Development of an Internet of Things based Electrical Load Management System

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Abstract. This paper presents an interoperable automation system that uses the Internet of Things technology for remotely controlling and monitoring electrical appliances connected to the power supply system. Transducers located inside the socket outlets collect vital information regarding the status of the electrical network. This information includes the AC consumption, appliance status, and information from the RFID tags. The sensor and actuators are integrated with a small microcontroller known as NodeMCU. This microcontroller is equipped with an onboard Wi-Fi transceiver thus data is processed and reliably transmitted from each socket outlet to a single board computer, known as the Raspberry Pi. The received information is processed and displayed on a standard web interface hosted by the LINUX based computer. The web interface has a variety of interactive widgets enabling the user to ‘talk’ to the appliances in real-time. Communication among the IoT devices is handled through a lightweight application layer protocol known as the MQTT protocol. Another unique feature of the presented system is its ability to identify various power quality issues that frequently occur in most electrical networks. The automation system contributes to the conservation of energy by increasing the awareness of the consumer on their daily electrical energy usage.

1. Introduction

The report by The World Energy Council indicates that globally the electricity demand will continue to rise sharply until the year 2040 because processes such as heating, manufacturing, and transportation are shifting towards electricity as the main energy resource [1]. But the currently available electrical power supply system is more than a century old and suffers from several shortcomings [2]. One of the major problems is that consumers lack clear-cut information specifically, transparent and actual energy consumption of their appliances. Also, the currently available technologies for remotely monitor and control electrical appliances are either overcomplicated or unaffordable to many consumers. According to Yang et al., an efficient remote management system incorporates three significant features which are: controllability, interconnectedness, and reliability [3].
The Internet of Things (IoT) is an ecosystem of interconnected devices or things provided with unique identifiers (UIDs) and having the autonomous capability to transfer data over a network without requiring external agents.

A recent survey conducted by CISCO [4] predicts that globally, machine to machine (M2M) connections will be doubled, from 7 billion in 2018 to 14.6 billion in the year 2022. Smart home technologies such as automation, connected sensors, smart home appliances, and security and video surveillance systems will represent half of the total M2M connections by 2022.

Automation in the context of electrical power supply systems can be defined as an intelligent system that manages, controls, and protects the electrical power supply system autonomously. An efficient automation system requires a robust communication infrastructure and reliable data collection tools. This can be achieved by integrating IoT technology to the automation system. The main components of an automated electrical power supply system include control and protection devices, measurement devices, monitoring system, and the communication infrastructure.

Automating a power system improves the efficiency of the grid. According to Cobus [5], the main advantages of using an intelligent and interactive electrical power supply system are:

- Better performance of protection devices
- The real-time status of the system is displayed
- Options of remotely controlling the system
- Advanced energy management is possible

The main objective of this project is to develop a prototype of an IoT based electrical power supply automation system which is suitable for domestic and industrial applications. The proposed system enables a user to remotely control the electrical network and monitor the real-time status of appliances in the system.

2. Review of Similar Technologies

In the past few years, several studies have been conducted in the area of IoT based energy monitoring and smart home systems. In this section, some of the most relevant technologies will be discussed. Lestari et al. developed a web-based electrical energy monitoring system. The system uses AC voltage and current sensors interfaced with an Arduino Nano microcontroller. A wireless transmitter hooked up with the Arduino publishes the data to a Raspberry Pi based central server. The IoT system employs an adaptive publish-subscribe concept in which data is only transmitted when there is a deviation from a
previously registered value [6]. Similarly, Thakare et al. [7] proposed the implementation of a portable energy metering system using a non-invasive current sensor. The sensor is interfaced with the analog port of the Arduino Nano microcontroller. The data from the microcontroller is transmitted to a server by using an ESP8266 WiFi module. Also, a Nokia 5110 LCD module connected with the microcontroller displays the real-time energy consumption in Kilowatt Hours. The web page was designed in such a way that it can display real-time energy consumption as well as provides a control interface for remotely switching on and off the electric power supply.

