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A smart IoT based system for monitoring and controlling the sub-station equipment

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ABSTRACT

Remote monitoring and controlling of the sub-station equipment is an important issue for the power/energy management department which is normally done manually, or using an expensive PLC and SCADA system. With the emergence of the internet and computational era, a smart monitoring and reliable controlling system over the entire sub-station equipment is highly desirable that can be achieved by introducing the Internet of Things (IoT) technology. IoT is the network of physical devices embedded with electronics, software, sensors, actuators and network connectivity which have the ability to identify, collect and exchange the data. Each thing is uniquely identifiable through its embedded computing system and able to interoperate within the existing internet infrastructure. This paper proposed an IoT based network strategy for monitoring and controlling the sub-station equipment so that managing time and resources can take place as efficiently as possible. The IoT based system allows objects to be sensed or controlled remotely across existing network infrastructure, creating opportunities for more direct integration of the physical world into computer-based systems and resulting in improved efficiency, accuracy and economic benefit with the added merits of minimum human intervention. Moreover, a prototype system has been implemented and tested for measuring the effectiveness of the proposed model.

1. Introduction

Sub-stations are an important part of the power system and a typical sub-station consists of different types of equipment such as transformers, circuit breakers (CB), relays, lightning arresters (LA), current transformers (CT), potential transformers (PT), isolators, capacitors, and so on [1,2]. In other words, sub-station is the assembly of apparatus used to change some characteristic (e.g. voltage AC to DC, voltage level, frequency, power factor, etc.) of electric supply [3]. Usually, the sub-stations are monitored and controlled manually, or by using expensive PLCs and SCADA system which required more manpower and involved a higher maintenance cost [4]. Under the conventional protection of sub-station especially in differential protection, the relay often requires pilot wires to operate itself which involves a greater capital cost in addition with a sudden interruption of relay operation. To mitigate the mentioned disadvantages, IoT based sub-station monitoring and controlling offers a promising solution with a fully automated system ensuring a greater level of reliability, and thereby increase of the system performance with the efficient use of the equipment.

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"Internet of Things" in short form IoT is created from the word "Internet" and "Things" where "Things" refers to any internet connected device [5]. The Internet of Things (IoT) is a system of interrelated computing devices, mechanical and digital machines, objects, animals or people that are provided with a unique identifier and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction. In recent years, the IoT is augmented with sensors and actuators, the technology becomes an instance of the more general class of cyber-physical-systems, which also encompasses technologies such as smart grids, virtual power plants, smart homes, intelligent transportation, and smart cities [6,7]. Because of low-cost, networkable micro-controller modules, the Internet of Things is considered as the key technology to establish a smart sub-station. However, IoT itself has still not reached into maturity and many IoT communication protocols such as CoAP [8] MQTT [9], XMPP [10] have been proposed as IoT standards. These protocols vary in characteristics with different strengths and limitations [11]. Finally, due to the technological revolution all over the world, smart technologies are replacing the old ones [12,13]. In the power sector, IoT technology is becoming more attractive nowadays. It is expected that within 2020, around 20–50 billion things would be connected to the internet throughout the world [14,15].

The main aim of this work is to develop a fully automated IoT based sub-station by which associated equipment can be protected, monitored and controlled from any place in the world only by the authorized personnel at a very low cost. Reliability and reduction of manpower using IoT technology are also the prime concerns while developing smart sub-station framework.

The rest of the paper is organized as follows. A thorough review of related studies is discussed in Section 2. Section 3 illustrates the system model highlighting the major parts of the system. Section 4 represents the experimental setup along with the practical circuit diagram. Section 5 includes the results and discussion. Finally, Section 6 concludes this paper.

2. Related studies

Over the last decade, numerous research work has been conducted and significant development has been made in the Internet of Things (IoT) technology related to power sector infrastructure. A number of relevant studies carried out on the IoT technology are summarized here. According to [16–20], IoT technology in the smart metering system has already been implemented worldwide for grid power measurement and residential electricity billing system. In the power sector, many studies have been conducted for improving the energy crisis by adopting renewable energy sources [21,22]. At the same time, researchers demonstrate that in the electric power saving and management sector, many IoT based devices are designed [23–28]. IoT technology is also proposed to develop a smart grid system that can be operated from a remote place [29–31]. IoT technology for improving and controlling renewable energy based system is also proposed [33–35]. Online monitoring of line currents, line voltages, power consumption and load forecasting based on IoT system are becoming popular day by day [36,37]. Automation of substation [4] and health monitoring of electrical equipment from a remote location using IoT is also a hot topic [38-40]. Qing-Hai et al. [41] proposed a model for status monitoring and early warning system for the power distribution network based on IoT. The authors tried to cover environmental monitoring i.e. immersion status of environmental temperature and humidity and water immersion. The system will display monitoring points of the latest environmental temperature, humidity and water immersion status data in distribution equipment i.e. real-time monitoring of temperature information of distribution network equipment, early warning and alarm and theft finding by installing door magnetic sensor in monitoring points such as cable channel, cable well cover, ring net cabinet, transformer control cabinet surface etc. R. Li, J. Liu and X. Li proposed a model for developing a networking scheme for transmission line on-line monitoring based on IoT [42]. Meanwhile, it optimizes networking protocol by means of low overhead control, taking into account the low-power needs of node device as well. X. Shen et al. designed a model of the management system of the life cycle of power transmission and transformation equipment based on Internet of Things [43]. It includes abnormal alarm of electrical equipment, comprehensive diagnosis of equipment status, and life cost analysis of electrical equipment. Authors in [44] focused on developed a model of IoT based SCADA integrated with fog for power distribution automation to take care of the consumer utilization, outage management, power quality control, and pole transformer health. This is supported by fog computing dealing with real-time streaming analytics. This helps in reducing the internet bandwidth and latency for immediate control action.

3. System model

Fig. 1 shows the architecture of the proposed system. This proposed system provides an operator at a remote location with sufficient information to determine the quality and present amount of oil in the transformer & oil circuit breaker (OCB). At any alarming condition, an alarm message with what corrective action to be taken will be provided to the operator. This system also allows the operator to perform circuit breaker operation and relay plug/transformer tap changing operation without being physically present at that sub-station. Any authorized person can also perform the same tasks by visiting the power system's official webpage. Besides monitoring & controlling, this system represents an alternative way to provide differential protection where the distance between two sides of the equipment has no effect on system performance.

