamlessly integrated with the existing infrastructure to provide data collection and analysis. In paper [9], an IoT-based online monitoring system for steel casting is developed, and four layers of IoT system architecture including sensing, network, service resource, and application layers have been integrated. Paper [4] presents an IoT-based control system for smart precision agriculture and farming in rural areas, and the overall performance can be enhanced from energy and delay perspectives. IoT has also been largely applied to the electric power and energy systems in all levels [10-15]. In paper [12], IoT is applied for a smart grid application to access real-time data for transformers to improve the reliability, performance, efficiency of the substation. In paper [13], a set of sensors are implemented at a power substation with IoT platform to promote the temperature monitoring standard in the industry. Paper [14] introduces a low-cost energy monitoring and control system using IoT devices. Paper [15] presented an IoT-based solution for home power energy monitoring.

Power substations are the interface between important parts of the power grid and are responsible for many critical operations, such as stepping-up and stepping-down the voltage level. Due to the importance of electrical substations, different types of monitoring systems have been developed. In paper [16], a visual monitoring system is developed for remote operation of an electrical substation to provide environmental viewing for system operators. Paper [17] presents an online monitoring system for high voltage equipment at a substation which could help system operators have a better understanding of the related equipment. Paper [18] proposes a new supervisory monitoring system for substations to identify errors in digital switching. Paper [19] proposed a real-time monitoring system for substation grounding potential rise under power system fault conditions. The authors of the paper [20] developed a real-time monitoring system at a substation to detect low-frequency power oscillation on tie-lines. Paper [21] shows a real-time monitoring system for transformers at a substation using a database application. Paper [22] developed a sensing monitoring system for substation equipment based on IoTs.

The motivation for the proposed development is to better help system operators understanding the system conditions using IoT platform and an integrated real-time monitoring system. In this manner, we can use a single device to efficiently capture both steady-state conditions and transient phenomena of the power system.

A high-sampling rate IIoT-based monitoring system with data logging functions is developed and implemented to monitor various critical parameters, including voltage, frequency, real power, reactive power, circuit breaker status, and transformer temperatures in power substations. Meanwhile, as an IoT application in power and energy systems, cybersecurity methods are introduced and implemented in this paper. The developed system has been implemented and installed at a power substation recently, and it has successfully detected and recorded the first fault event. The system operators have utilized the recorded data for further analysis so as to take the necessary actions.

This paper aims to show a practical development of an IIoT-based real-time monitoring system with high sampling rate for monitoring and control of substations. With this developed system, system operators can remotely monitor the overall conditions in both steady-state and transient conditions of the power substation. High-speed sampling and lossless data logging provide more detailed data for both online and offline analysis. In section II, the framework of the monitoring system is introduced. Section III presents the communication and data processing of this monitoring system. Section IV presents the cybersecurity setup, section V shows the field testing and application, and section VI discussed the novelty of the developed monitoring system. The conclusion of this paper is shown in section VI.

II. Framework of the IIoT-based Monitoring System

As one of the unique characteristics, IoT should have the capability to process and analyze data in real-time with very low latency [11]. A real-time monitoring system in power substations can provide system operators with the overall conditions of the monitoring objects so that the reliability of the system and efficiency of the operation can be enhanced. In this paper, an industrial-standard Field-Programmable Gate Array (FPGA) embedded controller with Linux operating system (OS) is programmed to collect voltage, real power, reactive power, circuit breaker status, and transformer temperature data with different sampling speeds in real-time. The FPGA is made of reprogrammable silicon chips which have more powerful computing ability and faster response speed comparing with digital signal processors (DSPs) [23], [24]. Currently, many studies have shown different implementations with FPGA technology. In paper [25], the authors designed an FPGA-based waveform character searching technology. A Kintex-7 chip of Xilinx with 34Mb internal RAM is adopted in their research. In paper [26], the authors discussed the FPGA technology for high-performance computing platforms. Communication-oriented and computation-oriented FPGA technologies are presented in the paper. In paper [27], a 3D FFTs and implications for molecular dynamics are developed on FPGA clouds to improve the performance. Also, a hardware generator is developed on FPGA to be applied for high-performance designs in paper [28].

In the power system, many analyses and studies require high-speed sampling frequency, such as signal frequency domain analysis and transient study analysis. Because the processing operations on FPGAs are entirely parallel without competing for the same resources, FPGAs have huge advantages for high-speed multiple-input-and-output (MIMO) applications. Meanwhile, the hardware execution has better determinism than most processor-based software solutions, and jitter issues of software execution can be eliminated, which is extremely helpful for a real-time system with high-sampling speed. Therefore, data acquisition and detection mechanisms are programmed on the FPGA target in this system to have a reliable and high-speed performance.

However, due to some technical limitations, some complex functions and communication functions such as sorting and searching methods or floating-point arithmetic cannot be solely realized on FPGAs. Therefore, processor-based devices are still needed. As a result, an FPGA target and a processor-based target combined could compensate each other and provide the most optimal performance for high-speed real-time monitoring systems with multiple I/Os. In this system, an industrial-standard controller with 1.91 GHz Quad-Core CPU, 2 GB DRAM, 16 GB Storage, Kintex-7 325T FPGA, and an RJ-45 Gigabit Ethernet port is used which is shown in the Fig. 1 [29]. As it is shown in Fig.1, three different input modules are applied with the controller. The analog input 1 is a DC + 10V 16-bit analog input module which has absolute accuracy 6230 μV at full scale [30]. The analog input 2 is an AC 300Vrms, 24-bit simultaneous analog input module with 2mVrms input noise, 50kS/s maximum data rate range using internal master timebase [31]. The digital input is a 24V sinking digital input module [32].