The IoT based power metering and controlling system developed by Kurde and Kulkarni [8] uses a current sensor and a relay connected with an Arduino Uno microcontroller. A Raspberry Pi computer collects data from the Arduino and transmits it to a cloud based IoT platform known as ThingSpeak. This platform is used for analyzing, visualizing, and storing the energy consumption data from remote sensors. Also, ThingSpeak provides virtual dashboards and buttons for remotely controlling the electrical appliances. Likewise, Aghenta and Iqbal [9] developed an open-source SCADA system consisting of current and voltage sensors, OLED display, ESP32 microcontroller, and a Raspberry Pi server. The ThingsBoard IoT server software is deployed on the Raspberry Pi and MQTT protocol is used for facilitating the communication between the sensor nodes and the server. The energy monitoring and control prototype developed by Hartman et al. [10] also uses the IoT technology in combination with the Amazon Web Service (AWS) for effective control and storage of the energy data. In the proposed system Raspberry Pi Zero was wired with a CT clamp sensor and a solid-state relay. Its compact size, robust communication capability, and low power consumption make the raspberry pi zero a perfect fit for the project. The data from the CT sensor was sent to a cloud-based MySQL database hosted in the AWS. A special iOS application was developed which interacts with the database and provides full graphical access to the user.

Pereira et al. [11] presented a renewable energy monitoring system (REMS) for a decentralized solar PV plant. The REMS uses IoT technology and embedded electronics for monitoring and analyzing parameters such as PV voltage and current, ambient temperature, solar irradiance, and relative humidity. A SanUSB microcontroller collects data from the sensors and transmits it to a Raspberry Pi computer through the serial COM port. The Raspberry Pi sends the data to the cloud and where a web application is generated. Analogously, Kekre and Gawre [12] presented an experimental setup for monitoring the status of solar PV systems using a low-cost IoT technology. The system uses temperature and current sensors interfaced with Arduino Uno. A SIM900A GPRS module is used for establishing the required connection to the internet. A dedicated computer system collects and processes the data from the sensors. Also, a stand-alone web hosting service running on the computer enables the user to monitor the PV system from any location. Friansa et al. [13] developed an IoB based battery monitoring and management system suitable for microgrids. The IoT system consists of Intelligent Electronic Device (IED) and a Raspberry Pi based embedded system for creating a communication link with the cloud. The IED measures battery temperature, voltage, and current and uses a proprietary serial communication for transmitting the data to the embedded system using the JSON format. The Raspberry Pi processes the data using PHP and transmits it to the cloud through TCP/IP protocol.

3. Materials and Methods
This section describes the methodology and the materials used for developing the IoT based electrical energy monitoring and management system.

3.1 Hardware development
The heart of the IoT system is a small credit-card-sized Raspberry Pi computer. The computer collects and processes the data sent by the microcontrollers and transmits commands from the web interface to the
Actuators. In addition, an HD night vision camera is directly integrated into the computer for real-time monitoring of the electrical power supply system. The NodeMCU microcontroller is directly connected to all the transducers embedded in the socket outlet. Each socket-outlet is equipped with an RFID module, a non-intrusive current sensor, and a solid-state relay. Every appliance was tagged with an RFID transponder and assigned with a unique alphanumeric code. An RC522 RFID module attached to each socket outlet identifies tagged appliances and shares information regarding their connection status to the microcontroller. The flow chart in figure 2 shows the algorithm implemented for identification and control of electrical appliances using the RFID system.

![Figure 2. Algorithm for appliance identification using RFID](image)

The NodeMCU is also responsible for orchestrating the flow of data between the transducers and the Raspberry Pi computer. The connection between the transducers and the microcontroller is shown in the schematic diagram in figure 3.