The algorithm of the proposed model is simplified to a flowchart as shown in Fig. 2. After the successful connection of communication devices with the internet the process actives by searching the instructions from a web server and ends by uploading the data to the server via Wi-Fi. In the suggested system, we performed programming into the microcontroller unit in accordance with the initial approximated values of multiple sensors for normal condition. To estimate the amount

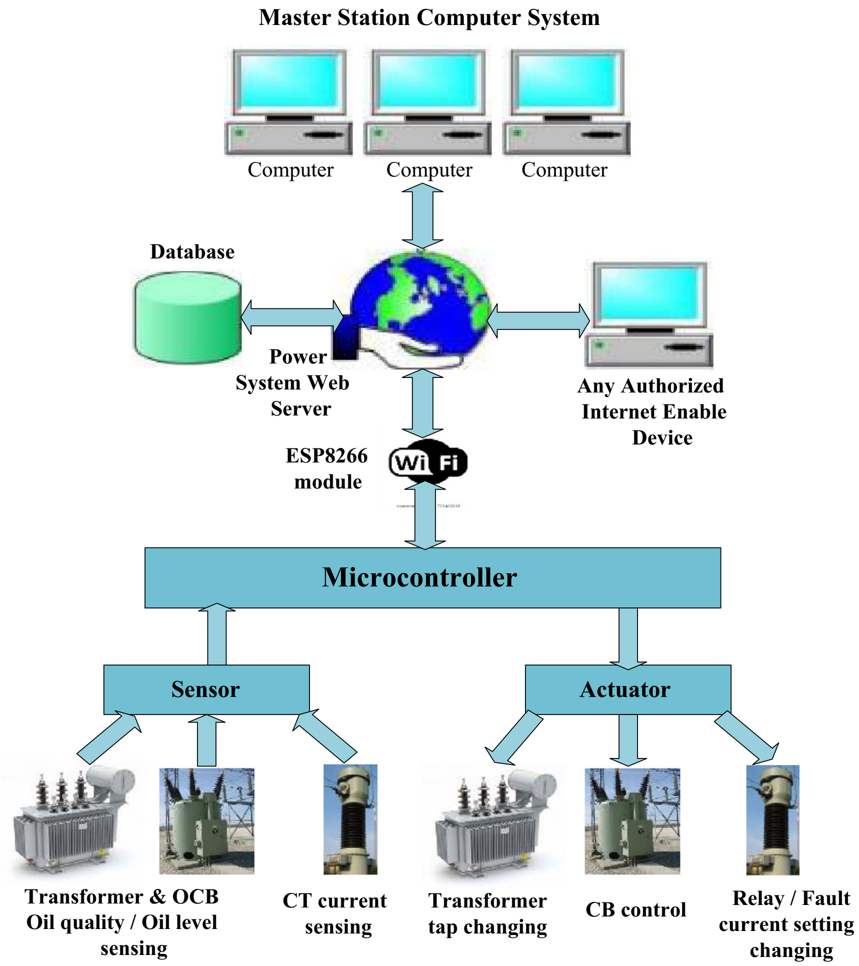

Fig. 1. Block diagram of the proposed model.

of oil in the transformer, a sensor is placed nearly 12 cm above on the oil surface. In this condition, the sensor measures the distance between its level and oil surface (12 cm) which is considered as the oil tank vacancy. If the oil level goes down, then its vacancy increases. The maximum allowable condition was predefined according to the system capabilities. The response of this level sensing system was satisfactory. For the oil deterioration sensor, we took reading for fresh soybean oil and blackish fuel oil. The outputs of those measurements were considered as 0%–100% deterioration level respectively. Then an allowable condition was approximated. The accuracy of this sensor was found very high and the observed output was satisfactory. A concise description of the major parts of the system is provided below.

3.1. Sensor

The sensor senses the transformer/OCB oil quality and oil amount and transmits data to the server. It also senses the current of the current transformers (CTs).

3.1.1. Transformer/OCB oil level sensor

In order to determine the transformer/OCB oil level, an ultrasonic sensor is widely used. An Ultrasonic sensor is a device that can measure the distance to an object by using sound waves. It measures distance by sending out a sound wave at a specific frequency and listening for that sound wave to bounce back. By recording the elapsed time between the sound wave being generated and the sound wave bouncing back, it is possible to calculate the distance between the sonar sensor and the object. Fig. 3 shows how the sonic sensor works.

Since it is known that sound travels through air at about 340 m/s, the distance can be calculated by knowing the total round-trip distance traveled by the sound wave. Round-trip means that the sound wave traveled 2 times the distance to the object before it was detected by the sensor; it includes the ‘trip’ from the sonar sensor to the object and the ‘trip’ from the

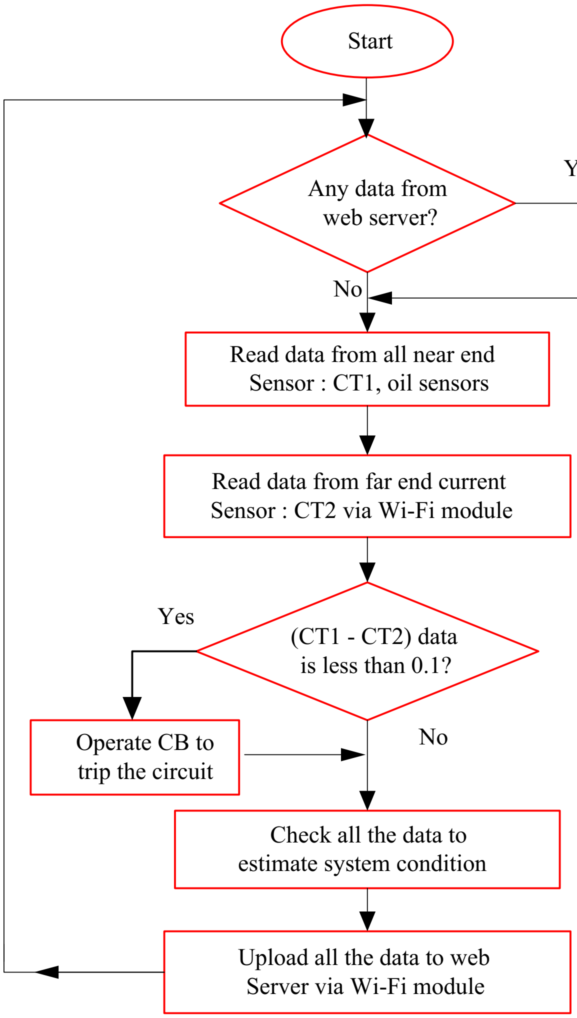

Fig. 2. Flowchart of the proposed model.