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2019.2940668, IEEE Transactions on Industry Applications

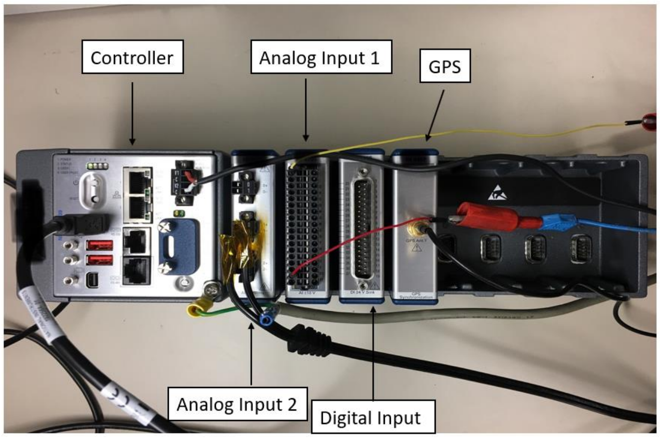


Fig. 1. FPGA Embedded Controller

In this IIoT-based monitoring system, a Network-Attached Storage (NAS) is adopted as the repository to store data and to enable remote access. Comparing with the direct-attached storage (DAS) and storage area network (SAN), NAS is file storage that can be accessed by multiple authorized users and heterogeneous client devices to retrieve the data in different categories from a centralized location in the network [33]. In this way, the system operator can retrieve the desired data based on the time and necessities using the network with a username and password.

As it is shown in Fig.2, inside of the substation, the FPGA-embedded controller, a host computer and the NAS are connected to a hardware firewall through ethernet cables. A computer in the control room receives the data in real-time. In this section, the structure of the system is introduced in sequential order of the data flow in the system.

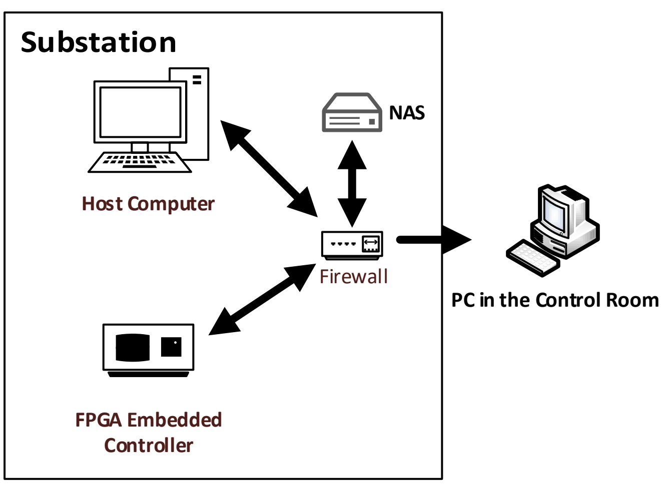


Fig. 2. Framework of IoT-Based Real-time Monitoring system

A. Data Acquisition

To acquire different types of input data with different sampling rates, three types of input modules are adopted in this system as shown in Table I. All data will be collected and processed on the FPGA. To have the high-resolution data of voltage and frequency signals for detailed analysis, AC analog voltage signals are sampled with 2000 samples/second. Real power, reactive power and transformer temperatures signals are converted by transducers. Power, temperature and circuit breaker status signals are acquired with sampling speed 10 samples/second.

TABLE I
DATA ACQUISITION MODULES AND SAMPLING RATES

Module Type	Measurement Objects	Sampling Rate
AC Analog Voltage Input Module (- 300 to 300Vrms)	Voltage and Frequency	2000 S/s
Analog Voltage Input Module (-10 to 10V)	Real Power, Reactive Power and Transformer Temperatures (Transducers)	10 S/s
Digital Input Module	Circuit Breaker Status	10 S/s

To acquire the system frequency f (Hz), the zero-crossing method [34] is used to find the period T(s) of the input voltage and to calculate the system frequency based on (1).

$$f\ (Hz) = \frac{1}{T} \tag{1}$$

Once the predefined events such as over-voltage, under-voltage, over-frequency, under-frequency, and transformer overheating are triggered, the sampled data will be recorded by the controller and sent to a NAS which can be accessed by the system operator anytime from the Local Area Network (LAN).

B. Timestamps and Synchronization

As a real-time monitoring system with high sampling speed, both high resolution and accurate time sources are also required. As an IoT-based monitoring system for power substations, cybersecurity is a critical factor which needs to be considered. One of the most commonly applied networking protocols for clock synchronization Network Time Protocol (NTP) is not adopted in the system considering the cybersecurity concern. Instead, an industrial standard GPS synchronization module with $\pm$100ns of accuracy is applied, providing timestamps for the sampled data. As a simplified illustration, the synchronization process is shown in Fig. 3. To synchronize and timestamp the collected data on the FPGA, the absolute time provided by a 40MHz FPGA internal clock is synchronized to the GPS time. Once the data are timestamped, they are sent to the processor-based on the device for the next step.

