MACHINE LEARNING APPROACH FOR SMART DISTRIBUTION TRANSFORMERS - LOAD MONITORING AND MANAGEMENT SYSTEM

A PROJECT REPORT

Submitted by

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ABSTRACT

The rapid growth in electricity demand and the increasing complexity of distribution networks have made conventional transformer monitoring systems inadequate for ensuring reliable and efficient power delivery. This project presents a machine learning-based smart distribution transformer system designed for real-time load monitoring and intelligent load management. The proposed system integrates advanced sensing, Internet of Things (IoT) technology, and data-driven predictive models to enhance the operational efficiency and lifespan of distribution transformers. The system continuously acquires critical parameters such as voltage, current, load, oil temperature, and ambient conditions using embedded sensors. These parameters are transmitted to a centralized platform through wireless communication modules, enabling real-time data analysis and remote monitoring. The collected data is preprocessed and used to train Machine Learning models capable of forecasting load demand, detecting anomalies, and predicting potential faults before their occurrence. Time-series forecasting techniques, such as Long Short-Term Memory (LSTM)

networks, are employed to predict future load patterns and identify peak demand periods. Additionally, anomaly detection algorithms are utilized to identify abnormal operating conditions, including overloading, overheating, and voltage fluctuations. Classification models further assist in fault prediction, enabling proactive maintenance and reducing the risk of unexpected transformer failures. The proposed system also incorporates intelligent load management strategies, such as dynamic load balancing and demand response mechanisms, to prevent overloading and ensure optimal utilization of transformer capacity. Real-time alerts and notifications are generated when critical thresholds are exceeded, allowing utility operators to take timely corrective actions. It minimizes downtime, reduces maintenance costs, and supports the transition toward smart grid infrastructure. The implementation of this approach demonstrates a scalable and cost-effective solution for modern power systems, contributing to sustainable energy management and improved service quality.

CHAPTER 1
INTRODUCTION

1.1 SMART DISTRIBUTION TRANSFORMERS

Transformers are one of the most critical components in electrical power systems, responsible for efficient transmission and distribution of electrical energy across different voltage levels. Any failure in a transformer can lead to significant power outages, economic losses, and safety hazards. Therefore, continuous monitoring and intelligent management of transformer parameters are essential to ensure reliable and efficient operation. Traditionally, transformer monitoring has been carried out using manual inspection or periodic maintenance methods. In such approaches, parameters like voltage, current, oil level, and temperature are checked at regular intervals by maintenance personnel. However, these conventional methods are not efficient in detecting real-time faults, as they depend heavily on human intervention and lack continuous monitoring capabilities.

As a result, faults such as overheating, oil leakage, insulation failure, or overload conditions are often identified only after serious damage has occurred. With the advancement of embedded systems and communication technologies, modern monitoring systems are shifting towards IoT-based smart solutions. The proposed system is designed based on a microcontroller-cantered architecture, where multiple sensors are integrated to continuously monitor transformer conditions. As shown in the block diagram, the system includes voltage sensors, current sensors, temperature sensors, humidity sensors, and oil level sensors, which collectively provide a comprehensive understanding of transformer health. The microcontroller acts as the central unit that collects data from all sensors and processes it in real time.

A keypad interface is also provided to allow user interaction, such as setting threshold values or controlling system operations. The processed data is then displayed on a display unit, enabling local monitoring of transformer parameters. In addition to basic monitoring, the system incorporates communication and control features. A GSM module is used to send alerts and notifications to users in case of abnormal conditions, ensuring immediate response even in remote locations. The system also includes control outputs such as load ON/OFF and transformer ON/OFF, which allow automatic or manual control actions to protect the transformer from damage during fault conditions.A major advancement in this proposed system is the integration of Machine Learning (ML) using an ESP32 module. Unlike traditional systems that rely on fixed threshold values, the ML model analyses historical and real-time sensor data to identify patterns and detect anomalies. This enables the system to distinguish between normal and abnormal operating conditions more accurately.

For example, instead of simply triggering an alert when temperature exceeds a predefined limit, the ML model can consider multiple parameters such as load current, ambient humidity, and oil level to predict potential overheating or insulation failure. The ESP32 for ML processing plays a crucial role in implementing edge intelligence, where data analysis is performed locally rather than relying entirely on cloud-based systems. This reduces latency, improves response time, and ensures system operation even in areas with limited internet connectivity. The ML model can be trained using datasets representing normal and faulty conditions of transformers, enabling it to classify system states and predict faults such as overload, oil leakage, or abnormal environmental conditions. Furthermore, the integration of ML enables predictive maintenance, which is a significant improvement over traditional reactive maintenance. In predictive maintenance, the system can forecast potential failures before they occur, allowing maintenance actions to be scheduled proactively.

This not only reduces downtime but also extends the lifespan of the transformer and minimizes maintenance costs. Another important aspect of the proposed system is its cost-effectiveness and scalability. By using components such as microcontrollers, ESP32 modules, and low-cost sensors, the system can be deployed in both urban and rural areas. It is especially beneficial for remote transformer installations where continuous human supervision is not feasible.

The combination of sensor-based monitoring, machine learning analysis, GSM communication, and control mechanisms makes the system highly reliable and efficient. It provides a comprehensive solution for transformer health monitoring by addressing the limitations of existing systems. The system not only detects faults but also predicts them, enabling timely intervention and improved operational safety.

1.2 PROBLEM IDENTIFICATION

Transformers are essential components in power distribution systems, and any failure can lead to serious consequences such as power outages, equipment damage, and financial losses. Despite their importance, many transformer systems still rely on traditional monitoring methods, which are not efficient in ensuring real-time safety and reliability. One of the major problems in existing systems is the lack of continuous monitoring. Parameters such as voltage, current, temperature, humidity, and oil level are often checked manually or at fixed intervals. This approach fails to detect sudden changes or faults in real time, increasing the risk of unexpected failures. Another critical issue is the absence of intelligent fault detection. Most systems operate based on predefined threshold values. If a parameter crosses a limit, an alert is generated. However, this method does not consider the relationship between multiple parameters.1 For example, a rise in temperature combined with high current and low oil level may indicate a serious fault, but traditional systems cannot analyse such complex conditions effectively.

The lack of predictive maintenance is also a significant limitation. Existing systems typically detect faults only after they occur, leading to reactive maintenance. This results in increased downtime, higher repair costs, and reduced transformer lifespan. In addition, there is limited remote monitoring capability. Many transformers are installed in remote or inaccessible areas, making it difficult for operators to monitor them continuously. Without proper communication systems like GSM or IoT, timely alerts cannot be delivered to maintenance personnel. Another problem is the absence of automated control mechanisms. In many cases, even if a fault is detected, manual intervention is required to turn off the transformer or disconnect the load. This delay can cause severe damage to the system. Furthermore, traditional systems do not utilize machine learning or data analytics, which limits their ability to learn from past data and improve decision-making. Without ML, it is difficult to identify hidden patterns or predict potential failures in advance. Finally, there is a need for a cost-effective and scalable solution. Advanced monitoring systems like SCADA are expensive and complex, making them unsuitable for small-scale or rural installations.

1.3 OBJECTIVE

The primary objective of this project is to design and develop a smart transformer monitoring and control system using IoT and Machine Learning (ML) techniques to ensure efficient, reliable, and safe operation of power transformers. The system aims to continuously monitor key transformer parameters such as voltage, current, temperature, humidity, and oil level using appropriate sensors integrated with a microcontroller. Another important objective is to implement an ESP32-based machine learning model that can analyse real-time and historical sensor data to detect abnormal conditions and predict potential faults.

Unlike traditional threshold-based systems, the ML approach enables intelligent decision-making by identifying complex patterns among multiple parameters, thereby improving fault detection accuracy. The project also aims to provide remote monitoring and alert mechanisms using communication modules such as GSM, allowing users to receive real-time notifications in case of abnormal conditions. Additionally, the system is designed to include automatic control features, such as switching the transformer or load ON/OFF during fault conditions, to prevent damage and enhance safety. Furthermore, the system focuses on developing a cost-effective and scalable solution that can be deployed in both urban and rural areas, especially in locations where continuous manual monitoring is not feasible. By integrating sensor-based monitoring, machine learning analysis, and communication technologies, the project aims to enable predictive maintenance, reduce downtime, minimize maintenance costs, and extend the lifespan of transformers.

1.4 CHALLENGES

The development and implementation of a smart transformer monitoring system with machine learning involve several technical and practical challenges. These challenges must be addressed to ensure reliable system performance and accurate fault detection. One of the primary challenges is accurate sensor data acquisition. Sensors such as voltage, current, temperature, humidity, and oil level must provide precise readings under varying environmental and electrical conditions. Noise, calibration errors, and sensor drift can affect data accuracy, which in turn impacts the performance of the monitoring system and machine learning model. Another major challenge is integration of multiple hardware components. The system involves microcontrollers, ESP32 modules, sensors, GSM communication, and display units. Ensuring seamless communication between these components without data loss or delay is a complex task, especially in real-time applications.

The implementation of machine learning on embedded systems (ESP32) presents additional difficulties. Since ESP32 has limited memory and processing power, deploying ML models requires optimization techniques such as lightweight algorithms, reduced model size, and efficient data handling. Balancing accuracy and computational efficiency is a key challenge. Data availability is also a critical issue. Training an effective ML model requires sufficient and high-quality datasets representing both normal and fault conditions. In real-world transformer systems, obtaining labelled fault data is difficult, which can affect the reliability of predictions. Another challenge is real-time data processing and decision-making. The system must analyse incoming sensor data continuously and respond quickly to abnormal conditions.

Any delay in processing or communication may result in late fault detection and potential damage to the transformer. The reliability of communication systems, such as GSM or IoT connectivity, is also a concern. Network failures or signal issues can prevent timely transmission of alerts and monitoring data, especially in remote areas. Power management is another important challenge. The system must operate continuously, often in harsh environments, requiring efficient power usage and protection against voltage fluctuations. Finally, ensuring system scalability and cost-effectiveness is essential. While advanced monitoring systems exist, they are often expensive. Designing a low-cost system using ESP32 and sensors without compromising performance is a significant challenge.

