INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2023, VOL. 69, NO. 4, PP. 819-824
Manuscript received July 12, 2023; revised October, 2023. DOI: 10.24425/ijet.2023.147708

Development Of A Monitoring System For Electric Power Substations Based On Ios And Implementation Of Designs On FPGA

Maksat Kalimoldayev, Waldemar Wójcik, and Zhazira Shermantayeva *

***Abstract*—In this article, a monitoring system based on IoT technologies of the substation electrical system in the Republic of Kazakhstan was developed. At the moment, the operation of power systems is extremely important to maintain the frequency of electric current over time. For management and monitoring applications, it is necessary to take into account communication within acceptable limits. IoT technologies are considered the main functions in applications for monitoring and managing energy systems in real time, as well as making effective decisions on both technical and financial issues of the system, for monitoring the main form of data registration on an electric power substation in the city of Shymkent of the Republic of Kazakhstan, for consistent effective decision-making by system operators. In this work, an Internet of Things-based monitoring system was implemented and implemented for the substation of the power system using a specialized device built into the FPGA controller for fast integrated digitalization of transformer substations of real-time distribution electrical networks.**

The IoT platform also provides complete remote observability and will increase reliability for power system operators in real time. This article is mainly aimed at providing a practical application that has been implemented and tested.

***Keywords*—IoT Internet of Things, FPGA; GPS; NAS**

I. Introduction

THE Internet of Things or IoT affects our way of life judging by how we react to how we behave. From air conditioners that you can control with your smartphone to smart cars that provide the shortest route or your smartwatch that tracks your daily activities.

The Internet of Things is a giant network with connected devices. These devices collect and exchange data for use in the work environment.

In his Message to the People of Kazakhstan dated September 1, 2021, the Head of State announced that Kazakhstan will have a shortage of electricity by 2030. But the lack of electricity in the country is already felt today. The shortage of electricity in the country is 1.3 GW. In 2022, an unprecedented situation has developed: consumption has grown by a record 7%, whereas previously the increase was 1.5-2% per year, which is estimated as a natural increase.

Maksat Kalimoldayev and Zhazira Shermantayeva are with the Institute of Information and Computing Technologies of the KN of the Ministry of Internal Affairs of the Republic of Kazakhstan (e-mail: mtu-2015@mail.ru).

Waldemar Wójcik Lublin University of Technology, Lublin, Poland(e-mail: waldemar.wojcik@pollub.pl).

The production of electric energy in Kazakhstan is carried out by 158 electric power stations of various forms of ownership. Since 1996, Kazakhstan Electricity Grid Operating Company "KEGOC" JSC has been defined as a single power grid operator.

On March 20, 2022, three serious accidents occurred at two Kazakhstani thermal power plants, in Petropavlovsk and in Stepnogorsk. And similar accidents tend to repeat. This is not surprising, given the current situation in the field of electric power in the country.

As a result of the fact that no complete renovation of power facilities has been carried out in the last 7-8 years, an unacceptably high degree of wear and tear of power equipment and assets has developed in the country. In particular, generating equipment is on average worn out by 65%, electrical networks - 83%, heating networks - 80%.

Thanks to the possibilities of using IoT technologies for monitoring and managing energy systems in real time, they can provide services to the system operator, exchanging information among themselves, giving instructions, configuring and providing access to data.

IoT devices are ordinary objects equipped with transceivers, microcontrollers and protocols that ensure their communication with other devices, as well as with external objects (for example, people) to ensure the implementation of fully automated systems that make them an integral part of the Internet. The purpose of IoT is to use networks to create connections between objects while reducing time and location constraints [1].

The Internet of Things focuses on the implementation of three main concepts, namely things-oriented, Internet-oriented and semantics-oriented:

- The thing-oriented concept includes intelligent devices such as RFID tags, sensors, actuators, cameras, laser scanners, Global Positioning System (GPS) and NFC.
- The Internet-oriented concept provides communication between smart devices using various communication technologies such as ZigBee, WiFi, Bluetooth, cellular communication and connects them to the Internet.
- The semantically oriented concept implements many applications using smart devices.

The capabilities of IoT monitoring and real-time management are used in various fields and in recent years several studies have been conducted on mapping tasks with neural networks [2], [3], [4], [5], [6]. To control all processes of production, transmission and distribution of electric energy, there is an operational dispatch control system [7, 8].