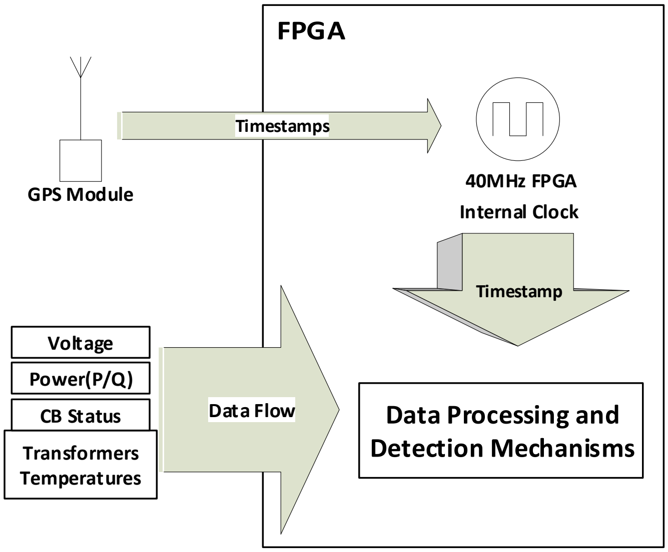


Fig. 3. Synchronization and Timestamping Process

All data are timestamped as they are processed for data display and logging. When the predefined detection mechanisms are triggered, all timestamps and sampled data are recorded to the NAS, which is shown in Fig. 4. In this case, epoch time is used as the GPS time reference, and the time refence starts from 01/01/1904 00:00:00.000 UTC [35].

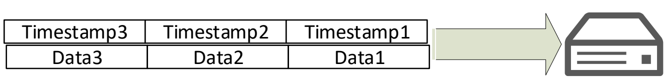


Fig. 4. Data Synchronization and Logging

C. Data Display

As mentioned in the previous sections, because of the computing capabilities and determinism, all the data acquisition and predefined detection mechanisms are programmed on the FPGA target. To display the data in real time on the computers at the substation and at the control room, data are continuously transferred through the network. Human-Machine Interface (HMI) on both computers are shown in Fig. 5. Due to security and confidentiality concerns, all power indicators and time are censored in this paper. Considering the scalability of the system and facilitating other authorized computers to access the HMI of the monitoring system, tag communication method which is introduced the following section is adopted in the system.

D. Data Logging

As one of the most important features of this monitoring system, data logging is processed on the CPU-based target. Once the predefined event mechanisms are triggered, the data is sent from the FPGA to the memory on the CPU-based target, and then saved to files in binary format in the local storage. File Transfer Protocol (FTP) is used to transfer these files from the local storage to the NAS. As an example of the recorded data, one phase of voltage recorded data file is shown in Table II. In this system, RMS and frequency data are calculated based on one cycle of raw voltage data.

TABLE II
ONE PHASE OF VOLTAGE DATA LOGGING FILE

Timestamp (μs)	**Raw (kV)**
1533116616359500	-71.96577761
1533116616360000	-34.92403722
1533116616360500	3.456600666
1533116616361000	40.08871722
1533116616361500	76.97151464
1533116616362000	110.4259613
RMS (kV)	**Frequency (Hz)**
137.6861599	60.0234375

III. DATA COMMUNICATION AND PROCESSING

Similar to most of the IoT applications, this monitoring system produces a large amount of data during operation. Three phases of voltages on two 138kV lines are measured simultaneously with a sampling rate of 2000 samples per second for each phase, which produces 12000 input data every second. Fourteen real/reactive power inputs signals, nine circuit breaker status and two transformer temperatures are measured simultaneously with a sampling rate of 10 samples per second, producing an additional 250 input data every second. Moreover, every datum will carry a corresponding timestamp. To overcome the data computing challenges and satisfy real-time communication (RTC) requirements, different types of communication methods are adopted. Meanwhile, it is worth noting that limited resources on the CPU and Dynamic RAM of the controller also need to be considered to maintain the reliability of the system according to the application specifications. In this section, the communication methods and protocols used in this monitoring system are introduced.

The IoT platform provides IP (Internet Protocol) addressability for the FPGA-embedded controller, NAS, and both computers. To build a network for this monitoring system, static IP addresses are provided for each device. TCP/IPv4 (Transmission Control Protocol/Internet Protocol version 4) is applied as the base communication protocol of the system.

As an IoT-based real-time monitoring system with data logging functions, different communication methods and protocols need to be considered to achieve an optimal and secure performance of the system.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2019.2940668, IEEE Transactions on Industry Applications