1.5 HARDWARE REQUIREMENTS

It defines the minimum or recommended technical specifications necessary for performance, compatibility, and functionality.

1. Arduino board with ATMEGA 328P with boot loader
2. Wi-Fi module ESP8266
3. Voltage Sensor
4. Current Sensor
5. Ultrasonics Sensor
6. DS18B20 Sensor

7. Transformer with rectifier board of 12V and 5V
8. Relay 12v board
9. Esp32 for ML
10. Display LCD 16x2
11. GSM
12. ESP32-CAM

1.6 SOFTWARE REQUIREMENTS

It serves as a foundational blueprint for development, covering behaviour, performance, security, and usability

1. Arduino IDE for programming ATmega 328p
2. Atmel Studio 7
3. HTML Coding C++
4. Flasher

CHAPTER 2
LITERATURE REVIEW

Review 2.1.1: Sajidur Rahman et al. (2017) [IRJET] – Design and Implementation of Real Time Transformer Health Monitoring System Using GSM Technology

With the progress and development of national economy as well as power system, reliability and safety issues of power system have been more important. Development of distribution Transformer Health Monitoring System (THMS) has been done in that reason. Distribution transformer is the most vital asset in any electrical distribution network and therefore it needs special care and attention. This THMS can monitor the health status of the distribution transformer in real time aspect. As many transformers are distributed over a wide area in present electric systems, it's difficult to monitor the condition manually of every single transformer. So automatic data acquisition and transformer condition monitoring has been an important issue.

This project presents design and implementation of a mobile embedded system to monitor load currents, over voltage, transformer oil level and oil temperature. The implementation on-line monitoring system integrates Global Service Mobile (GSM) Modem, with single chip microcontroller and sensors. It is installed at the distribution transformer site. The output values of sensors are processed and recorded in the system memory. System programmed with some predefined instructions to check abnormal conditions. If there is any abnormality on the system, the GSM module will send SMS (Short Message Service) messages to designated mobile telephones containing information about the abnormality according to the aforesaid predefined instructions.

This mobile system will help the utilities to optimally utilize transformers and identify problems before any catastrophic failure occurs. This system will be an advanced step to the automation by diminishing human dependency. As it is a wireless communicating system, there is no need of large cables which are of high cost. Thus, THMS offers a more improved transformer monitoring.

Review 2.1.2: Wang Lei and Liu Yan-nan (2011) [IEEE] – Design of Temperature Monitoring System for Oil-Immersed Power Transformers Based on MCU

With the expansion of electric capacity and large-scale extension of power grid, electric equipment is playing a significant role in modern life. At present, the technology of condition monitoring and fault diagnosing of power transformer has been made some improvement, yet its real-time performance and reliability still can't meet the requirement of safe production. Due to different thermal effects led by the natural or factitious fault, its temperature of oil-immersed power transformers is easy to change abnormally. An on-line measuring and controlling system based on MCU is discussed in this paper. In order to satisfy the requirement of state monitoring and fault diagnosis of power transformer on real-time and reliability, a kind of intelligent on-line monitoring instrument is designed. Each of its part is explained in this paper, including temperature signal collecting and data processing system. The simulation result showed the designed system was good in its real-time, reliability and running cost. Therefore, the designed state monitoring system for temperature and fault diagnosis of power transformer can be widely used in engineering and is expected to bring a bright future.

Review 2.1.3: Abdul-Rahman Al-Ali et al. (2004) [IEEE] – A New Method for Monitoring of Distribution Transformers

Distribution transformers are one of the most important equipment in power network. Because of, the large number of transformers distributed over a wide area in power electric systems, the data acquisition and condition monitoring is a important issue. This paper presents design and implementation of a mobile embedded system and a novel software to monitor and diagnose condition of transformers, by record key operation indictors of a distribution transformer like load currents, transformer oil, ambient temperatures and voltage of three phases. The proposed on-line monitoring system integrates a Global Service Mobile (GSM) Modem, with standalone single chip microcontroller and sensor packages. Data of operation condition of transformer receives in form of SMS (Short Message Service) and will be save in computer server. Using the suggested online monitoring system will help utility operators to keep transformers in service for longer of time.

Review 2.1.4: Pawel Kostyla (2014) [IEEE] – Utilization of the Monitoring System for MV/LV Transformers in Smart Grid Application

Continuous development of the power grid infrastructure in the area of distribution and legal regulations concerning the reliability of the powering consumers of electricity is a challenge for systems used for power system protection. This requires continuous improvement of an existing solutions and development of new methods for fast and reliable identification and location of the disturbances and failures occurring in the network. The application possibilities offered by modern digital devices go far beyond what was the primal purpose and allows the creation of “intelligent” electric networks.

This article presents the equipment used by Polish electricity distributors for monitoring load of the low voltage transformers, describes analyses carried out in the range of functionality and measurements and mentions capabilities of the data acquisition systems for other purposes. In this paper also considered are the possibilities of usage of existing metering systems and obtained data from them in automation systems supporting the operation of the medium and low voltage networks.

Review 2.1.5: S. Zhao, L. Zhang, and J. Li (2014) [IEEE] – Techniques of Online Monitoring and Diagnosis for Transformer

The transformer is crucial for the energy conversion and transmission in the process of power transmission and distribution and plays an important role in the security of grid. On-line monitoring and diagnostics provide a promising platform not only to help the operators to manage transformer in a targeted fault repair and maintenance manner, but also to avoid fatal accidents. This paper describes the technique of oil dissolved gas analysis (DGA) using combined diagnoses method based on Borda rule, which can improve the accuracy of the results. Partial discharge is both the symptom and reason of transformer insulation degradation. Technique of partial discharge monitoring can detect the level of PD and growth rate though pulse current, ultrasonic detection, ultra-high frequency detection method and detection of light. It indicates the changes taking place within the transformer or reflects solid insulation voids, metal particles, air bubbles etc. due to some defects arising. The DGA and PD is the most widely used on-line monitoring technique. If all the monitoring technology performs reasonably well, they can better help transformer operator to monitor the current state of operation and make decisions on continuing operation, maintenance or replacement.

Review 2.1.6: Amit Sachan (2012) [IJCA] – GSM Based Distribution Transformer Monitoring and Controlling System

Distribution transformers are one of the most important equipment in power network. Because of, the large number of transformers distributed over a wide area in power electric systems, the data acquisition and condition monitoring is important issue. The main aim of this system is distribution transformer monitoring and controlling through IOT. Also, it sends SMS to a central database via the GSM modem for further processing. The idea of on-line monitoring system mixes a global service mobile (GSM) Modem, with chip micro controller and different sensors. Here transformers are damaged due to the oil damage. Oil damage depends on different parameters and environmental conditions. Now in this system we are concentrating on temperature of transformer and viscosity of oil. In this system temperature and viscosity monitoring and control action is performed based on the AVR microcontroller. After interfacing the required components user has to develop one application program in embedded-c. Here controller is continuously reading the temperature, voltage and current and display on the LCD.

Review 2.1.7: P. Ramu et al. (2016) [IEEE] – Distribution Transformer Monitoring System Using Internet of Things (IoT)

Transformers are used for electricity distribution and transmission which reduces the primary voltage to the utilization voltage for customer use. As distribution transformers are very costlier in electrical industry therefore this paper presents the system which monitor different parameters of distribution transformer. There are two units which are remote terminal unit (RTU) and monitoring unit. Remote terminal unit consist of analysing parameters such as current, temperature, rise and fall in oil level, vibration and humidity with the help of PIC 18F4550.

All monitoring parameters are processed and if any abnormality occurs, the system sends Alert messages to the mobile phones and recorded in system memory through (ADC) analog to digital converter. All parameters' values are sent to monitoring node through GPRS. If any emergency condition occurs immediately message send to the corresponding engineer through GSM and similarly on webpage, we can get alert about it through GPRS. Near remote terminal unit buzzer will beep and LCD gives notification about emergency condition. An engineer at transformer cannot continuously keep an eye on transformer therefore given proposed system does communication with us at emergency conditions of distribution transformer through GSM/ GPRS module

Review 2.1.8: M. S. Sujatha and M. S. Srinath (2018) [IJAREEIE] – Real Time Transformer Health Monitoring System Using IoT Technology

Here this document presents design and implementation of a mobile embedded system to measure load currents, over voltage, transformer oil level and oil temperature. This is implemented by using on-line measuring system using Internet of Things (IOT), with single chip Arduino microcontroller and sensors. It is installed at the distribution transformer site. The output values of sensors are processed and recorded in the system memory. System programmed with some predefined instructions to check abnormal conditions. If there is any abnormality on the system, details are automatically updated in the internet through serial communication. This Internet of Things (IOT) will help the utilities to optimally utilize transformers and identify problems before any catastrophic failure occurs. Thus online-measuring system is used to collect and analyse temperature data over time. So, Transformer Health Measuring will help to identify or recognize unexpected situations before any serious failure which leads to a greater reliability and significant cost saving.

CHAPTER 3

EXISTING AND PROPOSED SYSTEM

3.1 EXISTING SYSTEM

Fig. 3.1 GSM based Distribution Transformer Monitoring System is about design and implementation of a mobile embedded system to monitor and record key parameters of a Distribution transformer like load currents, oil levels and ambient temperature. The idea of on-line monitoring system integrates a global service mobile (GSM) modem, with a standalone single chip micro-controller and different sensors. It is installed at the distribution transformer site, and the above parameters are recorded using the analog to digital converter (ADC) of the embedded system. The obtained parameters are processed and recorded in the system memory. If any abnormality or an emergency occurs the system sends SMS (short message ser- vice) message to the mobile phones containing information about the abnormality according to some predefined instructions programmed in the micro-controller.