The article [9] of the study suggests an innovative method for creating an intelligent health bracelet that could receive and transmit test results in real time using the BLYNK application.

How can fraud committed in the billing of energy consumption be stopped, to prevent offenders from evading any applicable penalties, to prevent their escape, to reduce the need for punishment, if any, and the amount necessary to bill and recover the money owed [10]. A lot of experimental work has been done on the management of household appliances, on health maintenance and tracking of electrical factors. Thus, after most of such work has been reported, an intelligent IoT device is installed for power management software that interacts with microcontrollers [11].The main interface between the electrical substation and the power system is responsible for raising and lowering the voltage level. Various types of monitoring systems have been developed. An IIoT-based monitoring system with a high frequency of data logging for monitoring various critical parameters, including voltage, frequency, active power, reactive power, switch status and transformer temperature at substations.

In this work, a power system has been developed that will be installed at the Shymkent substation, and it will successfully detect and record the first emergency event. The system operators will deal with resource losses in the networks, and also ensure the stability of the energy supply, using the recorded data for further analysis in order to take the necessary measures.

This article is intended to show the practical development of an IoT-based RT monitoring system with a high sampling rate for monitoring and controlling substations. With the help of this developed system, system operators can remotely monitor the general conditions in both steady-state and transient modes of an electrical substation. High-speed sampling and lossless data logging provide more detailed data for both interactive and offline analysis. Section I presents the developed model and algorithm of the Titan 2 FPGA and ESP-32 Microcontroller monitoring system and control. Section II presents data processing and research results. Section III shows field tests and applications and discusses the novelty of the developed monitoring system. The conclusion of this article is shown in Section IV.

Section I

The uniqueness of the development of system monitoring in IoT-based power substations lies in the ability to collect data processing and analyze data in real time in order to increase the reliability and efficiency of system operators. The design of the integrated controller of the industrial standard Titan 2 FPGA is shown in Figure-1.

To build the design of Titan 2 FPGA clusters , we decided to take five important points:

1. platform;
2. partitioning;
3. communication;
4. timing;
5. management.

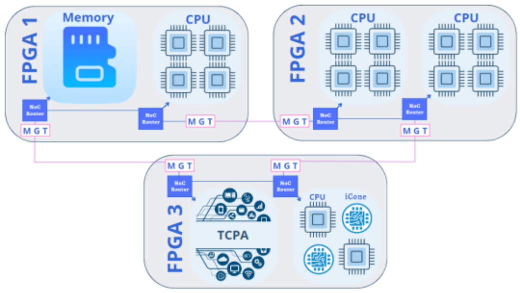

Fig.1. Algorithm of Titan 2 FPGA cluster designs

First, we determined the platform of use for building a board with a single Titan 2 FPGA, and also placed it on several different boards. Implemented communication between two boards to exchange data between each other. Next, the timing of these boards was determined so that the design divided into several boards worked as on one board. We have also developed a control system with the help of which it will be possible to simultaneously launch a synchro signal, a signal used to coordinate the operations of one or more digital circuits on all boards. Also, the control system monitors the state of communication between the boards, if suddenly there is some kind of error.

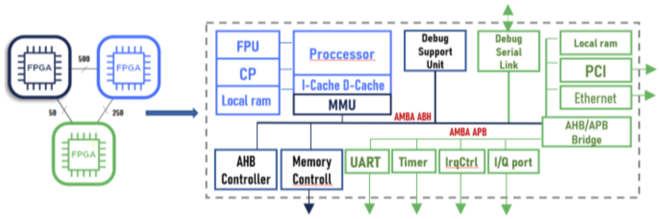

Fig. 2. Real-time FPGA implementation and architecture

As a result of the research, a platform for the development of a programmable logic integrated circuit (FPGA) was selected.

We also used the ESP32 functional module in our work. ESP32 is a functional module based on the ESP32 microcontroller, which is equipped with a dual-core processor. It supports the Wi-Fi 802.11 N standard and is additionally equipped with Bluetooth version 4.26. It has more peripheral device interfaces, which makes it more flexible and functional in various applications. Thus the ESP32 has more advanced features capabilities. The ESP32 has a built-in antenna and RF balun, power amplifier, low-noise amplifiers, filters and a power management module. The whole solution occupies the smallest printed area of the board. This board is used with dual-mode 2.4GHz Wi-Fi and Bluetooth chips using 40nm low-power TSMC technology, RF power and the best properties, which makes it safe, reliable and scalable for various applications.