![Figure 3. The developed automation system (a) prototype (b) Schematic diagram](image)

Just like any other transformer, the non-intrusive current sensor has primary and secondary windings. An alternating current passing through the primary coil induces a directly proportional current in the secondary. The induced current signal needs to be converted into a voltage signal to be intelligible by the microcontroller. The conversion was done by connecting a resistor, known as a Pull-up resistor, to the output of the sensor. The value of this resistor was determined mathematically and found to be 235 Ohms.
3.2 Calibration of the Sensors
Before integrating the sensors into the IoT system, calibration is necessary by exposing them to some predetermined events. The current sensor was calibrated by using purely active loads of different ratings. A high precision digital multimeter (DMM) was used for measuring the actual current and voltage consumption of the load. Meanwhile, the RMS (Root Mean Square) value of the output of the sensor was computed and recorded for each load. Table 1 shows the results of the experimental setup.

| Electrical Load (W) | DMM Reading (A) | Sensor Reading (RMS) |
|---------------------|-----------------|----------------------|
| 25                  | 0.113           | 284                  |
| 40                  | 0.173           | 329                  |
| 60                  | 0.273           | 356                  |
| 75                  | 0.348           | 367                  |
| 95                  | 0.411           | 375                  |
| 115                 | 0.508           | 384                  |
| 150                 | 0.665           | 393                  |
| 175                 | 0.777           | 397                  |

Next, a statistical analysis method was implemented for generating a trendline equation of the sensor readings. The results of the experiment were used to developing a C++ function that allows the NodeMCU to accurately convert sensor readings to amperes and send that data to a central IoT server. The graph in figure 5 shows the polynomial relationship between the sensor and DMM readings. The equation obtained from the trendline curve helps in converting future sensor readings into values of current consumption in amperes.

![Figure 4. The polynomial trendline for sensor and DMM readings](image)

4. Design of the Communication Infrastructure
The proposed system was built up by considering the OSI network model. This model describes a network architecture that enables data to be passed between computer systems through seven layers [14]. The physical layer is the lowest layer of the OSI network model. This layer is responsible for sending data from one device to another across the network. Before selecting a suitable one, various wireless protocols were considered and compared. Table 2 summarizes the most common physical layer protocols.
### Table 2. Comparison among wireless protocols

| Wireless protocol for IoT | Frequency          | Data Transmission Rate | Range   | Power Consumption | Open or Proprietary | Module Cost |
|--------------------------|--------------------|------------------------|---------|------------------|---------------------|-------------|
| Bluetooth5               | 2.4GHz             | 50Mbit/s               | 240m    | Medium           | Open                | Low         |
| LoRa                     | 150MHz-1GHz        | 50Kbit/s               | 32Km    | Low              | Open                | Medium      |
| MiWi                     | 2.4GHz             | 250Kbit/s              | 250m    | Low              | Proprietary         | Low         |
| NB-IoT                   | <1GHz              | 0.1 – 1Mbit/s          | 30Km    | Medium           | Open                | High        |
| SigFox                   | 868MHz             | < 1Kbit/s              | 30Km    | Low              | Proprietary         | High        |
| Weightless (W, N, P)     | 915MHz             | 200 bit/s – 100Kbit/s  | 2Km     | Low              | Open                | High        |
| Wi-Fi                    | 2.4GHz/5GHz        | 54Mbit/s               | <100m   | High             | Open                | Low         |
| ZigBee                   | 2.4GHz             | 250Kbit/s              | 250m    | Low              | Open                | Medium      |
| Z-Wave                   | 868MHz             | 20Kbit/s               | 100m    | Low              | Proprietary         | Medium      |
| 3G/4G                    | Cellular Bands     | 200Kbit/s and 10Mbit/s | 30Km    | High             | Proprietary         | High        |

The IoT system requires a wireless protocol high data rates and with small coverage area. Based on the data from Table 8, Wi-Fi was found to be an ideal solution for the system. Additionally, both the NodeMCU and the Raspberry Pi have built-in Wi-Fi transceivers thus adaptation of the Wi-Fi protocol is viable and less complex.