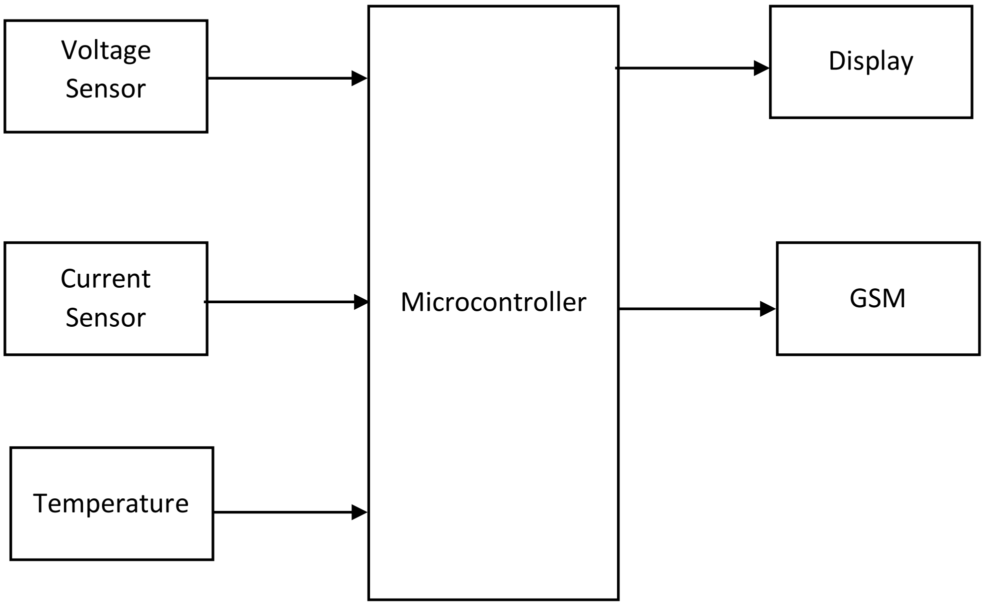

Fig. 3.1 Existing System Block Diagram

3.2 PROPOSED SYSTEM

Fig. 3.2 The proposed system is designed to provide a smart and intelligent solution for transformer monitoring by integrating sensors, a microcontroller, communication modules, and machine learning capabilities. The block diagram represents the overall architecture of the system, where each component plays a vital role in ensuring continuous monitoring, fault detection, and system control.

The system begins with a set of sensors that are connected to the transformer to measure important parameters such as voltage, current, temperature, humidity, and oil level. These sensors continuously capture real-time data related to the operating condition of the transformer. The collected signals are then fed into the microcontroller, which acts as the central processing unit of the system. The microcontroller processes the incoming data by converting analog signals into digital form and performs initial analysis by comparing the values with predefined thresholds. In addition to processing sensor data, the microcontroller is also interfaced with a keypad that allows user interaction.

Through this keypad, users can set or modify threshold values, control system parameters, and manually operate certain functions if required. The processed data is displayed on a display unit, enabling local monitoring of transformer conditions in real time.A key feature of the system is the integration of an ESP32 module, which is used for implementing machine learning. The microcontroller sends the processed sensor data to the ESP32, where a trained machine learning model analyzes the data to identify patterns and detect abnormal conditions. Unlike traditional systems that rely only on fixed threshold values, the machine learning model considers multiple parameters simultaneously, allowing more accurate and intelligent fault detection. This enables the system to predict potential failures such as overheating, overload, or oil leakage before they occur. The system also includes a GSM communication module, which is used to send alerts and notifications to users when abnormal conditions are detected.

This ensures that maintenance personnel are informed immediately, even if they are located far from the transformer site. In addition to monitoring and alerting, the system provides control functionality through output units that can switch the load or transformer ON or OFF. This automatic control mechanism helps in protecting the transformer from severe damage during fault conditions.

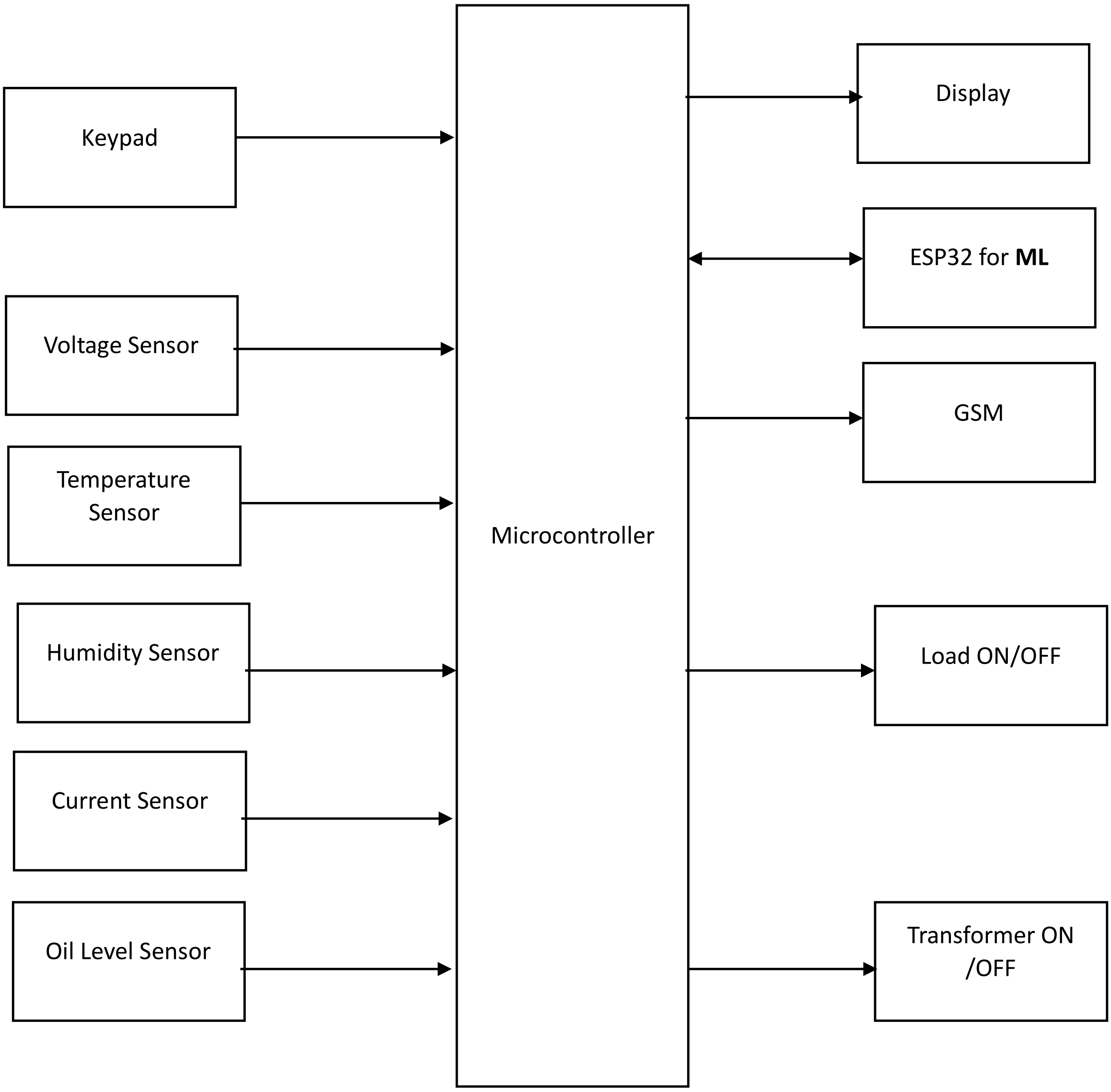

Fig. 3.2 Proposed System Block Diagram

3.3 CIRCUIT DIAGRAM

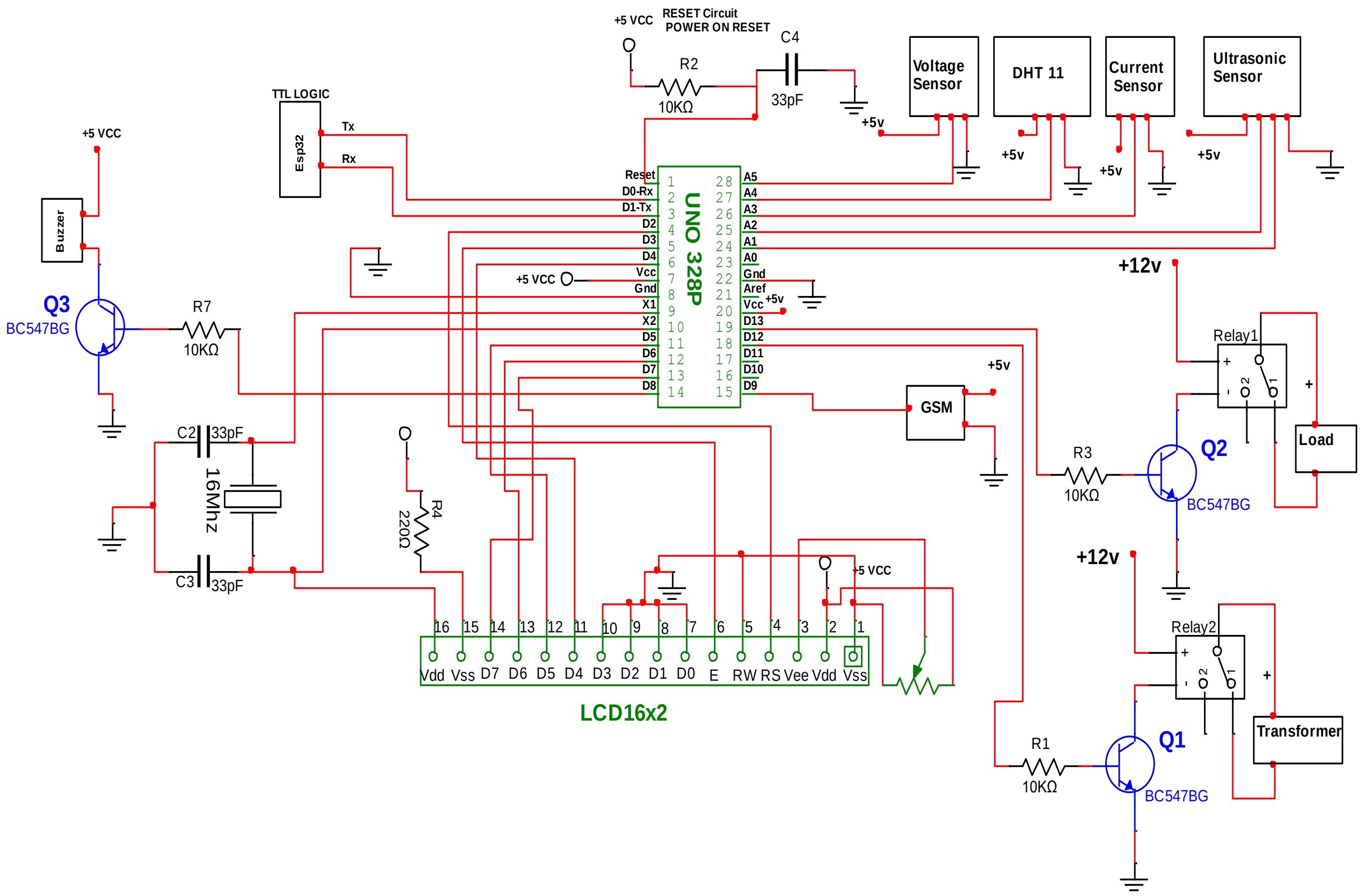

Fig. 3.3 Circuit Diagram

3.4 WORKING PRINCIPLE

The proposed smart transformer monitoring system operates by integrating real-time sensing, embedded processing, communication, and machine learning to ensure efficient and reliable transformer operation. The working of the system begins when power is supplied to the entire setup, activating the microcontroller, ESP32 module, sensors, GSM communication unit, display, and control circuitry.