In the power system, many analyses and studies require a high-speed sampling rate, for example, signal frequency domain analysis and transient analysis. Processing operations on the FPGA are completely parallel and do not compete for the same resources. FPGA applications have great advantages with multiple inputs and outputs. Compared to processor-based software solutions, it is possible to determine how many processors an information tool is based on, and it is possible to solve problems with vibration when executing software. This is very useful for our high-speed system. However, due to some technical limitations, some complex functions and communication functions, such as sorting and searching methods or floating-point arithmetic operations, cannot be implemented exclusively on FPGA. Therefore, processor-based devices are still needed [12]. In the course of the work, FPGA systems were developed for connecting FPGAs. We used the resources of the presses, all the pins. As a result, FPGA and CPU can complement each other. High-speed monitoring systems provide the most optimal performance multiple inputs/outputs.

This system uses:

- Titan 2 PG2T390H-6IFFBG900 FPGA;
- 8 GB DDR 4 64bit; 2 GB DDR3 64 bit;
- 64 MB QSPI FLASH;
- X1 QSFP fiber optic interface 40 Gb/s;
- X4 SFP optical fiber interface, 10 Gb/s;
- X1 FMC LPC extension port.

Management system

The last element of clocking is control (Figure - 3). If we split our design into several boards, we can guarantee that all synchro signals will start simultaneously at startup. If this is not observed, then one of the blocks will start clocking long before the others, then the system may be in an incomprehensible state. When the developed system starts working, it should work as a whole. Therefore, it is also necessary to implement a control system that is guaranteed to start clocking all synchro signals simultaneously.

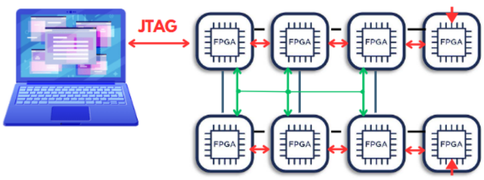

Fig.3. Design of the control timing system

In an Internet of Things-based monitoring system, network storage (SAN) is used as a storage for storing data and providing remote access. The existing file system is created and maintained within the remote system, while it can be simultaneously used for reading and writing by many clients. As shown in Figure - 4, inside the substation, the integrated FPGA controller, the main computer and the NAS are connected to the hardware firewall via Ethernet cables. The computer in the control room receives data in real time. In this section, the structure of the system is presented in the sequential order of the data flow in the system.

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	1500 S/s
Analog Voltage InputModule (-10 to 10V)	Real Power, Reactive Power and Transformer Temperatures (Transducers)	10 S/s
Digital Input Module	Circuit Breaker Status	10 S/s

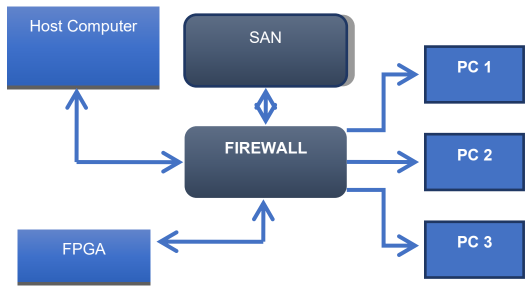

Fig.4. Structure of a real-time monitoring system based on the Internet of Things using FPGA

To obtain different types of input data with different sampling rates, 3 types of input modules are used in this system, as shown in table I. All data will be collected and processed in the FPGA. To obtain high-resolution voltage and frequency signal data for detailed analysis, analog AC voltage signals are sampled at a frequency of 1500 samples per second. Real power, reactive power and transformer temperatures, signals are converted by converters. Signals about the power, temperature and status of the circuit breaker are received at a sampling rate of 10 samples per second.

A real-time monitoring system requires both high-resolution and accurate time sources. In this study, an industrial-standard GPS synchronization module with an accuracy of +100 ns was used, providing timestamps for selected data. As a simplified illustration, the synchronization process is shown in Figure -5.