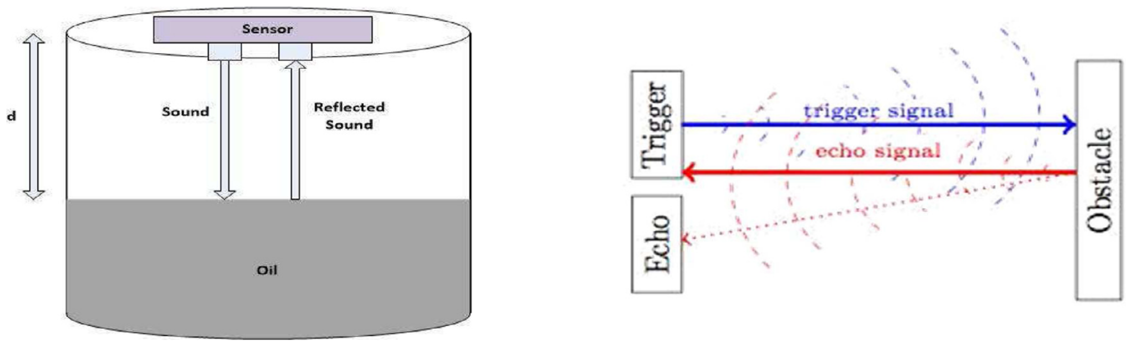

Fig. 3. The principle of the sonic sensor.

object to the Ultrasonic sensor.

$$v = \frac{2d}{t} \tag{1}$$

$$d = vt \tag{2}$$

Where the v = velocity of the sound wave (340 m/s), d = distance from the top of the reservoir to oil surface and t = time required from transmission to reception of reflected sound.

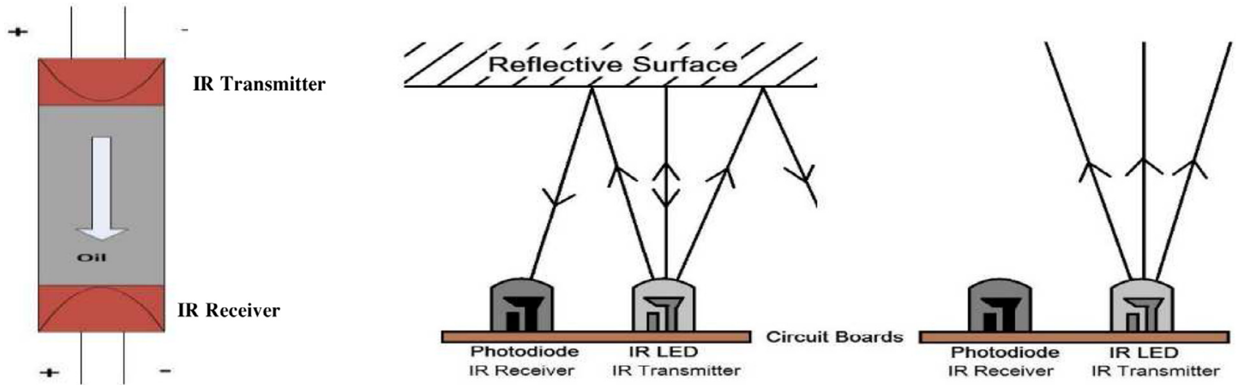

Fig. 4. The principle of oil deterioration sensor.

Fig. 5. IR transmission & reception.

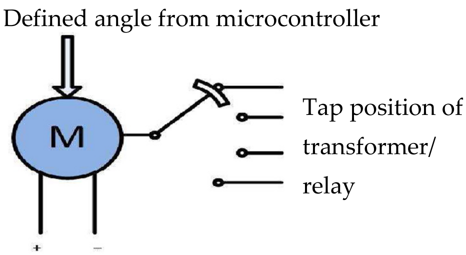

Fig. 6. Principle of tap changing.

3.1.2. Transformer/OCB oil quality sensor

For measuring the transformer/OCB oil quality IR sensor is a popular one. IR Sensors are basically electronic devices which are used to sense the changes that occur in their surroundings. The change may be in color, temperature, moisture, sound, heat, etc. They sense the change and work accordingly. In the IR sensor, there is emitter and detector. The emitter emits the infrared rays and detector/receiver detects it as shown in Fig. 4.

In summary, the IR transmitter and IR receiver are placed in an oil immersed vessel senses the oil deterioration level. Transformer oil itself is a hydrocarbon. Hydrogen, CO_2, vapor, carbon are the main products of transformer oil decomposition. Oil color changes from a light color to dark with deterioration. The infrared ray transmitted from the IR transmitter is traveled through the transformer which is then received by the IR receiver. With the deterioration of the oil, received signal by the IR receiver decays. A typical system for detecting infrared radiation is given in Fig. 5.

3.2. Actuator

Actuator performs the tasks that are required by the operator at a remote location. Microcontroller itself acts as an actuator device. It commands the I/O devices connected with it to perform a specific task. Servo motor connected with the microcontroller rotates at a specific angle to change the transformer tap position or relay plug setting according to the microcontroller's command as shown in Figs. 6 and 7. The relay connected with the microcontroller performs the on/off operation.

3.3. IoT based differential protection

Though the differential protection is one of the best protection schemes for electrical equipment, this protection scheme can't be applied for every system due to the fact that cost of pilot wire, the effect of pilot wire's capacitance on system performance increase with the increase of pilot wire length. IoT based differential protection is a smart solution where two modules send the secondary current data to the web server presented in Fig. 8. When the data coming from two different terminals of the protected zone differs from each other beyond permissible limit, the web server sends a command to an

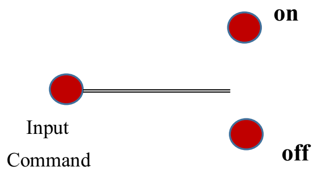

Fig. 7. Principle of CB control.

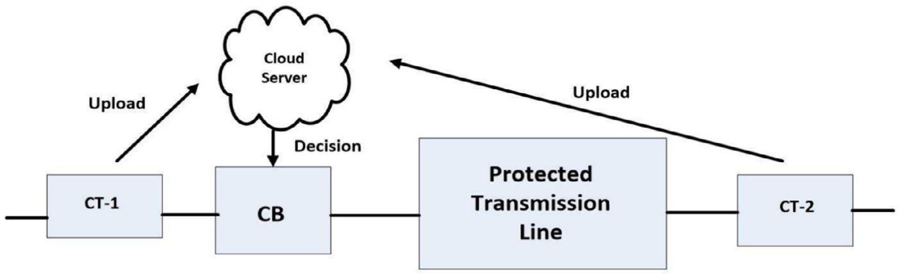

Fig. 8. IoT based differential protection.