Once initialized, the system enters a continuous monitoring mode where all components function in coordination to observe and analyse transformer conditions. The first stage of operation involves data acquisition through sensors. Various sensors are connected to the transformer to measure critical parameters such as voltage, current, temperature, humidity, and oil level. These parameters are essential indicators of transformer health. The sensors continuously generate signals corresponding to the measured values, which are then fed into the microcontroller. Since most sensors provide analog outputs, the microcontroller performs analog-to-digital conversion to obtain digital values suitable for processing. After acquiring the data, the microcontroller performs initial processing and validation. It checks whether the sensor values fall within predefined safe limits, which can be configured using the keypad interface. The keypad allows the user to set threshold values and customize system parameters as required. The processed data is simultaneously displayed on a display unit, enabling real-time local monitoring of transformer conditions. This ensures that operators present at the site can observe system behaviour directly.

The next stage involves data transfer to the ESP32 module, which is responsible for implementing machine learning-based analysis. The microcontroller sends the processed sensor data to the ESP32 through serial communication. The ESP32 acts as an intelligent processing unit that applies a trained machine learning model to analyse the incoming data. The model is designed to identify patterns in the sensor data and distinguish between normal and abnormal operating conditions. The machine learning model plays a crucial role in enhancing the system’s intelligence. Unlike conventional systems that rely solely on fixed threshold values, the ML model evaluates the relationship between multiple parameters simultaneously. For example, a slight increase in temperature may not indicate a fault under normal load conditions, but if it is accompanied by high current and low oil level, it may indicate a serious issue. The ML model is trained using historical data representing both normal and faulty conditions of the transformer. The model processes the real-time data and generates an output indicating whether the transformer is operating normally or if there is a potential fault.

This approach enables predictive maintenance, where faults are identified before they lead to system failure. Once the ESP32 detects an abnormal condition or predicts a fault, it sends a signal back to the microcontroller. The system then initiates alert and control actions. The GSM module is activated to send a notification message to the user or maintenance personnel, informing them about the detected issue. This ensures immediate awareness, even if the transformer is in a remote area. The alert message may include details such as parameter values and fault type. In addition to alert generation, the system also performs automatic control operations to protect the transformer. Depending on the severity of the fault, the microcontroller can trigger output devices to switch OFF the transformer or disconnect the load. This automatic response helps prevent further damage and enhances system safety. The control actions are designed to operate quickly and reliably, minimizing the risk of failure.

The system operates in a continuous loop, where sensor data is repeatedly collected, processed, and analysed. The integration of machine learning ensures that the system becomes more intelligent over time, especially if the model is updated with new data. The use of edge computing through the ESP32 allows data processing to be performed locally, reducing dependency on cloud infrastructure and minimizing response time. Overall, the working principle of the proposed system demonstrates a seamless integration of sensing, processing, communication, and intelligent analysis. By combining real-time monitoring with machine learning-based fault detection, the system provides a proactive approach to transformer maintenance. It not only detects faults but also predicts them, enabling timely intervention and improving the reliability and lifespan of the transformer. This makes the system highly suitable for modern smart grid applications, where efficiency, automation, and intelligence are essential.

CHAPTER 4
COMPONENTS DESCRIPTION

4.1 MICROCONTROLLER

Keeping in mind the economic constraints and the simplicity of the system, Arduino Uno has been used which abates the programming complexity. Atmega sense the current and voltage value through Analog pins. With the help of these values, microcontroller programming calculates the power and energy. The Arduino Uno is a microcontroller board based on the ATmega328, whereas Microcontroller Atmega328 it shown in the Fig.4.1. As of today, it is the most popular microcontroller development and prototyping board in the world. The Arduino Uno is a ideal board to get started with in the world of microcontrollers or in general in electronics. This microcontroller is heart of the circuit to receive the data from the air monitoring section and post to the internet with help of the ESP 8266 module.

Fig. 4.1 Microcontroller ATmega328

4.2 ESP 8266 IOT

ESP8266 offers a complete and self-contained Wi-Fi networking solution, allowing it to either host the application or to offload all Wi-Fi networking functions from another application processor ESP8266 Wi-Fi module as in Fig.4.2. When ESP8266 hosts the application, and when it is the only application processor in the device, it is able to boot up directly from an external flash. It has integrated cache to improve the performance of the system in such applications, and to minimize the memory requirements. It is easy to connect the Internet through WIFI Router and update the content of the data in internet.

Fig. 4.2 ESP8266 Wi-Fi

4.3 LCD DISPLAY

Liquid Crystal Cell Display or used in similar application where LEDs are used. These applications are display of numeric and alpha numeric characters in dot matrix and segment display. Display unit with larger size of 16x2 with columns and rows to show user details update from Database as in Fig.4.3.

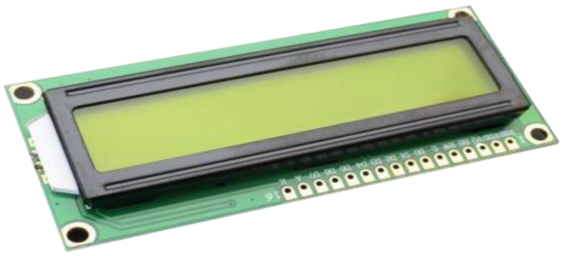

Fig. 4.3 LCD Display

4.3.1 LCD INTERFACE CIRCUIT

The Fig.4.4 shown An LCD interface circuit connects a microcontroller or microprocessor to a Liquid Crystal Display (LCD) module to visualises alphanumeric text or graphics. The industry standard for character modules is the Hitachi HD44780 controller.

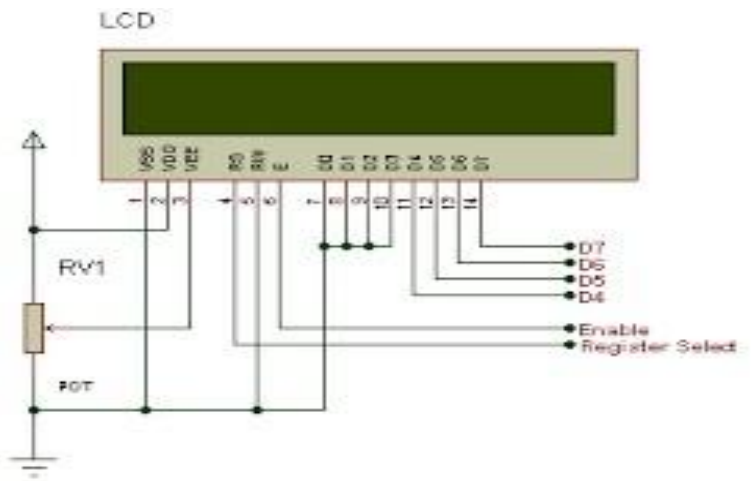

Fig. 4.4 LCD Interface Circuit

4.3.2 PIN DETAILS

The LCD standard requires 3 control lines and 8 I/O lines for the data bus as shown in Table. 4.1. Liquid Crystal Display is very important device in embedded system. It offers higher flexibility as the user can display any data on it. Copy and paste technique may not work when an embedded system engineer wants to apply LCD interfacing in real world projects. First thing to begin with is to know what LCD driver/controller is used LCD. LCD driver provides a link between microcontroller and LCD. In LCD initialization user has to send command bytes to LCD. Here the user sets the interface mode, display mode, address counter increment direction, set contrast of LCD, horizontal or vertical addressing mode, colour format. The command register stores the command instructions given to the LCD.

Table. 4.1 Pin Description of LCD

PIN NUMBER	SYMBOL	FUNCTION
1	Vss	GND
2	Vdd	+ 3V or + 5V
3	Vo	Contrast Adjustment
4	RS	H/L Register Select Signal
5	R/$\overline{W}$	H/L Read/Write Signal
6	E	H →L Enable Signal
7	DB0	H/L Data Bus Line
8	DB1	H/L Data Bus Line
9	DB2	H/L Data Bus Line
10	DB3	H/L Data Bus Line
11	DB4	H/L Data Bus Line
12	DB5	H/L Data Bus Line
13	DB6	H/L Data Bus Line
14	DB7	H/L Data Bus Line
15	A/Vee	+ 4.2V for LED/Negative Voltage Output
16	K	Power Supply for B/L (OV)

4.4 VOLTAGE SENSOR

The voltage sensor is used to sense the voltage produce by solar panel. This sensor works in basis of voltage sensor. The Fig.4.5 mentioned as Voltage Sensor. The output of the sensor is connected to the microcontroller. This voltage sensor works in Voltage division rule which has two resistors in series. The total voltage is applied across these resistors. The output is taken from the centre of these resistors.