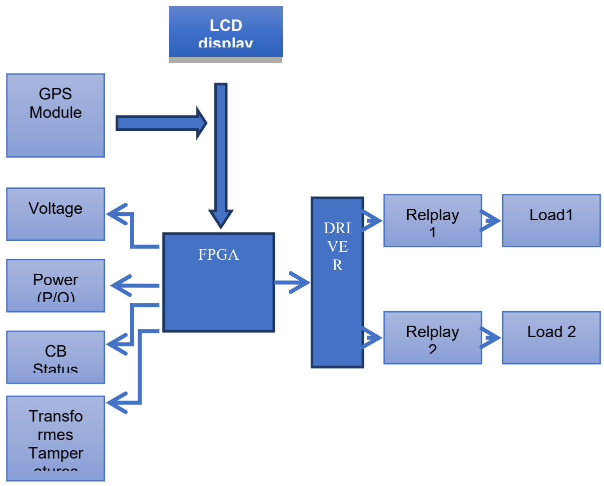

Fig.5. Industrial standard GPS synchronization module

To synchronize and timestamp the collected data on the FPGA, the absolute time provided by the internal FPGA clock with a frequency of 40 MHz is synchronized with the GPS time. Once the data is timestamped, it is sent to the device-based processor for the next step.

Section II
Research results

This article presents a standard circuit breaker signal source to make up for the lack of existing signal sources, such as a variety of types of signal sources, low automation, low work efficiency and waste of human resources. The standard circuit breaker signal source simulates all parameters during normal and abnormal operation of an electrical circuit: primary circuit opening current, switching coil closing current, storage motor current, stroke sensor voltage signal/current signal. In order to avoid defects on the part of signal sources and human resources, a standard circuit breaker signal source has a number of advantages:

1) It is necessary to conclude 3 switch signals; 2) The current output of the short circuit coil with switching to 1 channel, which simulates the output current at which the circuit breaker performs a switching circuit operation. The output current is 0~5A. The accuracy is 1%. The output current must be feedback; 3) Single-channel output current of the storage device, which simulates the output signal of the circuit breaker stroke (current output). The accuracy is 1%. The output current should be feedback; 4) The output of the first channel is 4-20 mA, an imitation of the output current appears, at which the circuit breaker ensures the operation of the storage motor. The output current is 0~5A. The accuracy is 1%. The output current must be feedback; 5) A single-channel 0-5 V output simulates the output current at which the circuit breaker ensures the operation of the storage motor. The output current is 0~5A. The accuracy is 1%. The output voltage should be feedback; 6) The above outputs should guarantee the accuracy and stimulate the output of the time sequence of the circuit breaker; 7) The signal source can exchange data with the main computer via a WI-FI interface; 8) 5 groups of different waves can be pre-stored; 9) Receive 5 groups of different waves pre-stored from the main computer; 10) Have the function of liquid crystal display.

The circuit breaker is a very important means of control and protection in the field of power grid systems. When the electrical equipment or circuit is in an emergency state, the relay protection and circuit breaker quickly cut off the damage area from the network and guarantee the safe operation of the network. However, there are many high-voltage circuit breakers. According to the traditional model of planned overhaul to check the circuit breaker, there will be some phenomena such as heavy workload, high costs and so on. At the same time, different circuit breakers require different signal sources. During maintenance of this nature will lead to a waste of human resources and will cause artificial errors. Therefore, the article presents a new standard source of the circuit breaker signal. He implemented an integrated, informational and intellectual reform for various types of signal sources. Using a standard signal source to calibrate conventional equipment can reduce the maintenance burden and increase the relevance of maintenance. This is very useful for improving the operational reliability and efficiency of electrical equipment.

All mechanisms of data collection, monitoring, as well as programming are investigated in the FPGA device. To display data in real time on computers at the substation and in the control room, data is continuously transmitted over the network.

To increase the operational efficiency of the monitoring system, an automated process control system (APCS) is used for the substation of the power system. In order to solve this problem, adhere to the following steps:

1) elimination of emergency situations and assessment of the condition of individual substation nodes of the power system according to sensor readings;

2) ensuring the autonomous operation of the installation.

With the help of these two stages, this technological process allows you to reduce operating costs and reduce the influence of the human factor on the reliability of the substation system of the power system.

Fig.6. Dispatching control of the substation of the power system in SCADA

One of the main ways to automate the substation system of the power system is the use of specialized software and hardware complexes, which allowed to solve the following tasks:

1) get data on the state of the system and changes in technological processes on the control controller;

2) to process data on changes in technological parameters of the substation system of the power system in real time;

3) to improve algorithms for managing technological processes in the substation system of the power system;

4) monitor the technical condition of the installation in real time.