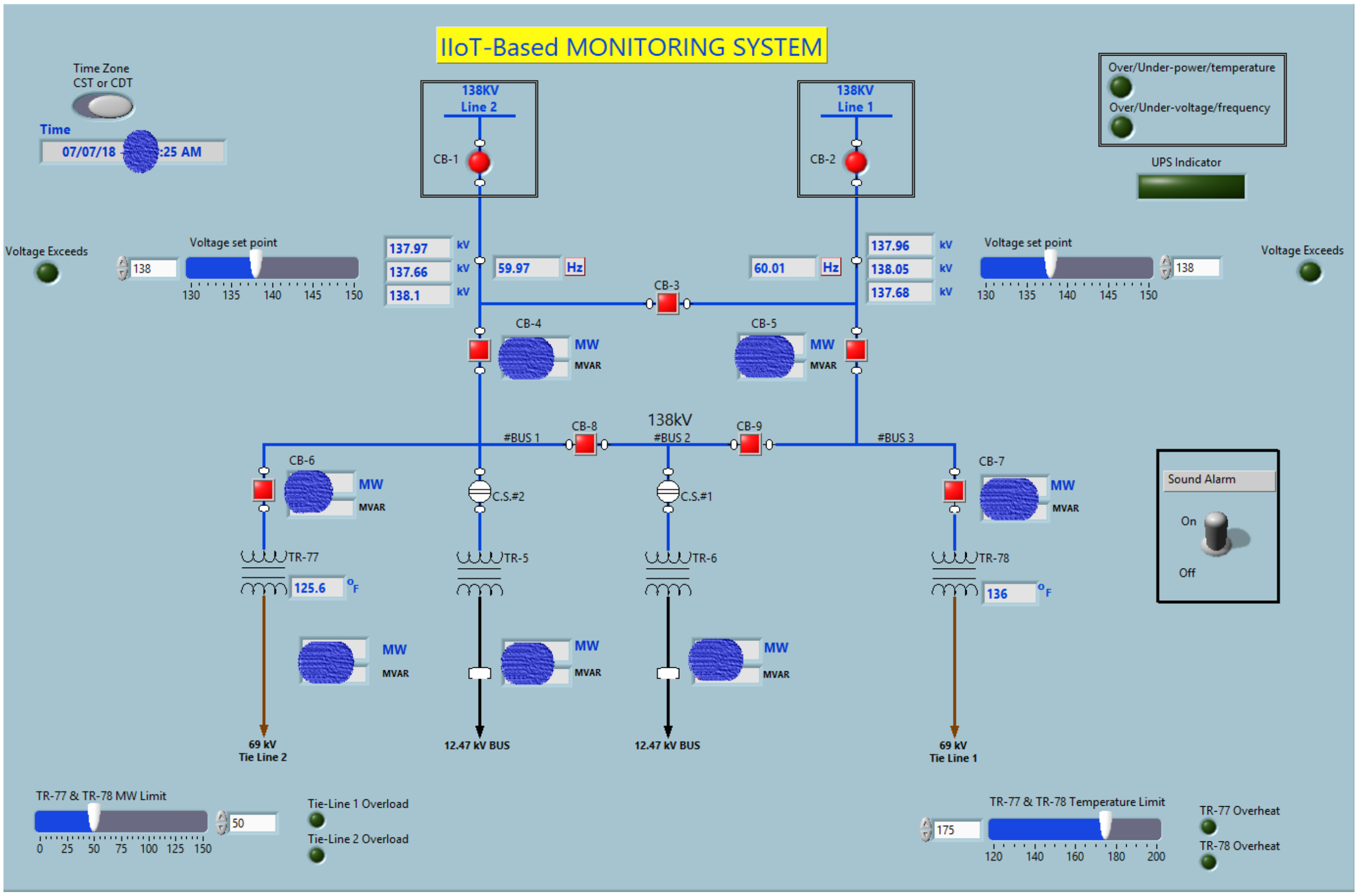


Fig. 5. HMI of the Monitoring System

A. *Tag Communication method*

To display all the most updated data in real-time on the HMI, tag communication (latest value communication) is implemented. Tag communication is defined as “transfer only the current (most recent) data value between two process loops or between two targets” [36]. For the display purpose, tag communication provides the most updated information with low latency and high-channel-count for system operators without using too much CPU and RAM resources of the controller [37]. In this system, the data update frequency on the HMI is set to one sample per second to reduce the CPU usage on the controller. However, tag communication is a lossy communication that might lose some of the data during the communication. Therefore, the tag communication method is only applied to the data display in this system.

B. *Stream Communication method*

As an embedded controller, communication between the FPGA-based target and the CPU-based target of the controller is extremely critical. Once the data acquisition and the detection mechanisms are complete on the FPGA target, all the data need to be transferred to the CPU-based target for further communication and processes.

To make sure all the high-speed-sampled data are recorded once the predefined events are detected, a lossless communication called stream communication method is adopted. Stream communication uses buffering to transfer each data point. Comparing with the tag communication method, stream communication provides better throughput but higher latency. Fig. 6 shows the stream communication on the controller.

As one of the stream communication options, Direct Memory Access (DMA) First-In-First-Out (FIFO) queues are applied between the FPGA and CPU targets. A DMA channel has two buffers on both the FPGA-based target and CPU-based target respectively. Every data point available is then transferred from the FPGA target buffer to the CPU target buffer. Computational overhead of the CPU is drastically reduced since data transfer and data processing can take place at the same time. Hence, more computing and processing power can be used for other tasks on the CPU-based target [38-40].

Once the data are transferred from the FPGA target to the CPU target by using DMA FIFO in the controller, the data are stored on the CPU-based target before being transferred to the NAS in the network. In order to do this, a fixed-size queue called Real-Time FIFO (RT FIFO) is applied to achieve a deterministic process within the CPU and pre-allocate memory for the data in the controller [41]. The data can then be stored to binary files in the local storage without data loss. To optimize the memory in the controller and avoid

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2019.2940668, IEEE Transactions on Industry Applications

overflow in the buffer, appropriate buffer sizes need to be considered for the RT FIFO according to the application.

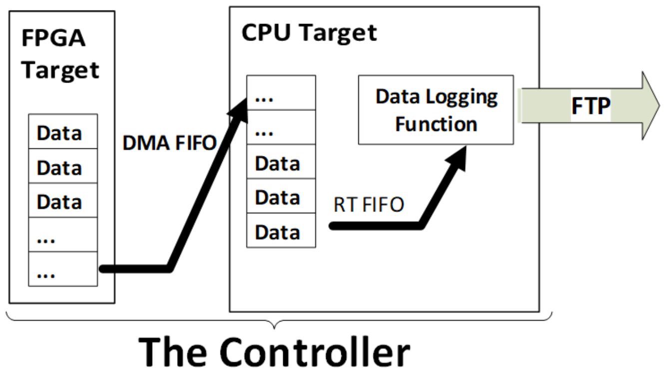


Fig. 6. Stream Communication on the Controller

C. File Transfer Protocol (FTP)

To transfer the binary files from the local storage of the CPU-based target to the NAS over the network, a connection-oriented protocol called File Transfer Protocol (FTP) is applied in this system considering the low latency requirements. Comparing with connectionless protocols such as WebDAV, FTP has a higher one-time overhead because a session between the NAS and the controller needs to be built before the data are sent. However, WebDAV usually carries artificial session information that increases the latency. As a result, successive requests of FTP sessions have a lower latency, which is critical for this IoT-based real-time system [42].