Fig. 4.5 Voltage Sensor

4.5 CURRENT SENSOR

This current sensor is used to sense the current flow in the load by linear Hall effect method. Applied current flowing through this copper conduction path generates a magnetic field which the Hall IC converts into a proportional voltage. Device accuracy is optimized through the close proximity of the magnetic signal to the Hall transducer. The output of the device has a positive slope (>VIOUT(Q)) when an increasing current flows through the primary copper conduction path (from pins 1 and 2, to pins 3 and 4), which is the path used for current sampling as shown in Fig. 4.6.

Fig. 4.6 Current Sensor

4.6 DHT11 SENSOR

The Fig.4.7 shown as the DHT11 is a basic, ultra low-cost digital temperature and humidity sensor. It uses a capacitive humidity sensor and a thermistor to measure the surrounding air and outputs a digital signal on the data pin. It is factory calibrated, making it reliable for hobby and basic environmental sensing applications.

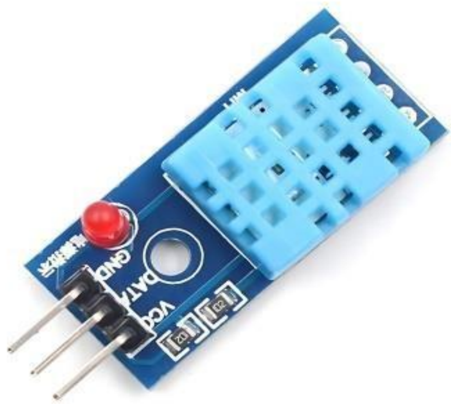

Fig. 4.7 DHT11 Sensor

4.7 RELAY MODULE

A single-channel relay module used to switch high-voltage devices (like motors, lamps, pumps) using low-voltage signals from a microcontroller (like Arduino, ESP32, etc.), whereas in Fig.4.8.

Fig. 4.8 Relay Module

4.8 LM2596 DC - DC BUCK CONVERTER

The LM2596 is a popular DC-DC buck converter used to step down a higher voltage to a lower, regulated output voltage. It is efficient, compact, and widely used in power supply circuits for electronics projects and embedded systems is shown in Fig.4.9.

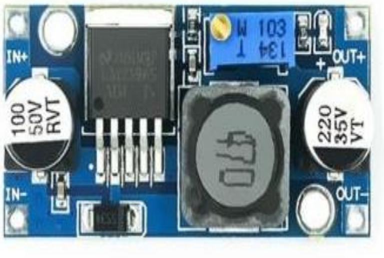

Fig. 4.9 LM2596 DC - DC Buck converter

4.9 TRANSFORMER

A 12V regulated power supply module. It takes 240V AC input, steps it down using a transformer, converts it to DC using a bridge rectifier, and smooths it with filter capacitors. Voltage is then regulated (likely via a 7812 regulator or similar) to provide a stable 12V DC output as shown in Fig.4.10

Fig. 4.10 Transformer

4.10 ESP32 – CAM

The Fig.4.11 shown as ESP32-CAM development board equipped with a small camera module, designed for internet-connected camera projects. It supports Wi-Fi and Bluetooth connectivity, allowing for wireless video streaming or remote image viewing. The module typically features a MicroSD card slot on the back for saving photos and video clips directly. It is often used for AI-related tasks like face detection and recognition, as well as home surveillance systems.

Fig. 4.11 ESP32 - CAM

4.11 DS18B20 SENSOR

The Fig.4.12 shown as DS18B20 is a highly popular digital temperature sensor manufactured by Analog Devices. It measures temperatures ranging from -55°C to +125°C with a reliable accuracy of ±0.5°C. Unlike traditional analog sensors, it sends information as a digital signal over a unique "1-Wire" communication protocol, meaning multiple sensors can share a single microcontroller data pin without interference. It can even derive operational power directly from its data line through "parasite power" mode, eliminating the need for an external power supply. Because it is widely available in a rugged, waterproof stainless-steel probe format, it is heavily used by hobbyists using Arduino microcontrollers for tracking environmental, liquid, and soil temperatures.

Fig. 4.12 DS18B20 Sensor

4.12 ULTRASONICS SENSOR

The Fig.4.13 shown as ultrasonic distance sensor module, commonly used with Arduino for obstacle detection and distance measurement. Function: It measures distances between 2 cm and 400 cm by emitting ultrasonic sound waves and measuring the time they take to bounce back. Pins: The module has four pins: VCC (power), Trig (Trigger), Echo (Receiver), and GND (Ground). Operating Voltage: It typically operates on a 5V DC power supply.

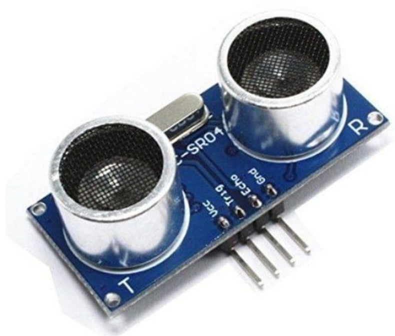

Fig. 4.13 Ultrasonics Sensor

4.13 GSM

The Fig.4.14 shown as Global System for Mobile Communications (GSM) is a foundational digital cellular technology used for transmitting mobile voice and data services. This is a miniature cellular GSM modem used in IoT projects to send and receive SMS messages, make voice calls, and connect to the internet via GPRS data. It is a quad-band module, meaning it can operate on 850/900/1800/1900MHz frequencies and is compatible with 2G SIM cards globally. The module requires a power supply voltage between 3.4V and 4.4V (ideally 3.7V–4.2V), and it can draw up to 2A of current during transmission. It communicates with microcontrollers like Arduino using a TTL serial interface (TX/RX pins) controlled by AT commands

Fig. 4.14 GSM Modem

4.14 OLED DISPLAY MODULE

The Fig.4.15 shown as a 0.96-inch dual-colour OLED display module mounted on a wooden surface and wired for serial communication. The module features a 128x64 pixel resolution split into a yellow upper section and a blue lower section. It utilizes a four-pin Inter-Integrated Circuit (\(\text{I}^2\text{C}\)) interface, with the pins clearly labelled from left to right as VCC for power, GND for ground, SCL for the serial clock line, and SDA for the serial data line. The screen currently displays five lines of diagnostic data from a connected microcontroller system. The readout includes "ML Health" as a header, "ST: NORMAL" indicating standard system health, "HL: OFF" showing an inactive loop or status, "TR OFFLD: OFF" denoting that task offloading is disabled, and a concluding line stating "Cause: TRANS OF" to pinpoint a transmission shutoff or timeout error.

Fig. 4.15 OLED Display Module

CHAPTER 5
HARDWARE DISCRIPTION

5.1 VOLTAGE SENSOR WORKING

Resistor voltage dividers are commonly used to create reference voltages, or to reduce the magnitude of a voltage so it can be measured and may also be used as signal attenuators at low frequencies. For direct current and relatively low frequencies, a voltage divider may be sufficiently accurate if made only of resistors; where frequency response over a wide range is required (such as in an oscilloscope probe), a voltage divider may have capacitive elements added to compensate load capacitance. In electric power transmission, a capacitive voltage divider is used for measurement of high voltage. A current transformer (CT) is a type of transformer that is used to measure alternating current (AC). It produces a current in its secondary which is proportional to the current in its primary. The instrument transformers isolate measurement or protection circuits from the high voltage of the primary system. In output of the CT transformer, simple diode and capacitor is used to convert the ac output voltage in terms of DC voltage by conversion in RMS factor. Hence, we can find the AC rms voltage in terms of sensor. The Current Transformer (C.T.) is a type of "instrument transformer" that is designed to produce an alternating current in its secondary winding which is proportional to the current being measured in its primary. The current transformer consists of only one or very few turns as its primary winding. This primary winding can be of either a single flat turn, a coil of heavy-duty wire wrapped around the core or just a conductor or bus bar placed through a central hole.

5.2 MICROCONTROLLER WORKING

This circuit consists of ATMEGA 328 p which is used to collect the data from the sensor and post to main unit through wireless transceiver. It has 14 digital I/O pins, of which 6 can be used as PWM outputs and 6 analog input pins. These I/O pins account for 20 of the pins. 2 of the pins are for the crystal oscillator.

This is to provide a clock pulse for the Atmega chip. A clock pulse is needed for synchronization so that communication can occur in synchrony between the Atmega chip and a device that it is connected to. The chip needs power so 2 of the pins, Vcc and GND, provide it power so that it can operate. The Atmega328 is a low-power chip, so it only needs between 1.8-5.5V of power to operate. The Atmega328 chip has an analog-to-digital converter (ADC) inside of it. This must be or else the Atmega328 wouldn't be capable of interpreting analog signals. Because there is an ADC, the chip can interpret analog input, which is why the chip has 6 pins for analog input. The ADC has 3 pins set aside for it to function- AVCC, AREF, and GND. AVCC is the power supply, positive voltage, that for the ADC. The ADC needs its own power supply in order to work. GND is the power supply ground. AREF is the reference voltage that the ADC uses to convert an analog signal to its corresponding digital value. Analog voltages higher than the reference voltage will be assigned to a digital value of 1, while analog voltages below the reference voltage will be assigned the digital value of 0. Since the ADC for the Atmega328 is a 10-bit ADC, meaning it produces a 10-bit digital value, it converts an analog signal to its digital value, with the AREF value being a reference for which digital values are high or low.

5.3 MODULES

5.3.1 ATmega328/P

ATmega 328 has 1KB Electrically Erasable Programmable Read Only Memory (EEPROM). This property shows if the electric supply supplied to the micro-controller is removed, even then it can store the data and can provide results after providing it with the electric supply. Moreover, ATmega-328 has 2KB Static Random Access Memory (SRAM). Other characteristics will be explained later. ATmega 328 has several different features which make it the most popular device in today’s market.

These features consist of advanced RISC architecture, good performance, low power consumption, real timer counter having separate oscillator, 6 PWM pins, programmable serial USART, programming lock for software security, throughput up to 20 MIPS etc. ATmega-328 is mostly used in Arduino. ATmega328 is an eight (8) bit micro-controller. It can handle the data sized of up to eight (8) bits. It is an AVR based micro-controller. Its built-in internal memory is around 32KB. It operates ranging from 3.3V to 5V.It has an ability to store the data even when the electrical supply is removed from its biasing terminals. Its excellent features include the cost efficiency, low power dissipation, programming lock for security purposes, real timer counter with separate oscillator. ATmega-328 is an AVR micro-controller having twenty-eight (28) pins in total. All of the pins in chronological order, are listed in the table shown in the figure given below.