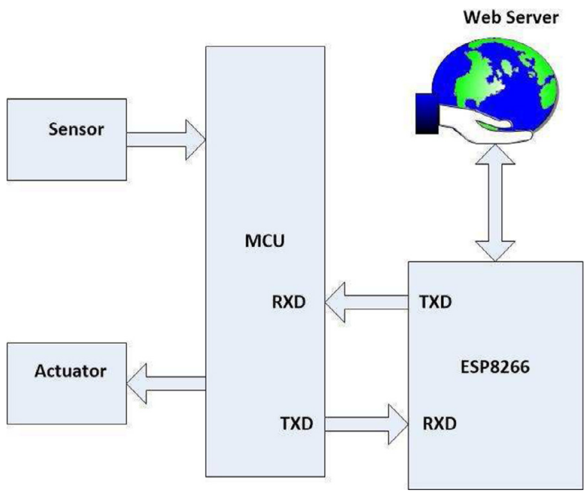

Fig. 9. The function of the microcontroller & Wi-Fi module.

internet module which initiates the CB operation to protect the system. In this way, the problem associated with a pilot wire can be eliminated.

3.4. Microcontroller

The microcontroller reads the sensors data then transmit these values serially to the ESP8266 Wi-Fi module through TXD pin. It also receives the serial data sent by the ESP8266 Wi-Fi module by its RXD pin. According to this incoming data from the web server via the ESP8266 Wi-Fi module, microcontroller enables the responsible I/O device connected to it and send a command to that device to perform the required task.

3.5. Wi-Fi module

Wi-Fi module (ESP8266) communicates with the microcontroller through serial communication. It can also access the internet when connected to an access point which is the internet service provider. This module receives data from the specified web-page and transmits those data to the microcontroller. It also uploads data sent from the microcontroller to the specified web page as shown in Fig. 9.

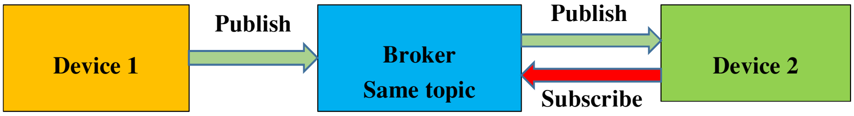

Fig. 10. MQTT protocol system.

Fig. 11. Control panel.

3.6. Web server

A web server is an internet-connected device that stores and serves files. Clients can request such a file or another piece of data, and the server will then send the right data/files back to the client. Requests are made using a different protocol like HTTP, MQTT, etc. Hyper Text Transfer Protocol or HTTP is great for things like downloading web pages, uploading photos, etc., but it's quite slow. For IoT, MQTT protocol is preferable. It is a nice lightweight publish and subscribe system where anyone can publish and receive messages as a client.

3.6.1. MQTT publish/subscribe

MQTT stands for Message Queuing Telemetry Transport. MQTT is a lightweight publish/subscribe messaging protocol. MQTT is fast becoming one of the main protocols for IoT (Internet of Things) deployments.

In the MQTT protocol, all the devices subscribed to a topic are called clients. All clients can publish (broadcast) and subscribe (receive). Messages are published to a broker on a topic as shown in Fig. 10. Messages are the information that you want to exchange between your devices. Whether it's a command or data. Topics are the way you register interest for incoming messages or how you specify where you want to publish your message. The broker is primarily responsible for receiving all messages, filtering the messages, decide who is interested in it and then publishing the message to all subscribed clients. The job of an MQTT broker is to filter messages based on topic, and then distribute them to subscribers. There is no direct connection between a publisher and a subscriber. To publish data to a client, there's no need to know the address of the receiver. A client can receive messages just by subscribing to that topic on the same broker.

3.7. Control and monitor

From every internet enabled a device which can access the official website's controlling & monitoring web page can perform the tasks of monitoring the sub-station equipment's current status and control the equipment. The user must verify himself to access the official web page by a password. Fig. 11 depicts the front side of the webpage from which controlling and monitoring the equipment is possible.

4. Experimental setup

Experimental setup of the prototype system has been provided in Fig. 12 where the precision of the system depends on the sound design of the circuit and the proper arrangement of the circuit elements. In this experimental work, a servo motor has been operated instead of CB and the oil of the transformer/OCB has been placed in a vessel. Additionally, a simple circuit has been made using a lamp to apply the differential protection scheme by sensing the CTs currents. However, all the real-time data processing was done on the central microcontroller unit. After gathering the sensors data, it checks for any data limit violation. If there is a violation, then the predefined decision is made and proper action is done. then it sends all

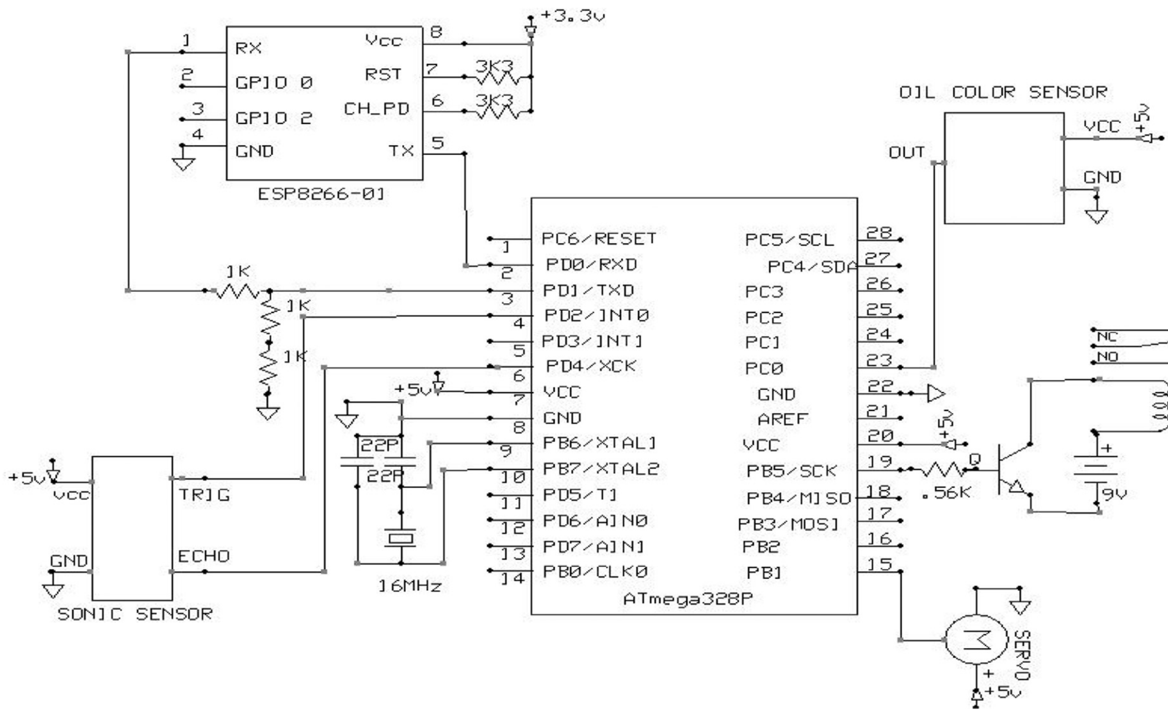

Fig. 12. Circuit diagram of the prototype system.