D. Publish-Subscribe Pattern (PSP)

To send the data from the substation to the control room, PSP is used between the controller at the substation and the computer in the control room. PSP provides publishers and subscribers in the communication between the data senders and receivers. Subscribers only receive the data that they subscribed to receive [43], without knowledge of who the publisher is. Publishers also do not know who the subscribers are. This messaging pattern allows for easy communication and increases scalability, facilitating other authorized computers to be added at any time to the system and act as subscribers without having to configure the messages and publishers again. In this system, the computer in the control room subscribes to receive the information published by the controller in the network for displaying purposes. Due to security concerns, this computer can only read the data from the controller without writing access capabilities.

IV. Cybersecurity of The System

As an IoT-based real-time monitoring system, cybersecurity is a vital factor which needs to be considered in the application. As mentioned in previous items, the first main cybersecurity concern led to the use of the GPS synchronization method instead of NTP. The second concern led to denying writing access to the controllers from the computers with displaying purposes.

Additionally, to improve the cybersecurity of the IoT application, adding hardware security features and more layers of security may be considered as possible solutions [11]. For this developed system, a hardware firewall is installed at the substation. The FPGA-embedded controller and NAS which have the highest security level are protected by the hardware firewall, while the host computers and computer in the control room are in a demilitarized zone (DMZ), as shown in Fig. 7. DMZ is defined as a subnetwork that is between a trusted network and an untrusted network [44]. The DMZ provides an additional layer of security to prevent unwanted access to the controller and allow time to take necessary actions to detect and block breaches. Meanwhile, the source code in the host computer and the computer in the control room can be removed. In this way, even if the attacker/unauthorized person accesses the either computer, they would not be able to modify or disrupt the monitoring system easily.

To easily distribute the application and to facilitate authorized computers to have HMI of the monitoring system without having access to the internal code, an executable file of the monitoring system is generated. The authorized computers could easily install the file to observe the condition of the system in real-time through HMI. In this way, scalability and security of the system can be satisfied at the same time. To access the NAS, a username and password are also required every time.

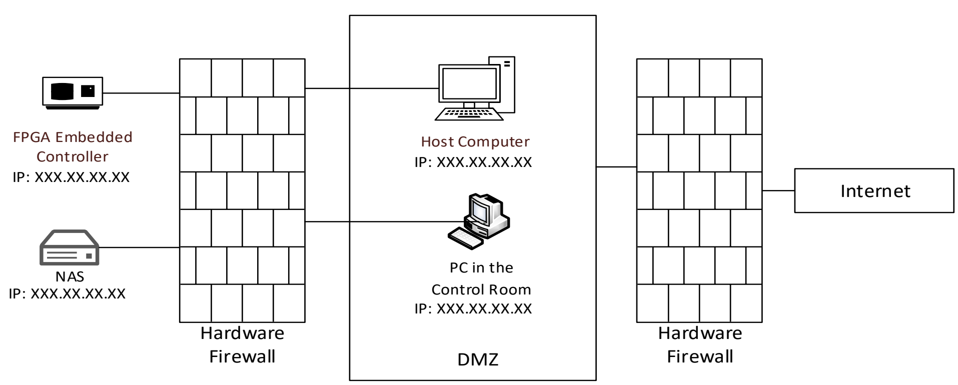


Fig. 7. Cybersecurity Setup of the System

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2019.2940668, IEEE Transactions on Industry Applications

V. IN-FIELD TEST AND APPLICATION

The developed monitoring system has been installed in a local power substation of a petrochemical facility recently in Texas, USA, as shown in Fig. 8. Considering the redundancy scheme requirements [45], two sets of FPGA-embedded controllers which have the same inputs and functionalities are installed.

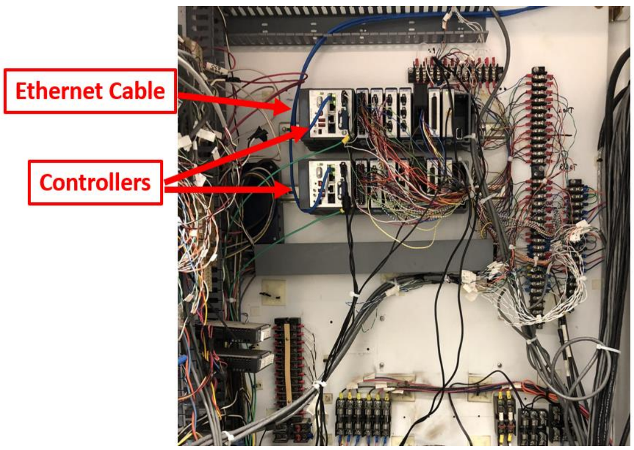


Fig. 8. Installation at the Substation.

On Aug 1st, 2018, all circuit breakers in the feeders at the substation opened at 4:43:39 AM due to an under-voltage event on phase B of the 138kV lines. During the fault, both voltage RMS values dropped from 138kV to around 35kV for three cycles. With the newly developed IoT platform, the operators in the control room received the alarm immediately and retrieved the recorded data on the network from the NAS. The monitoring system was triggered and successfully recorded the circuit breaker statuses, raw voltage data, RMS values and frequency on both 138kV lines. As an example, the recorded raw voltage data during the event on both Line 1 and Line 2 are plotted in Fig. 9. As it is shown, three cycles of fault voltage data on both 138kV lines are recorded with the high sampling rate. High-resolution GPS provides the accurate timestamps for the recorded data with the 1904 epoch time reference in ns [46]. The Digital Fault Recorder (DFR) that was previously installed at the substation did not provide all this detailed information. The implemented IoT-based monitoring system provides accurate and detailed information for system operators to do the post-fault analysis.