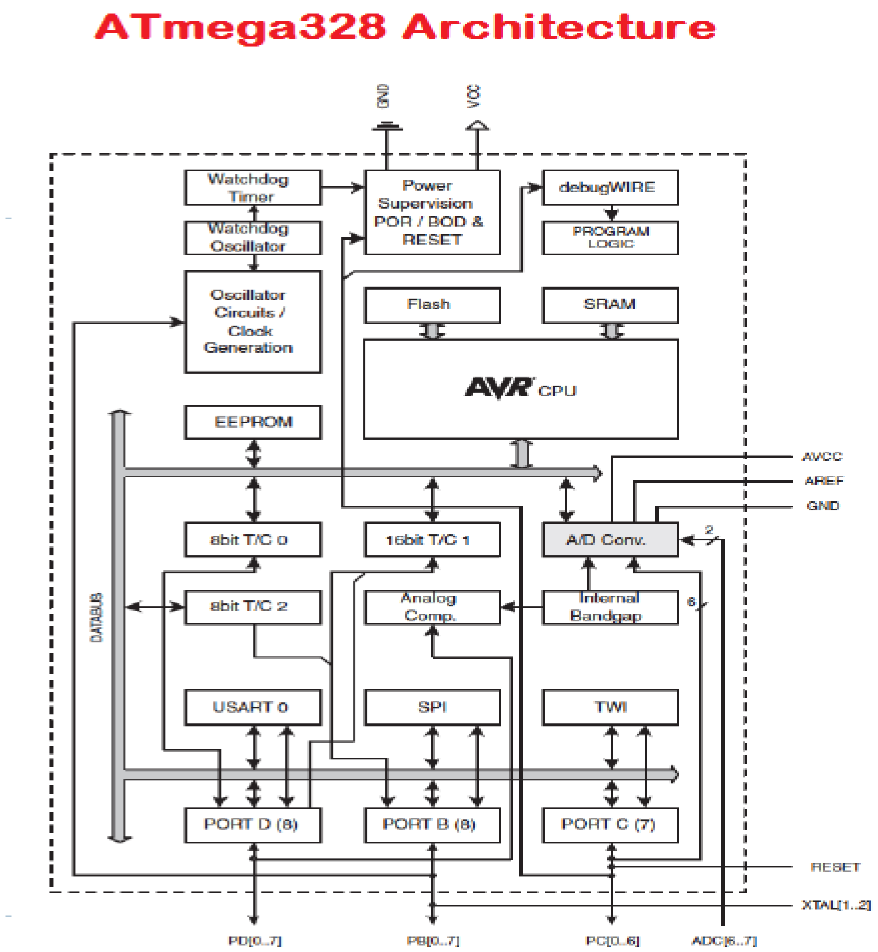

Fig. 5.1 Block diagram of 328p microcontroller

ATmega 328 has three types of memories e.g. EEPROM, SRAM etc. The capacity of each memory is explained in detail below. Flash Memory has 32KB capacity. It has an address of 15 bits. It is a Programmable Read Only Memory (ROM). It is non-volatile memory. RAM stands for Static Random Access Memory. It is a volatile memory i.e. data will be removed after removing the power supply. EEPROM stands for Electrically Erasable Programmable Read Only Memory. It has a long-term data. ATmega-328 has thirty-two (32) General Purpose (GP) registers. These all of the registers are the part of Static Random Access Memory (SRAM).All the registers are given in the figure shown below.

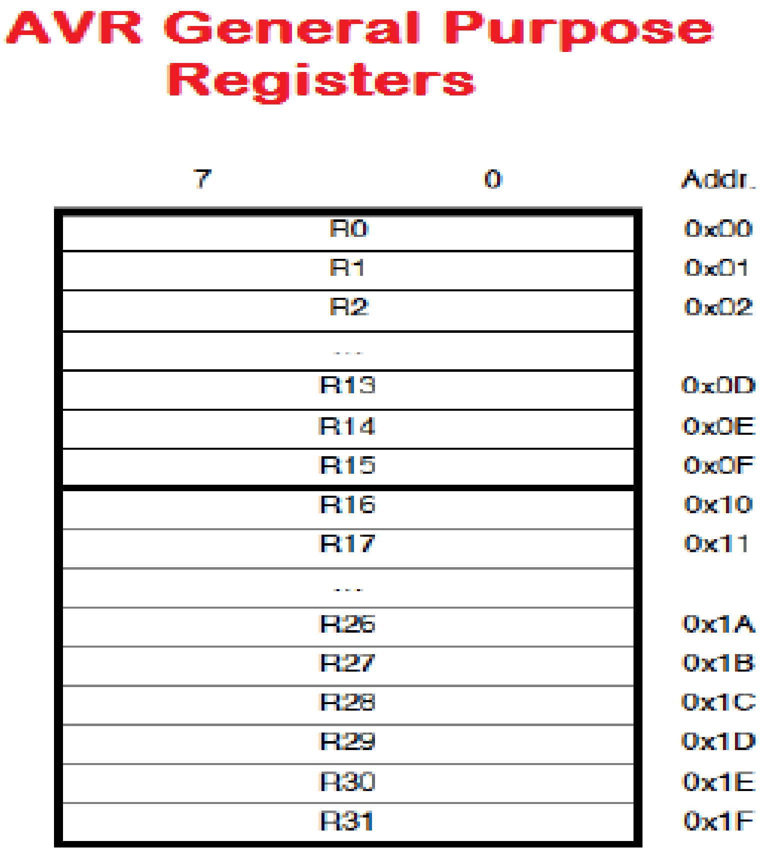

Fig 5.2 Register of Microcontroller

The different versions of the same device are denoted by the different packages of that device. Each package has different dimensions, in order to differentiate easily.

ATmega 328 packages are given in the table shown in the figure given below. A complete package including ATmega 328 and Arduino can be used in several different real-life applications. It can be used in embedded systems projects. It can also be used in robotics. Quadcopter and even small aeroplanes can also be designed through it.Power monitoring and management systems can also be prepared using this device. An important aspect of the Arduino is its standard connectors, which let users connect the CPU board to a variety of interchangeable add-on modules termed shields. Arduino is used to communicate the input analog signals and given an output digital signal. Arduino is having a set of arrangements that should be in this system have an input from the Arduino UNO. That is ultrasonic sensor for the user of the application.

An Arduino board historically consists of an Atmel 8-, 16- or 32- bit AVR microcontroller with complementary components that facilitate programming and incorporation into other circuits. An important aspect of the Arduino is its standard connectors, which let users connect the CPU board to a variety of interchangeable add-on modules termed shields. Some shields communicate with the Arduino board directly over various pins, but many shields are individually addressable via an I2C serial bus, so many shields can be stacked and used in parallel. Official Arduino's had used the Atmel megaAVR series of chips, specifically the ATmega8, ATmega168, ATmega328, ATmega1280 and ATmega2560. These systems provide sets of digital and analog I/O pins that can interface to various expansion boards and other circuits.

5.4 RELAY WORKING

Relays are switching that open and close circuits electromechanically or electronically. Relays control one electrical circuit by opening and closing contacts in another circuit. As relay diagrams show, when a relay contact is normally open (NO), there is an open contact when the relay is not energized. When a relay contact is Normally Closed (NC), there is a closed contact when the relay is not energized.

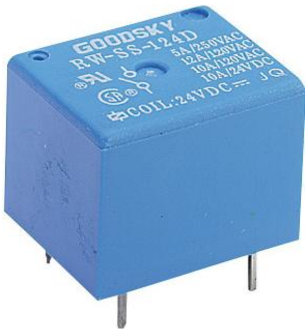

Fig. 5.3 Relay

In either case, applying electrical current to the contacts will change their state. Relays are generally used to switch smaller currents in a control circuit and do not usually control power consuming devices except for small motors and Solenoids that draw low amps. Nonetheless, relays can "control" larger voltages and amperes by having an amplifying effect because a small voltage applied to a relays coil can result in a large voltage being switched by the contacts. Protective relays can prevent equipment damage by detecting electrical abnormalities, including overcurrent, undercurrent, overloads and reverse currents. In addition, relays are also widely used to switch starting coils, heating elements, pilot lights and audible alarms. Relays are either electromechanical relays or solid-state relays.

In electromechanical relays (EMR), contacts are opened or closed by a magnetic force. With solid-state relays (SSR), there are no contacts and switching is totally electronic. Solid State Relays switch the current using non-moving electronic devices such as silicon-controlled rectifiers. These differences in the two types of relays result in advantages and disadvantages with each system. Because solid state relays do not have to either energize a coil or open contacts, less voltage is required to "turn" Solid State Relays on or off. Similarly, Solid State Relays turn on and turn off faster because there are no physical parts to move. Although the absence of contacts and moving parts means that Solid State Relays are not subject to arcing and do not wear out, contacts on Electromechanical Relays can be replaced, whereas entire Solid-State Relays must be replaced when any part becomes defective.

Because of the construction of Solid-State Relays, there is residual electrical resistance and/or current leakage whether switches are open and closed. The small voltage drops that are created are not usually a problem; however, Electromechanical Relays provide a cleaner ON or OFF condition because of the relatively large distance between contacts, which acts as a form of insulation.