To implement the development and research of the automation system of the substation of the power system, SCADA was used. Figure -6 shows the dispatching control of the substation of the power system in SCADA.

Receiving data from the FPGA Programmable Logic Controller, the SCADA system is able to evaluate the technological parameters of processes occurring in various nodes of the installation, namely:

– receives temperature data;
– receives voltage data;
– receives data on electricity;
– receives data from a standard circuit breaker signal source;

– calculates the amount of transmitted electrical energy in various circuits based on the readings of temperature, voltage and electricity sensors;

The SCADA system in automatic mode, without operator involvement, supports the operation of the substation system of the power system under various external influences.

Section III

The novelty of the developed monitoring system

Currently, there are various devices and platforms that can be used to monitor electrical substations. Among the various monitoring devices, the IEC 61850 standard application is one of the most frequently used monitoring platforms for power systems [47]. Compared to IEC 61850, the developed monitoring system has more flexibility for use with various functions. Thanks to the FPGA programmability, the monitoring system functions can be changed or added depending on the operator's needs at no additional cost. The monitoring system is designed with energy monitoring and registration functions, which allows power units to participate in demand response programs in unregulated electricity markets. Thus, the developed system can bring financial and technical benefits to both the generating unit and the system operator. As a real application system, this monitoring system was applied to the Demand Response (DR) program at the Texas Market Power Reliability Council to improve the system's performance and brought significant financial benefits to the DR participant. Thus, compared to most monitoring platforms on the market, the system can be used as a reprogrammable multi-purpose monitoring platform at electrical substations.

In this paper, a new design of a control controller for monitoring an electrical substation has been developed (Figure - 7). The electrical substation monitoring controller is equipped with an ESP 32 processor, which initializes and starts data collection on transformer temperature, power, voltage and circuit breaker status. After the above process, ESP 32 starts a Wi-Fi connection and turns on the Internet. Once enabled on the Internet, ESP 32-1 connects to the domain URL using the Hypertext Transfer Protocol (HTTP). Data on temperature, power, voltage and the status of the circuit breaker are sent to the database. Data is extracted from the database using a PHP script. The extracted data is stored in the database. The saved data is interpreted in the web interface for users (Figure-8). The web interface works for the mobile version and the personal computer.

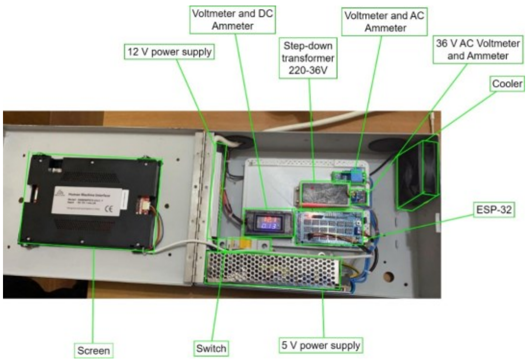

Fig.7. Electrical substation monitoring controller

Communication between the client and the server is carried out using the Hypertext Transfer Protocol (HTTP). In this protocol, the client initializes the link by requesting a specific web page using HTTP. One of the main features of the FPGA is that it can be both connected to a Wi-Fi network and act as a web server, and can also configure its own network, allowing other devices to connect directly to it and access web pages. This is possible because the FPGA can operate in different modes: station mode, soft access point mode and both at the same time. This makes it possible to build power grids.

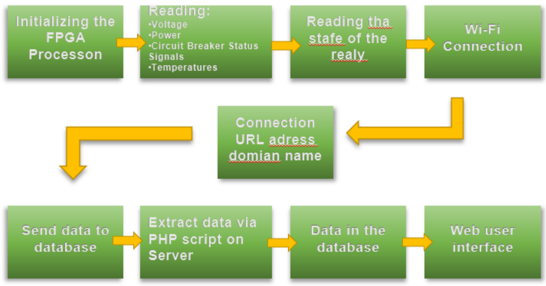

Fig.8. Electrical substation monitoring system

The novelty of the developed monitoring system is that a research methodology has been developed for monitoring an electrical substation. The FPGA monitoring system has more flexibility for applications with different functionality. Thanks to the FPGA programmability, the monitoring system functions can be changed or added depending on the operator's needs at no additional cost. A control controller was also developed to monitor the condition of the substation. Thus, the developed system could bring financial and technical benefits to both the generating unit and the system operator. Thus, compared to most monitoring platforms on the market, this system can be used as a reprogrammable multi-purpose monitoring platform at power substations.