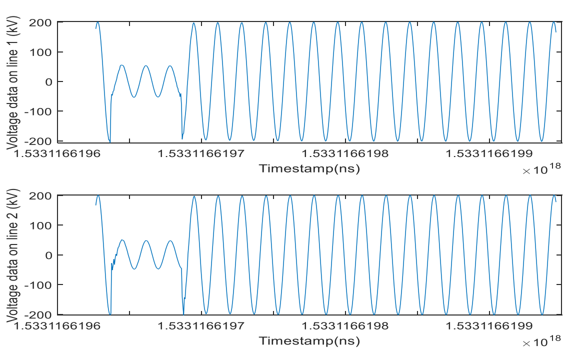


Fig. 9. Recorded Voltage Fault Event Data

VI. NOVELTY OF THE DEVELOPED MONITORING SYSTEM

Currently, there are various devices and platforms which can be applied for the power substations monitoring. Among different monitoring devices, IEC 61850 standard application is one of the most commonly used monitoring platforms for power systems [47]. Comparing with IEC 61850, the developed monitoring system has better flexibility to be applied with different functionalities. Due to the programmability of the FPGA, the features of the monitoring system can be modified or added based on the operator's needs without extra costs. Meanwhile, the developed monitoring system is designed with energy monitoring and recording functions, which enables the power generation units to participate in the demand response programs in deregulated electricity markets. In this way, the developed system could benefit both the generation unit and system operator financially and technically. As a real-world application system, this developed monitoring system has been applied for Demand Response (DR) program in electric reliability council of Texas (ERCOT) market to improve the operation of the system and brought significant financial benefits to the DR participant. Thus, comparing with most of the monitoring platforms in the market, this system can be applied as a reprogrammable multipurpose monitoring platform at the power substations.

VII. CONCLUSION

In this paper, an Industrial IoT-based monitoring system for a power substation was developed in the FPGA-embedded controller. All the critical parameters at the substation, including voltage, frequency, power, circuit breaker status, and transformer temperatures are monitored in real-time. The predefined event triggering mechanisms are also programmed on the controller with the recording functions. Once these events are triggered, the data is recorded by the controller and transferred to a NAS in the network. Industrial-Standard GPS is applied to provide high-resolution timestamps and synchronization functions. The FPGA-embedded controller provides high-speed and reliable data acquisition and processing functionalities. Due to the high sampling rate of the system, both steady-state and transient conditions of the power systems are monitored using a single time source. With the IoT platform, the data are transferred and stored through the LAN. System operators can remotely access the data in real-time and retrieve the data from the NAS on the network. The communication methods and protocols, along with the cybersecurity measures demonstrated, were implemented in this IoT-based monitoring system, which at last enables the system operator to visualize the overall operations of the substation in real-time. Recorded high-speed sampled data in the NAS provides detailed information for the system analysis to avoid similar fault incidents in the future. This IoT-based monitoring system has been installed at a local power substation of a petrochemical facility in Texas, USA. It has successfully captured the first fault event and provided valuable information to the system operators for post-event analysis.

References

[1] E. Spano, S. D. Pascoli and G. Iannaccone, "Low-power wearable ECG monitoring system for multiple-patient remote monitoring," *IEEE Sensors Journal*, vol. 16, no. 13, pp. 5452–5462, Jul. 2016, 10.1109/JSEN.2016.2564995

[2] F. Stradolini, A. Tuoheti, T. Kilic, S. L. Ntella, N. Tamburrano, Z. Huang, G. D. Micheli, D. Demarchi and S. Carrara, "An IoT solution for online monitoring of anesthetics in human serum based on an integrated fluidic bioelectronic system," *IEEE Trans. Biomedical Circuits and System*, vol. 12, no. 5, pp. 1056–1064, Oct. 2018, 10.1109/TBCAS.2018.2855048

[3] S. Yang, B. Gao, L. Jiang, J. Jin, Z. Gao, X. Ma and W. L. Woo, "IoT structured Long-Term wearable social sensing for mental wellbeing" *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 3652-3662, Apr. 2019, 10.1109/JIOT.2018.2889966

[4] N. Ahmed, D. De and M. I. Hussain, "Internet of things (IoT) for smart precision agriculture and farming in rural areas," *IEEE Internet of Things Journal*, vol. 5, no. 6, pp. 4890-4899, Dec. 2018, 10.1109/JIOT.2018.2879579

[5] P. Hambarde, R. Varma, and S. Jha, "The survey of real time operating system: RTOS," in *Proc*. *ICESC*, Nagpur, India, 2014, pp. 34-39.

[6] S. Du, B. Liu, H. Ma, G. Wu, and P. Wu, "IIoT-Based intelligent control and management system for motorcycle endurance test," *IEEE Access*, vol. 6, issue. 2, pp. 30567–30576, Dec. 2016, 10.1109/ACCESS.2018.2841185.