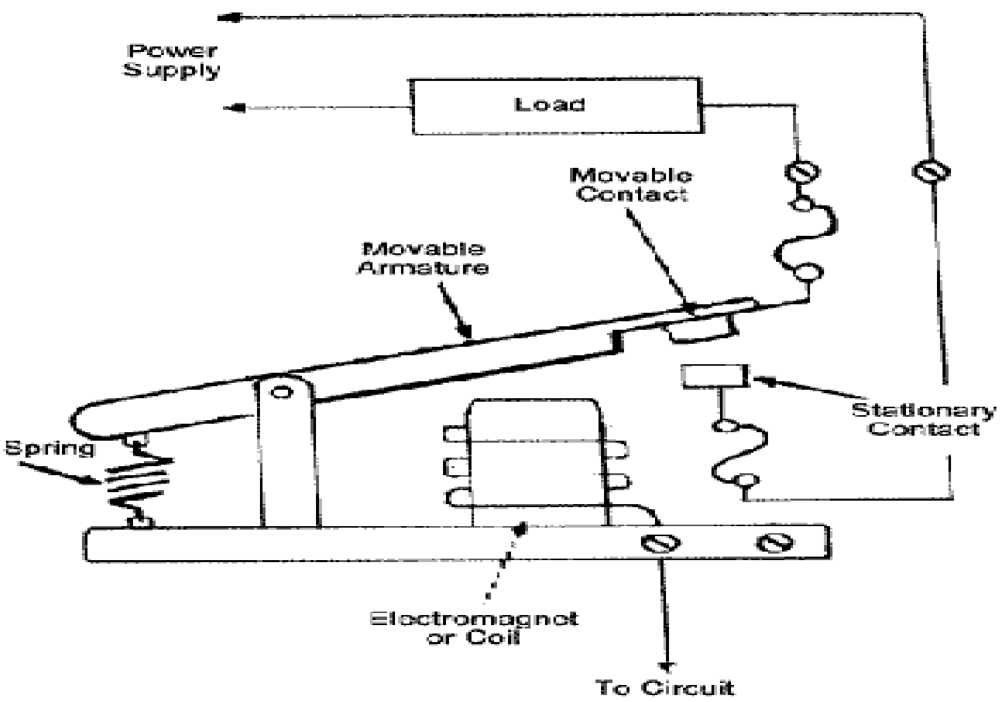

Fig 5.4 Relay Internal Diagram

Relays involve two circuits: the energizing circuit and the contact circuit. The coil is on the energizing side; and the relays contacts are on the contact side. When a relays coil is energized, current flow through the coil creates a magnetic field. Whether in a DC unit where the polarity is fixed, or in an AC unit where the polarity changes 120 times per second, the basic function remains the same: the magnetic coil attracts a ferrous plate, which is part of the armature. One end of the armature is attached to the metal frame, which is formed so that the armature can pivot, while the other end opens and closes the contacts. Contacts come in several different configurations, depending on the number of Breaks, poles and throws that make up the relay.

This is the number of separate places or contacts that a switch uses to open or close a single electrical circuit. All contacts are either single break or double break. A single break (SB) contact breaks an electrical circuit in one place, while a double break (DB) contact breaks it in two places. Single break contacts are normally used when switching lower power devices such as indicating lights. Double break contacts are used when switching high-power devices such as solenoids. Pole -This is the number of completely isolated circuits that relays can pass through a switch. A single-pole contact (SP) can carry current through only one circuit at a time. A double-pole contact (DP) can carry current through two isolated circuits simultaneously. The maximum number of poles is 12, depending upon a relays design. Throw -This is the number of closed contact positions per pole that are available on a switch. A switch with a single throw contact can control only one circuit, while a double-throw contact can control two.

5.5 CURRENT TRANSFORMER

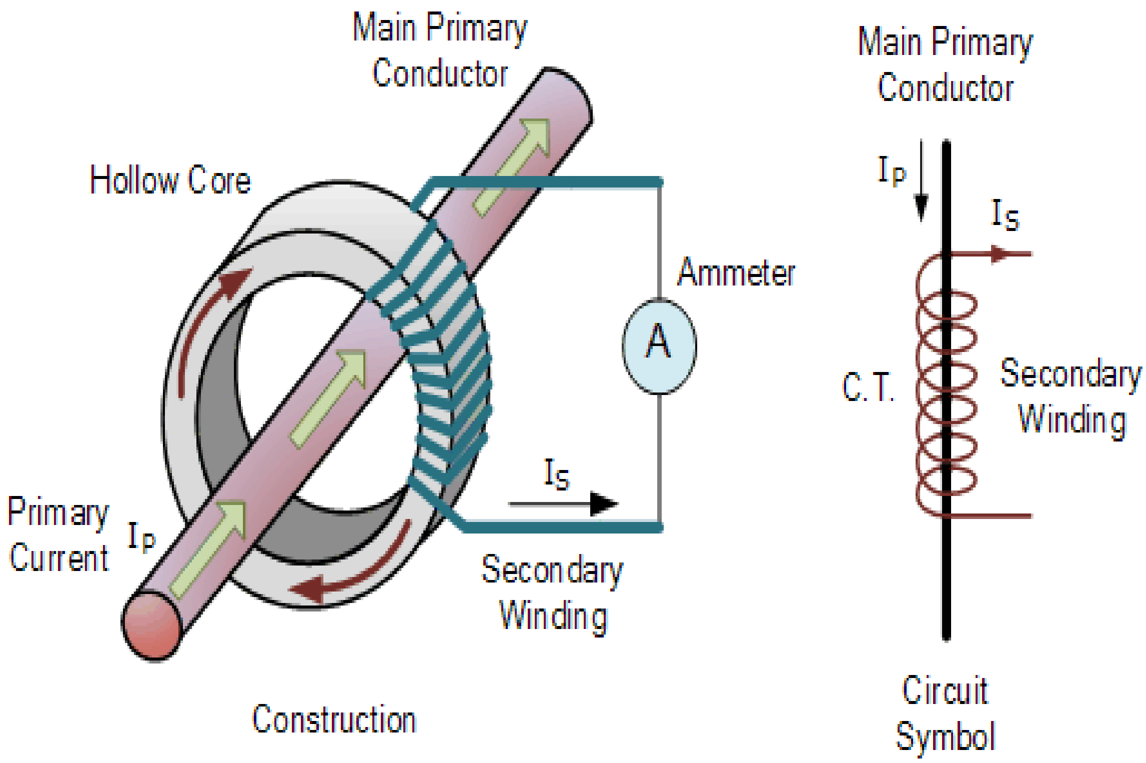

Fig. 5.5 Current Transformer Diagram

The Current Transformer (C.T.) is a type of "instrument transformer" that is designed to produce an alternating current in its secondary winding which is proportional to the current being measured in its primary. The current transformer consists of only one or very few turns as its primary winding. This primary winding can be of either a single flat turn, a coil of heavy-duty wire wrapped around the core or just a conductor or bus bar placed through a central hole as shown. Due to this type of arrangement, the current transformer is often referred to as a "series transformer" as the primary winding, which never has more than a very few turns, is in series with the current carrying conductor supplying a load. The secondary winding however, may have a large number of coils turns wound on a laminated core of low-loss magnetic material. This core has a large cross-sectional area so that the magnetic flux density created is low using much smaller cross-sectional area wire, depending upon how much the current must be stepped down as it tries to output a constant current, independent of the connected load. The secondary winding will supply a current into either a short circuit, in the form of an ammeter, or into a resistive load until the voltage induced in the secondary is big enough to saturate the core or cause failure from excessive voltage breakdown. Unlike a voltage transformer, the primary current of a current transformer is not dependent of the secondary load current but instead is controlled by an external load. The secondary current is usually rated at a standard 1 Ampere or 5 Amperes for larger primary current ratings.

5.6 POWER SUPPLY

Power supply is a reference to a source of electrical power. A device or system that supplies electrical or other types of energy to an output load or group of loads is called a power supply unit or PSU. The term is most applied to electrical energy supplies, less often to mechanical ones, and rarely to others. Power supplies for electronic devices can be broadly divided into linear and switching power supplies. The linear supply is a relatively simple design that becomes increasingly bulky and heavy for high current devices.

The voltage regulation in a linear supply can result in low efficiency. A switched-mode supply of the same rating as a linear supply will be smaller, is usually more efficient, but will be more complex.

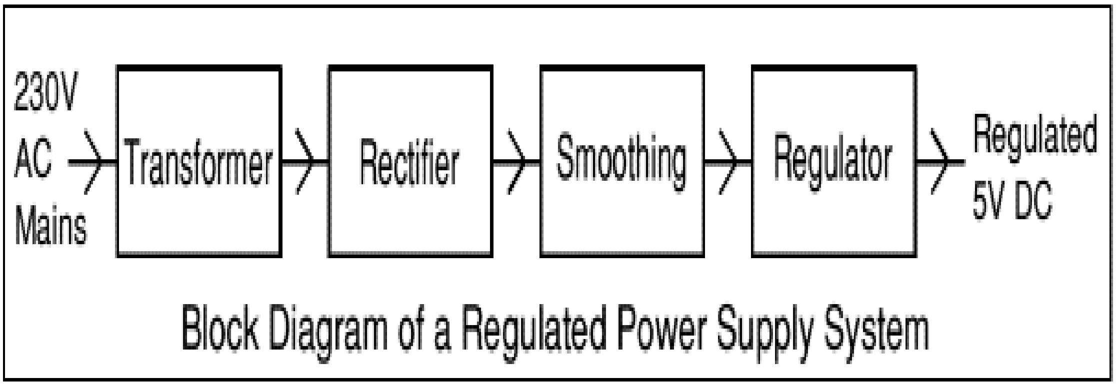

Fig 5.6 Power Supply Block Diagram

5.6.1 LINEAR POWER SUPPLY

An AC powered linear power supply usually uses a transformer to convert the voltage from the wall outlet (mains) to a different, usually a lower voltage. If it is used to produce DC, a rectifier is used. A capacitor is used to smooth the pulsating current from the rectifier. Some small periodic deviations from smooth direct current will remain, which is known as ripple. These pulsations occur at a frequency related to the AC power frequency (for example, a multiple of 50 or 60 Hz). The voltage produced by an unregulated power supply will vary depending on the load and on variations in the AC supply voltage. For critical electronics applications a linear regulator will be used to stabilize and adjust the voltage. This regulator will also greatly reduce the ripple and noise in the output direct current. Linear regulators often provide current limiting, protecting the power supply and attached circuit from over current. Adjustable linear power supplies are common laboratory and service shop test equipment, allowing the output voltage to be set over a wide range.

For example, a bench power supply used by circuit designers may be adjustable up to 30 volts and up to 5 amperes output. Some can be driven by an external signal, for example, for applications requiring a pulsed output.