The next step in the design of an effective communication infrastructure for the IoT system is the determination and implementation of a suitable Application layer protocol of the OSI network model. The main tasks of the application layer are the identification of communication partners, determination of availability of network resources, and synchronization of communications. In general, the application layer is responsible for the data exchange between the two systems. There are different application layer messaging protocols specially crafted for IoT systems [15, 16]. Some of the most popular messaging technologies available are the CoAP(Constrained Application Protocol), XMPP (Extensible Messaging and Presence Protocol), MQTT (Message Queue Telemetry Transport), AMQP (Advanced Message Queuing Protocol), and the DDS (Data Distributed Service) protocol.

Among them, the MQTT protocol was selected for use in this project. This protocol is suitable for IoT based application where a large wireless sensor network is managed by a single server. The MQTT architecture is based on the Publish/Subscribe model and has three elements which are, Publisher, Broker, and Subscriber. Publishers are responsible for transmitting data to the broker while Subscribers are applications that collect the data. The broker implemented for use in the proposed system is MOSQUITTO. Eclipse Mosquitto is a lightweight and open-source message broker that uses the MQTT protocol [17].
5. Development Power Quality Monitoring Strategy

The term power quality is used to indicate stable and steady values of voltage, current, and frequency that fall within a predefined limit. The proposed automation system continuously monitors the power supply system for any anomaly in the power quality. The quality parameters considered in this project are voltage dip, impulse voltage, voltage interruption, frequency deviation, and harmonic distortion. If any of the values deviate from the predefined range, the system automatically sends a warning to the user via the web interface. Based on the information provided, the user can take the necessary action to fix the problem. Figure 6 shows part of a JavaScript function that enables the system to monitor one of the power quality parameters i.e. Voltage Dip.

```javascript
var sensorVal = msg.payload;
var V_min = 1.0; // Minimum value of V drop
var V_max = 1.0; // Maximum value of drop
if (sensorVal < V_max && sensorVal > V_min){
    msg.payload = "Voltage Dip detected!
the mains voltage decreased to " + sensorVal;
}
return msg;
```

Figure 6. Snippet of JavaScript function for PQ monitoring

6. Results and Discussion

The IoT communication system, particularly the MQTT, was tested by sending several packets of data from each sensor node. In all cases, the data reached successfully the IoT server and displayed correctly on the HMI. A similar result was also obtained by using a LINUX computer configured as a sensor node and publishing 57 bytes of data to the broker. Figure 6 shows the track of events occurring while testing the MQTT broker. The results indicate that the developed system is interoperable and can easily be expanded to a wide variety of applications.

Similarly, the accessibility of the HMI was evaluated by sending requests from different devices. A command sent from the web interface took about 1500 milliseconds to reach the actuators connected with the socket outlets. Similarly, updates regarding the connection of an appliance to the outlet took on average about 1600 milliseconds to appear on the HMI. Figure 7 illustrates a snippet of the interactive web interface appearing when the IoT system is in actual operation.
7. Conclusion

In this paper, it has been shown the development of an IoT based electrical energy management system. The system employed an array of sensors and actuators for monitoring and controlling electrical appliances. Also, each appliance was tagged with unique RFID transponders. An IoT firmware, known as NodeMCU, processes and transmits the information from the transducers to a central server. Communication between the sensor nodes and the broker was achieved through a lightweight MQTT protocol. A LINUX based Raspberry Pi computer functions as a server and a central node of the wireless sensor network. The computer processes information from all the sensors and makes it available on a web-interface. Fundamental parameters of the electrical network such as current, voltage, power consumption in real-time, and appliance status are displayed on the webpage of the IoT system. Also, an algorithm was developed for monitoring the quality of the power in the network and notify the user if variations from standard values are detected. Finally, it can be concluded that electrical power supply systems and appliances can effectively be controlled, monitored, and managed by using the developed IoT platform. Besides the system is versatile and scalable thus it can easily be adapted for application in high voltage networks. The potential application scenarios for the developed system include smart homes, microgrids, and smart grids. Furthermore, there is a possibility of using the data, harvested by the system, for other applications such as machine learning and artificial intelligence.

It is assumed that the results of this work will be included in the training course of the new master's program “Conceptual Design and Engineering of Improving Energy Efficiency” [18] for the training of engineering skills, scientific personnel and management personnel in the power industry, grid companies and related sectors.
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