[7] M. T. Lazarescu, "Design of a WSN platform for long-term environmental monitoring for IoT applications," *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, vol. 3, no. 1, pp. 45-54, Mar. 2013, 10.1109/JETCAS.2013.2243032

[8] G. Wang, M. Nixon and M. Boudreaux, "Toward cloud-assisted industrial IoT platform for large-scale continuous condition monitoring," *Proceedings of IEEE*, vol. 107, issue 6, pp. 1193-1205, Jun. 2019, 10.1109/JPROC.2019.2914021

[9] F. Zhang, M. Liu. Z. Zhou and W. Shen, "An IoT-based online monitoring system for continuous steel casting" *IEEE Internet of Things Journal*, vol. 3, no. 6, pp. 1355-1363, Dec. 2016, 10.1109/JIOT.2016.2600630

[10] S. E. Collier, "The emerging enernet: convergence of the smart grid with the internet of things," *IEEE Mag. Industry Application*, vol. 23, issue. 2, pp. 12–16, Dec. 2016, 10.1109/MIAS.2016.2600737.

[11] G. Bedi, G. K. Venayagamoorthy, R. Sigh, R. R. Brooks, and K. C. Wang, "Review of internet of things (IoT) in electric power and energy systems," *IEEE IoT J*, vol. 5, issue. 2, pp. 847–870, Feb. 2018, 10.1109/JIOT.2018.2802704.

[12] R. V. Jadhav, S. S. Lokhande, and V. N. Gohokar, "Monitoring of transformer parameters using internet of things in smart grid," in *Proc. ICCUBEA*, Pune, India, 2016, pp. 1-4.

[13] Y. Tian, Z. Pang, W. Wang, L. Liu, D. Wang, "Substation sensing monitoring system based on power internet of things," in *Proc. IEEE ITNEC*, Chengdu, China, 2017, pp. 1613-1617.

[14] W. T. Hartman, A. Hansen, E. Vasquez, S. EI-Tawab, and K. Altaii, "Energy monitoring and control using internet of things (IoT) system," in *Proc. SIEDS*, VA, USA, 2018, pp. 13–18.

[15] L. M. L. Oliveira, J. Reis, J. J. P. C. Rodrigues, and A. F. de Sousa, "IoT based solution for home power energy monitoring and actuating," in *Proc. INDIN*, Cambridge, UK, 2015, pp. 988-992.

[16] M. R. Bastos, and S. S. L. Machado, "Visual, real-time monitoring system for remote operation of electrical substation," in *Proc. IEEE/PES T&D-LA*, Sao Paulo, Brazil, 2011, pp. 417-421.

[17] Q. Gao, W. Ge, C. Wang, J. Zhang, B. Geng, and X. Jiang, "High voltage equipment online monitoring system of smart substation," in *Proc. IEEE PES ISGA*, Tianjin, China, 2012, pp. 1-5.

[18] S. Park, E. Lee, W. Y, H. Lee, and J. Shin, "State estimation for supervisory monitoring of substations," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 406–410, Feb. 2013, 10.1109/TSG.2013.2240322.

[19] M. B. Bastian, W. D. Carman, and D. J. Woodhouse, "Real-time monitoring of substation ground potential rise and grounding system impedance using power system faults," *IEEE Trans. Industry Application*, vol. 51, no. 6, pp. 5298–5304, Apr. 2015, 10.1109/TIA.2015.2425361.

[20] W. Lee, J. Gim, M. Chen, S. Wang, and R. L, "Development of a real-time power system dynamic performance monitoring system," *IEEE Trans. Industry Application*, vol. 33, no. 4, pp. 1055–1060, Jul/Aug. 1997, 10.1109/28.605748.

[21] F. Zhao, Q. Sun, J. Zhan, L. Nie, and Z. Xu, "The real-time database application in transformer substation hotspot monitoring system," in *Proc. ICACT*, PyeongChang, South Korea, 2014, pp. 941-944.

[22] Y. Tian, Z. Pang, W. Wang, L. Liu, and D. Wang, "Substation sensing monitoring system based on power internet of things," in *Proc. ITNEC*, Chengdu, China, 2018, pp. 1613-1617.

[23] *NI FPGA*. [Online]. Available: http://www.ni.com/fpga/

[24] *Introduction to FPGA Technology: Top 5 Benefits*. [Online]. Available: http://www.ni.com/white-paper/6984/en/

[25] Z. Hao, G. Lianping, M. Jie and Y. Peng, "Research on the hardware co=processing technology for waveform character searching with a digital oscilloscope," in *Proc. IEEE ICEMI*, Yangzhou, China, 2017.

[26] F. A. Escobar, X. Chang and C. Valderrama, "Suitability analysis of FPGAs for heterogeneous platforms in HPC," *IEEE Trans. Parallel and Distributed System*, vol. 27, no. 2, pp. 600–612, Feb. 2016, 10.1109/TPDS.2015.2407896

[27] J. Sheng, C. Yang, A. Sanaullah, M. Papamichael, A. Caulfield and M. C. Herbordt, "HPC on FPGA clouds: 3D FFTs and implications for molecular dynamics," in *Proc. 2017 27th International Conference on Field Programmable Logic and Applications (FPL), Ghent, Belgium.*

[28] R. Chen and V. K. Prasanna, "Computer generation of high throughput and memory efficient sorting designs on FPGA," *IEEE Trans. Parallel and Distributed System*, vol. 28, no. 11, pp. 3100–3113, Nov. 2017, 10.1109/TPDS.2017.2705128

[29] *cRIO-9039 CompactRIO Controller*. [Online]. Available: http://www.ni.com/en-us/support/model.crio-9039.html

[30] *NI-9205*. [Online]. Available: http://www.ni.com/pdf/manuals/374188f.pdf

[31] *NI-9225*. [Online]. Available: http://www.ni.com/pdf/manuals/374707e.pdf

[32] *NI-9425*. [Online]. Available: http://www.ni.com/pdf/manuals/373782j.pdf

[33] *Data Center Storage Evolution*. [Online]. Available: https://www.siemon.com/us/white_papers/14-07-29-data-center-storage-evolution.asp