Section IV
Conclusion

In this article, a monitoring system based on the Internet of Things was developed, and the implementation of designs on FPGAs for substations. Two variants of an IoT-based monitoring system for an electrical substation have been developed, one on an integrated FPGA controller and the other on an integrated ESP32. In real time, all parameters at the substation, voltage, frequency, power, circuit breaker status and transformer temperature, are monitored in real time. A substation control controller has been developed, where the starting mechanisms are also programmed. After a while, the mechanisms are triggered, the data is recorded by the controller and transferred to the NAS. Industry standard GPS is used to provide high resolution timestamps and synchronization functions. The integrated FPGA controller provides high-speed and reliable data acquisition and processing functions. With the help of the Internet of Things platform, data is transmitted and stored via a local network. System operators can remotely access real-time data and retrieve data from a SAN on the network. The dispatching control of the substation of the power system in SCADA was also developed. In future works, experimental works on this topic will be implemented for further analysis.

REFERENCES

[1] IoT: Communication protocols and security threats Internet of Things and Cyber-Physical Systems, 4 January 2023Volume 3 (Cover date: 2023)Pages 1-13 Apostolos Gerodimos, Leandros Maglaras, Ioanna Kantzavelou.

[2] Ch. L. Chou , Yu. Yu. Color , R. Marculescu Incremental comparison taking into account power consumption and performance for NoC with multiple voltage levels IEEE trans. calculation. Help Des. integra. System Circuits., 27 (10) (2008) , page 1866-1879
https://doi.org/10.1002/cac2.12147

[3] E.Khajekarimi, M.Hashemi Communication and congestion aware run-time task mapping on heterogeneous MPSoCs, May 2012
http://doi.org/10.1109/CADS.2012.6316432

[4] T. Ley, S. Kumar, A two-stage genetic algorithm for matching problem graphs with a network based on a chip architecture, in: Proceedings of the Euromicro Symposium on Digital Systems Design (DSD), Belek-Antalya, Turkey, 2003, p.180–187.
http://doi.org/10.1109/DSD.2003.1231923

[5] Jingcao Hu, R. Marculescu Energy- and performance-aware mapping for regular NoC architectures. IEEE Trans Comput-Aided Des Integr Circ Syst. May 2005IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems 24(4):551 - 562
http://doi.org/10.1109/TCAD.2005.844106

[6] Kh. Wang, M. Yang, Yu Jiang, P. Liu, Energy-aware mapping for network-on-chip architectures with bandwidth and latency constraints, in: International Conference on Embedded and Multimedia Computing (EM-COM), Jeju, Korea, 2009, p.1–6.

[7] Arzamassev D.A., Bartolomey P.I., Kholyan A.M. Automated control systems and optimization of power systems modes. – M.: Higher School, 1983. – 208 p.

[8] Alekseev A.A., Suvorov A.A. Phase-by-phase identification of the parameters of the replacement circuits of the elements of the EES. // Materials of the sixth All-Russian Scientific and Technical Conference "Energy: ecology, reliability, safety". Tomsk: TPU Publishing House, 2000. pp.22-24.

[9] Aakesh U, Yaswant Rajasekaran, Sabarivani, Sudhakar T. Review on Healthcare Monitoring and Tracking Wristband for Elderly People using ESP-32. 2023 5th International Conference on Smart Systems and Inventive Technology (ICSSIT) | 978-1-6654-7467-2/23/$31.00 ©2023
http://doi.org/10.1109/ICSSIT55814.2023.10061134

[10] Y. T. Lee, W. H. Hsiao, C. M. Huang, and S. C. T. Chou, “An integrated cloud-based smart home management system with community hierarchy,” IEEE Trans. Consumer Electron, vol. 62, no. 1, pp. 1-9, Feb. 2016

[11] Bhushan Chaudhari, Nachiket Shinde, Gitesh Yelave, Real-Time Electricity Bill Management System Using IoT. 2023 International Conference on Emerging Smart Computing and Informatics (ESCI) AISSMS Institute of Information Technology, Pune, India. Mar 1-3, 2023.

[12] Long Zhao, Igor Matsuo, Yuhao Zhou, Wei-Jen Lee. Design of an industrial monitoring system of electrical substations based on IoT. Authorized licensed use limited to: Politechnika Lubelska. Downloaded on June 22, 2023