the data to the webpage via Wi-Fi module. If there is no data limit violation, it just passes the data to the Wi-Fi module. The encryption of every sensor's data is also done by this unit for proper detection of data in the Wi-Fi module. Similarly, when a message arrives from the webpage to the central microcontroller via the Wi-Fi module, it decodes the message and takes a decision. Figs. 13 and 14 illustrate the PCB layout and corresponding hardware implementation of the prototype system. The operating principle of the key units are described below:

4.1. Functions & design of microcontroller side

Atmel pico power 8bit microcontroller ATmega328-P is the heart of the system. It communicates with the ESP8266-01 Wi-Fi module which is connected to the web server by serial communication technique. It receives a command from the ESP8266-01 Wi-Fi module through its RXD pin and sends the sensors data to ESP8266-01 Wi-Fi module by its TXD pin. All the sensors and actuators are connected to the microcontroller as I/O device. The microcontroller reads data from the sensors continuously and encodes them to transmit serially to ESP8266-01 Wi-Fi module. According to the received command at its RXD pin, the microcontroller controls the relay and servo motor which act as CB control system and tap/relay current setting changer respectively.

4.1.1. Sensing oil level

To sense the distance of the oil surface from the top of the oil tank, an ultrasonic sensor is connected with the microcontroller as shown in Fig. 15. The "TRIG" pin & "ECHO" pin of the sensor is connected to digital I/O pin 4 & 6 of the microcontroller respectively. The sensor is triggered by a HIGH pulse of 10 or more microseconds. A short LOW pulse provided beforehand to ensure a clean HIGH pulse. Reading the signal from the sensor: a HIGH pulse whose duration is the time (in microseconds) from the sending of the ping to the reception of its echo off of an object, the distance can be determined easily by (2).

4.1.2. Sensing oil quality

To sense the oil darkness level, an IR receiver terminal is connected to analog pin 23 of the microcontroller as shown in Fig. 16. Pin 23 can sense a 0V-5 V range of voltage variation and generates a 10 bits output. The terminal voltage of the IR receiver depends on the receipt IR emission traveled through the oil which is inversely proportional to the oil deterioration.

4.1.3. Circuit breaker control

To control the tripping and closing of the circuit breaker, a 9 V relay along with other additional components is connected to digital pin 19 of the microcontroller as shown in Fig. 17. When a command from the web server to close the circuit comes

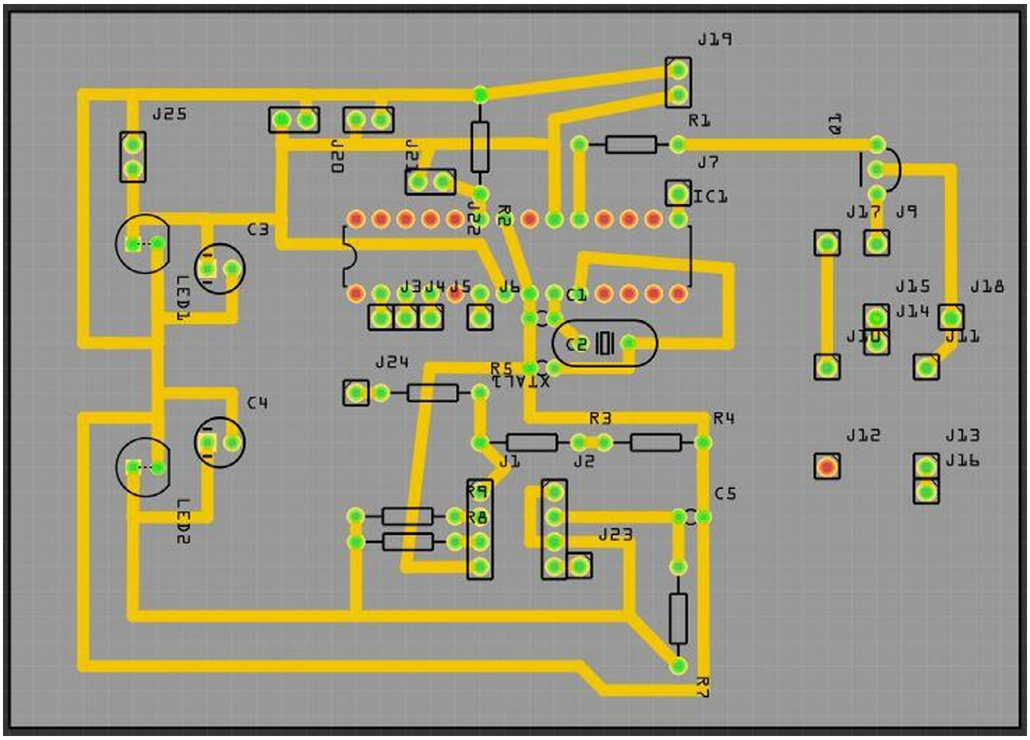

Fig. 13. PCB layout.

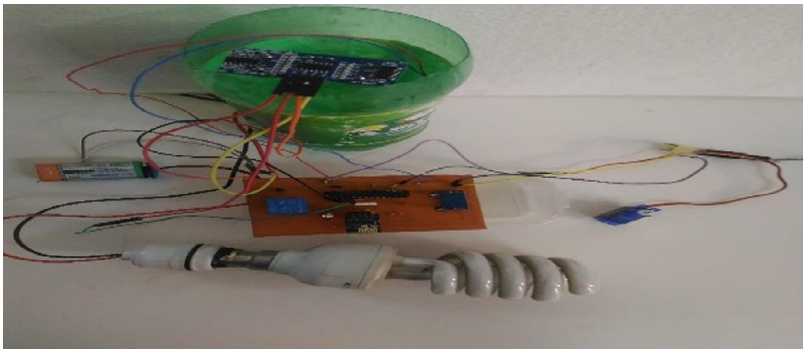

Fig. 14. Practical system.

to RXD pin of the microcontroller via the Wi-Fi module, microcontroller makes its digital pin 19 logic “High”. This makes an NPN transistor switched on, and drive the relay connected to it. When the microcontroller receives a command to trip the circuit, it simply makes its pin 19 logic “Low”. Zero voltage at NPN transistor’s base makes the transistor circuit turned off. So, the relay opens the AC circuit connected to it.

4.1.4. Changing tap position

To provide a tap changing facility, a servo motor is connected to microcontroller PWM pin 15 as shown in Fig. 18. A servo motor can rotate at a fixed angle determined by the microcontroller. Servo motor has three terminals. Two terminals are connected to a 5 V power source. And controlling pin is connected to pin 15 (PWM). When an angle value is written on PWM pin, servo motor rotates to that angle.