[34] *Analog period measurement expresses VI*. [Online]. Available: http://zone.ni.com/reference/en-XX/help/371599N-01/lvfpga/fpga_period_measurement/

[35] *LabVIEW Timestamp*. [Online]. Available: http://www.ni.com/tutorial/7900/en/

[36] *RIO Developer Essentials Guide for Academia Glossary*. [Online]. Available: https://learn-cf.ni.com/teach/riodevguide/glossary.html#tag

[37] *Understanding Communication Options Between the Windows HMI, RT Processor, and FPGA*. [Online]. Available: http://www.ni.com/white-paper/53345/en/#RTHMICommunication

[38] A. Rubni and J. Corbel, "Direct memory access and bus mastering," in *LINUX Device Drivers, 2nd* ed. Boston, MA, USA: O'Reilly & Associates, 2001, ch. *13*, pp. *401-403.*

[39] *Host memory buffer overview*. [Online]. Available: http://www.ni.com/white-paper/53881/en/

[40] L. Zhao, I. Matsuo, Y, Zhou and W. Lee, "Design of an industrial IoT-based monitoring system for power substations," presented at the IEEE 55th I&CPS. Conf, Calgary, Canada, 2019.

[41] *Getting stared with the LabVIEW real-time module*. [Online]. Available: http://www.ni.com/pdf/manuals/371375d.pdf

[42] P. C. Heckel, "Minimizing remote storage usage and synchronization time using deduplication and multichunking: syncany as an example," M.S. thesis, Dept. Bus Infor Math., Mannheim Univ., Mannheim, Germany, 2012.

[43] C. Esposito, A. Castiglione, F. Palmieri, M. Ficco, K. R. Choo, "A published/subscribe protocol for event-driven communications in the internet of things," in *Proc. IEEE DASC/PiCom/DataCom/CyberSciTech*, Auckland, New Zealand, 2016, pp. 376-383.

[44] D. C. Mazur, R. A. Entzminger, P. A. Morell, J. A. Kay, and E. Syme, "Defining the industrial demilitarized zone and its benefits for mining applications," *IEEE Trans. Industry Application*, vol. 52, no. 3, pp. 2731–2736, Feb. 2016, 10.1109/TIA.2016.2530045.

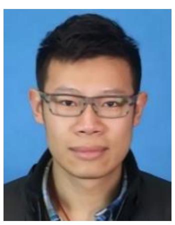
[45] I. B. M. Matsuo, L. Zhao, and W. Lee, "A dual modular redundancy scheme for CPU-FPGA platform-based systems," *IEEE Trans. Industry Application*, early access, Jul. 2018, 10.1109/TIA.2018.2859386.

[46] *LabVIEW Timestamp*. [Online]. Available: http://www.ni.com/tutorial/7900/en/

[47] S. Matsuda, Y. Watabe, I. I. Asrizal, S. Katayama, K. Okuno, and K. Kasuga, “Issues overcome in the design and application of iec 61850–compliant substation automation systems,” in Advanced Power System Automation and Protection (APAP), 2011 International Conference on, Oct. 2011, pp. 198–202.

Long Zhao (S’12) received the B.S. degree in electrical engineering from the Eastern Washington University, Cheney, WA, USA, in 2012 and M.S. degrees in electrical engineering from the Wichita State University, Wichita, KS, USA, in 2014. Currently he is pursuing the Ph.D. degree in Power and Energy Systems at the University of Texas at Arlington as a member of the Energy System Research Center (ESRC). His research interests include power system analysis, demand response, renewable energy, energy storage, power system markets and arc flash protection. He is currently the IEEE Industry Applications Society Student Chapter Chair at UT Arlington.

Igor B. M. Matsuo (S’16) received his B.S. (2012) and M.S. (2015) degrees from the University of Sao Paulo, Brazil. He is currently pursuing his Ph.D. degree in Power and Energy Systems at the University of Texas at Arlington, USA, where he is a member of the Energy Systems Research Center (ESRC). He has also worked for Techimp; the Foundation for the Technological Development of Engineering (FDTE, in Brazil); and Calpine. His experiences include monitoring systems; partial discharges; sub-synchronous oscillations; power system planning and analysis; and automation and protection systems in the generation, transmission and distribution levels.



Yuhao Zhou (S’17) received the B.S. degree and M.S. degree both in electrical engineering from Huazhong University of Science and Technology, Wuhan, Hubei, China, in 2013 and 2016, respectively. Currently he is pursuing the Ph.D. degree in the University of Texas at Arlington as a member of the Energy Systems Research Center (ESRC). His research interests include dynamic equivalent modeling of wind farm, power system analysis, renewable energy, energy storage and arc flash protection.

Wei-Jen Lee (S’85–M’85–SM’97–F’07) received the B.S. and M.S. degrees in electrical engineering from National Taiwan University, Taipei, Taiwan, in 1978 and 1980, respectively, and the Ph.D. degree in electrical engineering from The University of Texas at Arlington, Arlington, TX, USA, in 1985. In 1985, he joined The University of Texas at Arlington, where he is currently a Professor with the Department of Electrical Engineering and the Director of the Energy Systems Research Center. He has been involved in research on power flow, transient and dynamic stability, voltage stability, short circuits, relay coordination, power quality analysis, renewable energy, and deregulation for utility companies. Prof. Lee is a Registered Professional Engineer in the State of Texas.