4.1.5. IoT based differential protection

IoT based differential protection is a smart solution where two ESP8266 modules send the current sensor’s data to the web server as shown in Fig. 19. When the data coming from two different terminals of the protected zone differs from each other beyond permissible limit, the web server sends a command to an internet module which initiates the CB operation to protect the system.

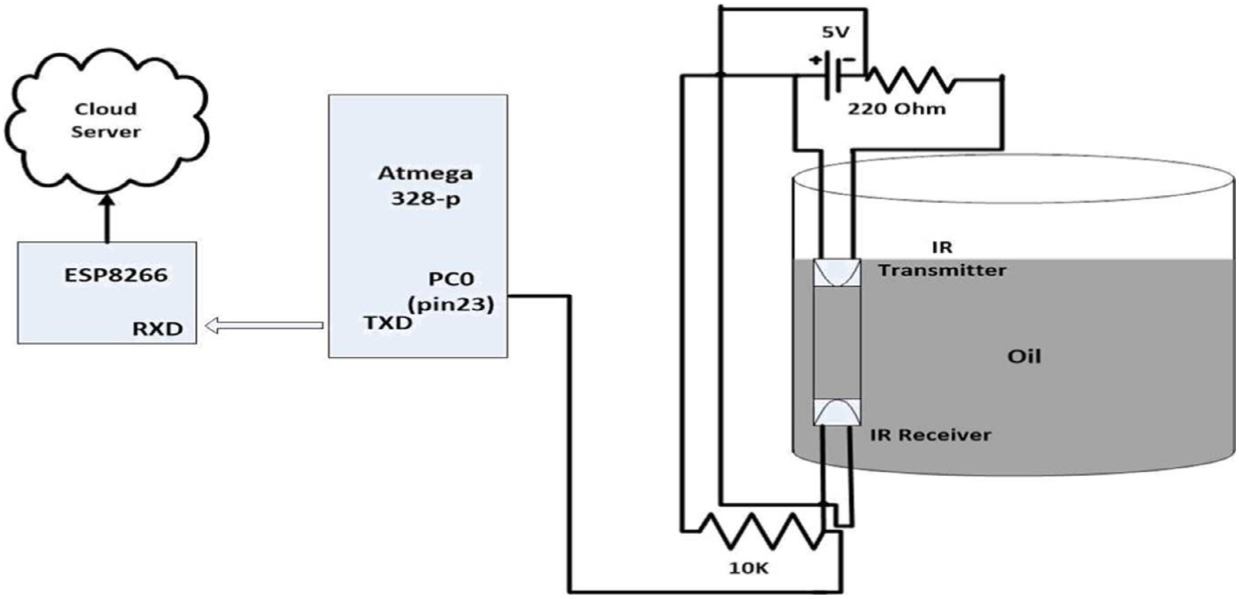

Fig. 15. Circuit for oil amount measurement.

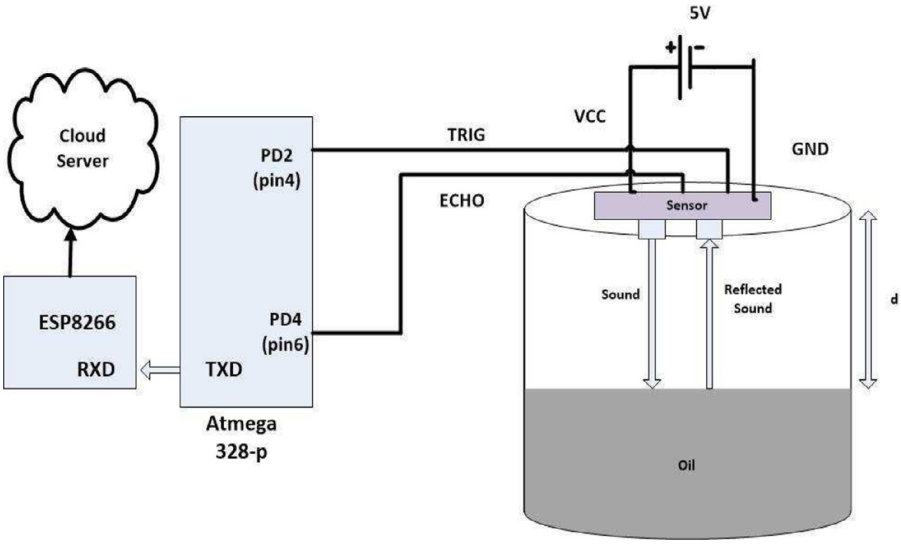

Fig. 16. Circuit for oil quality measurement.

4.2. Functions & design of ESP-8266 Wi-Fi module side

The ESP8266 is a System on a Chip (SoC), manufactured by the Chinese company Espressif. It consists of a Tensilica L106 32-bit microcontroller unit (MCU) and a Wi-Fi transceiver. It receives information by its TX pin from the RXD pin of the microcontroller and uploads them in the web server. It also gets commands from a web server and transmits them to the RXD pin of the microcontroller by serial communication.

There are different ways to program the ESP8266. Arduino IDE is used for programming ESP8266 in this work. Fig. 20 represents a circuit arrangement for programming the ESP8266. To program the module, a flasher is needed. USB-to-serial converter or Arduino UNO is used as a burner in this work. As refer to the Table 1 ESP8266-01 can be operated on different modes depending on its GPIO pin's status. To upload a program, it must be operated in programming mode.

Program uploading steps are as follows:

1. Press and hold the reset button
2. Press and hold the program button
3. Release the reset button, the ESP will boot in program mode

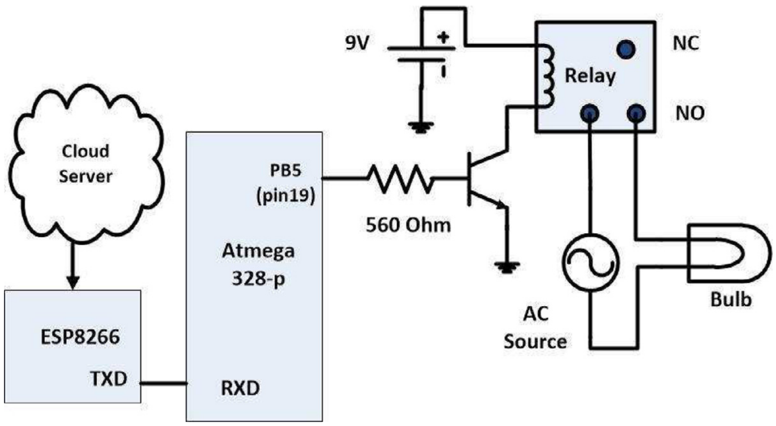

Fig. 17. Circuit for CB control.

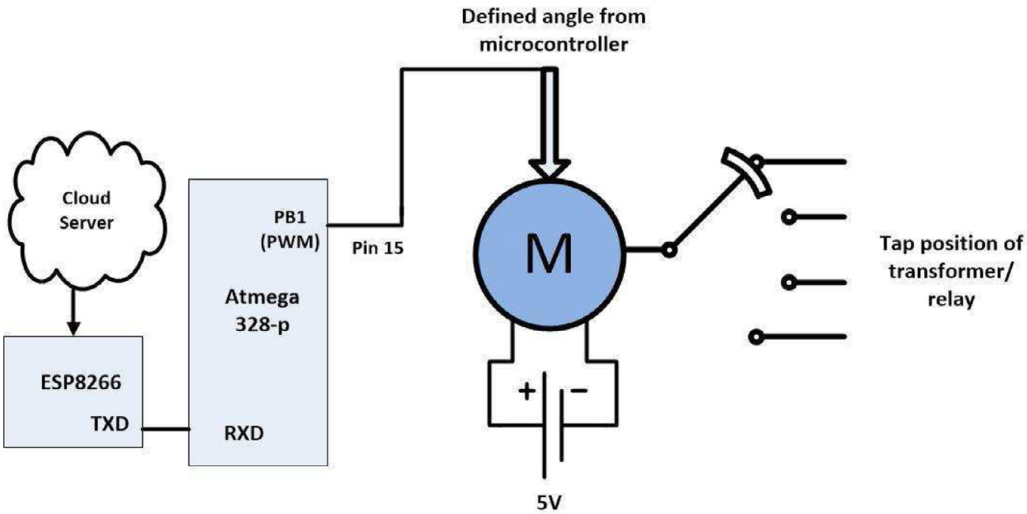

Fig. 18. Circuit for tap changing.

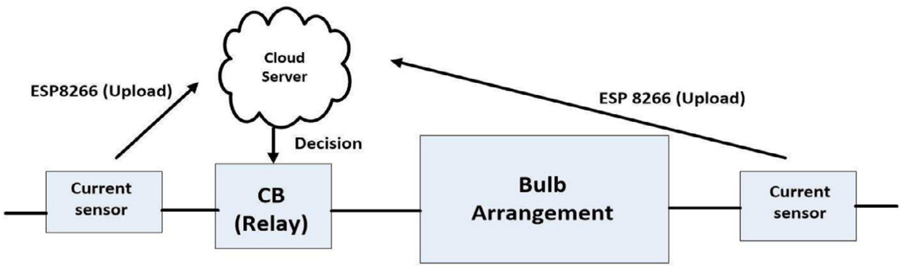

Fig. 19. Circuit for differential protection.

Table 1
ESP8266-01 Boot options.

GPIO 0	Title 2	Mode	Comments
13.3 V	3.3	Flash	Boot from SPI flash
0 V	3.3 V	UART	Program via UART (TX/RX)

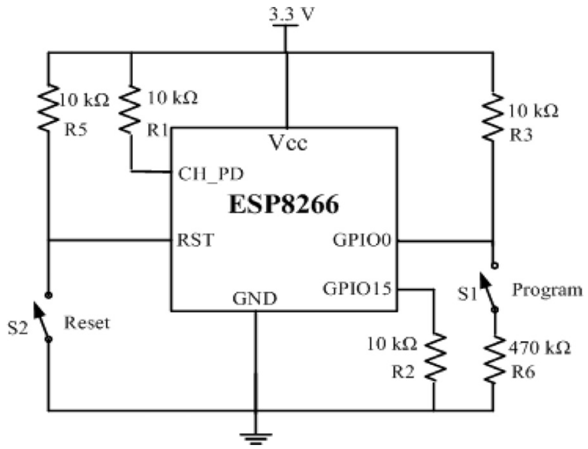

Fig. 20. Circuit for programming ESP8266.

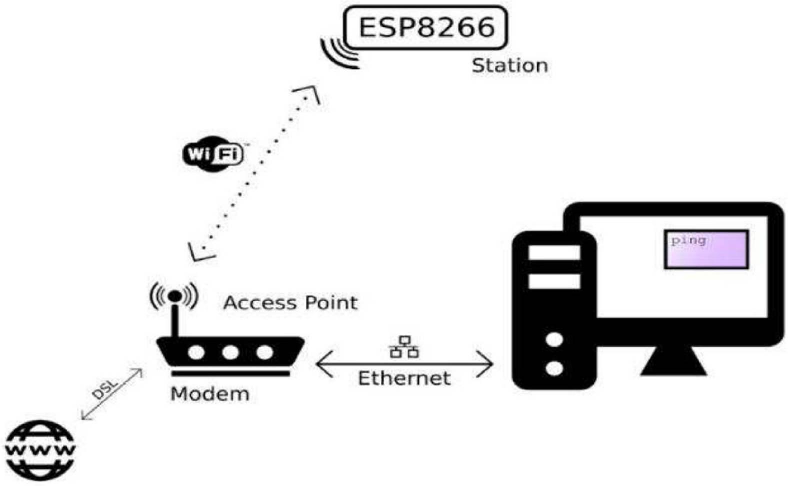

Fig. 21. The connection of ESP8266 in station mode.

4. Release the program button
5. Upload the sketch

ESP8266 can operate in three different modes: Wi-Fi station, Wi-Fi access point, and both at the same time for Wi-Fi communication. In station mode, the Wi-Fi module is to be connected to one specific network as shown in Fig. 21. In access point mode, and Wi-Fi enables can be connected to the module. The device is in station mode in this project.

The device with the antenna in Fig. 20 serves many different purposes:

- Point: Wi-Fi devices can connect to it, to be part of the local network.
- Router: It routes IP packets to the right sub-nets so that they will arrive at their destination. E.g. if the computer sends a message that is meant for the ESP over the Ethernet sub-net, the router will send the packet to the Wi-Fi sub-net, because it knows that's where the ESP is.
- Modem: If the router can't find the addressee on the local network, the packet will be passed on to the integrated modem, and it will be sent to the Internet Service Provider over a DSL line, heading for the Internet, where lots of other routers will try to get the packet to the right destination.

4.3. Functions and design of web server side

The parameters received on the webpage is stored in the cloud which can be analyzed at any time from anywhere. The web server displays all the data at the same time when the stored data in the web server surpass the permissible limit then web server sends a comment to an internet module which performs the specific task such as initiate the CB operation, tap changing the transformer, and so on. Additionally, if any customer desire a file or another piece of data the server will then send the right data/files back to the customer. Requests are made using the MQTT protocol. It is a nice lightweight

Table 2
Alarm message setting.

Oil deterioration level	Oil tank vacancy	Message to server
<75%	<12 cm	Normal
>75%	<12 cm	Oil reconditioning is necessary
<75%	>12 cm	Add more coil
>75%	>12 cm	Oil adding & reconditioning is necessary

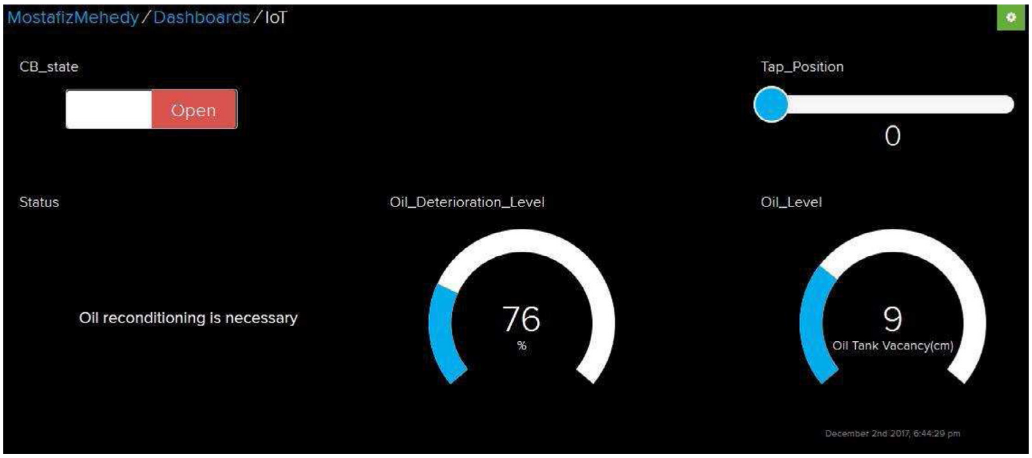

Fig. 22. Webpage for sub-station monitoring & control.

Fig. 23. Webpage for this experiment.

publish and subscribe system where anyone can publish and receive messages as a client. It makes really easy to establish communication between multiple devices.

5. Results and discussion

This section going to demonstrate the experiment results of the prototype system because the accuracy of the proposed model mostly depends on the performance of the prototype version. After the successful connection of communication devices to the server, oil tank vacancy level & oil deterioration level and CTs current are sent to the web server in an automatic manner. At the violation of their normal values, an alarming message with a corrective step to be taken to solve the specific problem was sent to the web server. Table 2 shows the different states of oil deterioration and oil tank vacancy with the corresponding alarming message.

Figs. 22 and 23 shows the front end of the webpage which will display all the data of sub-station equipment. The received data are remaining stored in the cloud so that by entering the password an authorized person can monitor the data and control the system at any time from anywhere. Figs. 24 and 25 show the command button in order to control the servo motor (CB state) and changing the tap position of the transformer from the webpage. Based on the experiment results it is terminated that the proposed new IoT based sub-station controlling and monitoring system worked successfully

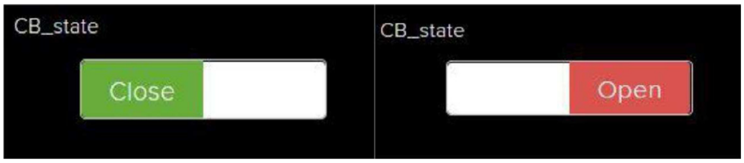

Fig. 24. CB controller button on a web page.

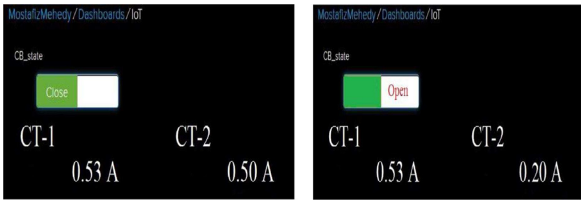

Fig. 25. Different protection button on a web page.

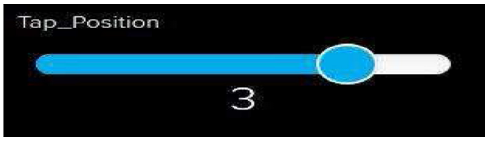

Fig. 26. Slider for changing tap position in the web page.

Table 3
Servo motor's rotation control.

Tap position value (from the web server)	Servo motors rotation from zero position
0	0°
1	45°
2	90°
3	135°
4	180°

when implemented on the practical circuit. The circuit breaker can be controlled from a button feed which has two states: Open/Close. Fig. 25 displays the differential protection; the system is made to initiate CB when two current sensor's readings have a minimum difference of 0.1A.

The transformer tap position can be controlled from a slider button of the web page which is shown in Fig. 26. Additionally, a tap changer feed with 5 tap position as shown in Table 3 which is used to control the tap position.

5.1. Application in smart grid

Recently, the power grid is transforming towards the smart grid which involves various intelligent operation and energy measures including smart meters, smart appliances, renewable energy sources, and energy efficient resources. The automation, intellectualization and the development of most aspects of the smart grid would be enhanced by integrating the proposed IoT technology. As an ever emerging technology, IoT can support the smart grid by its revolutionized information and telecommunication for improving the quality of service [32,45]. Moreover, IoT also provides more solid and variant technical support to the smart grid in terms of interacting with the environment and things.

6. Conclusions

In this paper, IoT based smart system has been developed for remote monitoring and controlling the entire sub-station equipment which is very reliable, user-friendly and low cost as compared to the conventional system. The proposed system is an absolutely automatic system that includes self-checking of oil level and oil quality from the transformer/oil circuit breaker, continuous sensing of two CTs secondary current, sending data to the web server, storing and displaying data in web page, and sending a comment to an internet module for performing the specific task such as initiating the CB operation, tap changing the transformer, and so on. In light of this, a prototype system has been implemented and tested with the real data to evaluate the system performance. Both the theoretical analysis and experimental results indicate that the IoT based network strategy is a remarkable approach for preparing a smart sub-station which substantially overcome the various difficulties over the traditional scheme. Moreover, this system also enables only an authenticated operator to control a CB, relay and changing the tap position of the transformer from a remote location using the webpage and thereby avoids the unauthorized innervation. To the end, the suggested model has the potential to operate automatically in a more efficient way with minimum manpower requirement and least operation & maintenance cost. Finally, as an ever emerging technology, there is a huge scope of applying this smart technology in all spheres of power system operations starting from generation, to transmission, to distribution and to utilization of electrical energy.

Conflicts of interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Md. Sanwar Hossain: Conceptualization, Writing - original draft. **Mostafizur Rahman:** Software, Formal analysis. **Md. Tuhin Sarker:** Software, Data curation. **Md. Ershadul Haque:** Methodology. **Abu Jahid:** Writing - review & editing.

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