5.6.2 SWITCHED-MODE POWER SUPPLY

A switched-mode power supply (SMPS) works on a different principle. AC mains input is directly rectified without the use of a transformer, to obtain a DC voltage. This voltage is then sliced into small pieces by a high-speed electronic switch. The size of these slices grows larger as power output requirements increase. The input power slicing occurs at a very high speed (typically 10 kHz — 1 MHz). High frequency and high voltages in this first stage permit much smaller step-down transformers than are in a linear power supply. After the transformer secondary, the AC is again rectified to DC. To keep output voltage constant, the power supplies need a sophisticated feedback controller to monitor current draw by the load.

5.7 TRANSFORMER WORKING

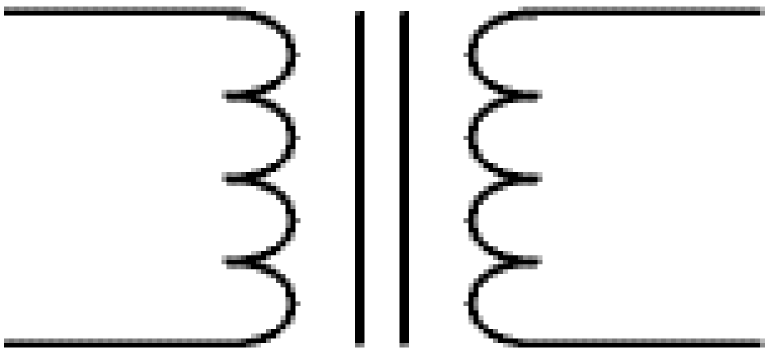

Fig. 5.7 Transformer working diagram

Transformers convert AC electricity from one voltage to another with little loss of power. Transformers work only with AC, and this is one of the reasons why mains electricity is AC. Step - up transformers increase voltage, step-down transformers reduce voltage. Most power supplies use a step-down transformer to reduce the dangerously high mains voltage (230V in UK) to a safer low voltage.

There is no electrical connection between the two coils; instead they are linked by an alternating magnetic field created in the soft-iron core of the transformer. The two lines in the middle of the circuit symbol represent the core. Transformers waste very little power so the power out is (almost) equal to the power in. Note that as voltage is stepped down current is stepped up. The ratio of the number of turns on each coil, called the turn's ratio, determines the ratio of the voltages. A step-down transformer has a large number of turns on its primary (input) coil which is connected to the high voltage mains supply, and a small number of turns on its secondary (output) coil to give a low output voltage. Turns ratio=Vp/Vs=Nn/Ns and Power out=Power in Vs*Is=Vp * Ip

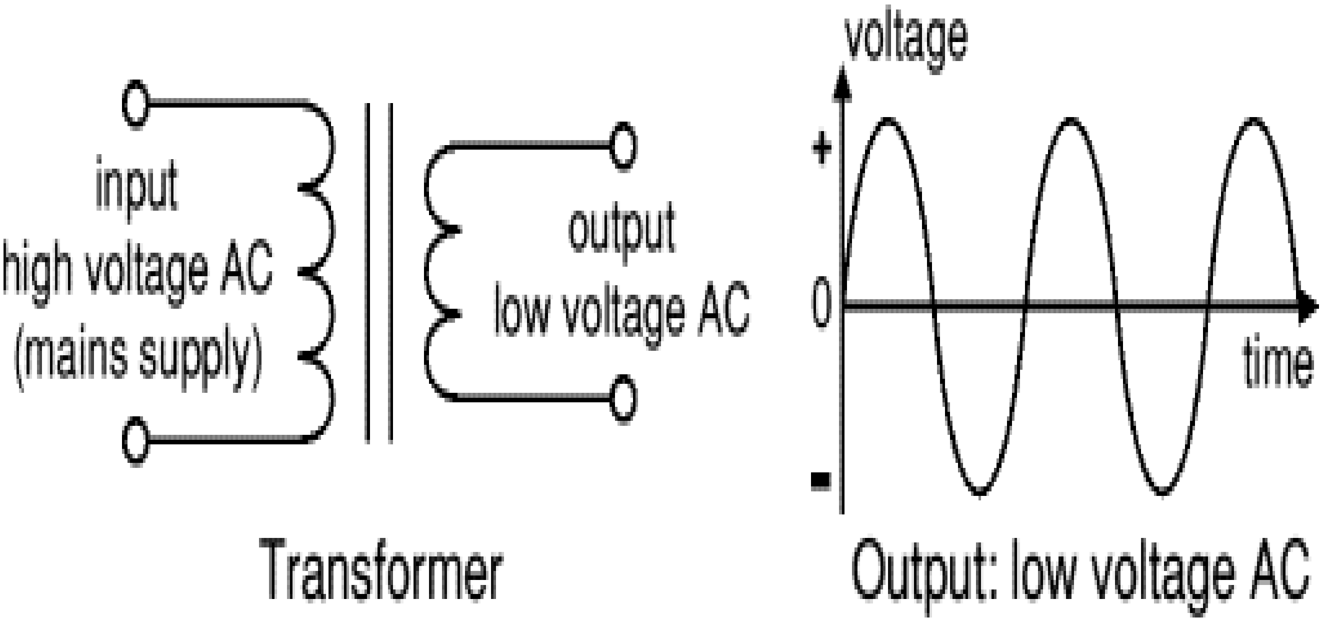

Fig. 5.8 Output of Transformer

The low voltage AC output is suitable for lamps, heaters and special AC motors. It is not suitable for electronic circuits unless they include a rectifier and a smoothing capacitor.

5.8 RECTIFIER

There are several ways of connecting diodes to make a rectifier to convert AC to DC. The bridge rectifier is the most important and it produces full-wave varying DC. A full-wave rectifier can also be made from just two diodes if a centre-tap transformer is used, but this method is rarely used now that diodes are cheaper. A single diode can be used as a rectifier, but it only uses the positive (+) parts of the AC wave to produce half-wave varying DC.

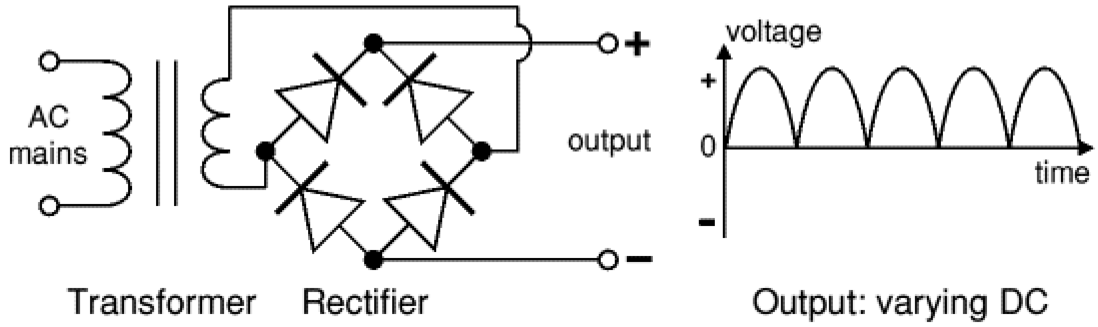

Fig. 5.9 Rectifier Output

The varying DC output is suitable for lamps, heaters and standard motors. It is not suitable for electronic circuits unless they include a smoothing capacitor.

5.9 BRIDGE RECTIFIER

A bridge rectifier can be made using four individual diodes, but it is also available in special packages containing the four diodes required. It is called a full-wave rectifier because it uses the entire AC wave (both positive and negative sections). 1.4V is used up in the bridge rectifier because each diode uses 0.7V when conducting and there are always two diodes conducting, as shown in the diagram below. Bridge rectifiers are rated by the maximum current.

They can pass and the maximum reverse voltage they can withstand (this must be at least three times the supply RMS voltage so the rectifier can withstand the peak voltages). Please see the Diodes page for more details, including pictures of ridge rectifiers.

5.10 REGULATOR

Voltage regulator ICs are available with fixed (typically 5, 12 and 15V) or variable output voltages. They are also rated by the maximum current they can pass. Negative voltage regulators are available, mainly for use in dual supplies. Most regulators include some automatic protection from excessive current ('overload protection') and overheating ('thermal protection'). Many of the fixed voltage regulator ICs has 3 leads and look like power transistors, such as the 7805 +5V 1A regulator shown on the right. They include a hole for attaching a heat sink if necessary.

5.11 BASIC OF IOT

The Internet of Things is simply "A network of Internet connected objects able to collect and exchange data." It is commonly abbreviated as IoT. The word "Internet of Things" has two main parts; Internet being the backbone of connectivity, and Things meaning objects / devices The Internet of Things (IoT), also sometimes referred to as the Internet of Everything (IoE), consists of all the web-enabled devices that collect, send and act on data they acquire from their surrounding environments using embedded sensors, processors and communication hardware.

The Internet of Things (IoT) refers to the ever-growing network of physical objects that feature an IP address for internet connectivity, and the communication that occurs between these objects and other Internet-enabled devices and systems. The IoT platform is a suite of components that enable Deployment of applications that monitor, manage, and control connected devices. Remote data collection from connected devices. Independent and secure connectivity between devices. Device/sensor management.

The Internet of Everything (IoE) is a concept that extends the Internet of Things (IoT) emphasis on machine-to-machine (M2M) communications to describe a more complex system that also encompasses people and processes. The Internet of things (stylised Internet of Things or IoT) is the internetworking of physical devices, vehicles (also referred to as "connected devices" and "smart devices"), buildings and other items—embedded with electronics, software, sensors, actuators, and network connectivity that enable these objects to collect information The processing of data on web-connected servers in large data centres, what we refer to as the cloud, has also contributed greatly to the ability of everyday gadgets to become part of the IoT. These devices may connect to the Internet by sending data to your phone or some other dedicated hardware in your home that acts as a hub over a local communication method.

The connected gadgets of the IoT contain computing hardware, including processors with embedded programming telling them what to do, sensors that gather various sorts of readings (such as temperature, moisture, light, motion, chemical levels, heart rate and body movement) and communication hardware that can send and receive signals. Some connected systems may be able to use other nearby devices to gather data, like city road systems that signal smart phones to help monitor traffic conditions. Smart devices can work in conjunction with tagging technology including RFID tags, QR codes, barcodes and the like to obtain data about items

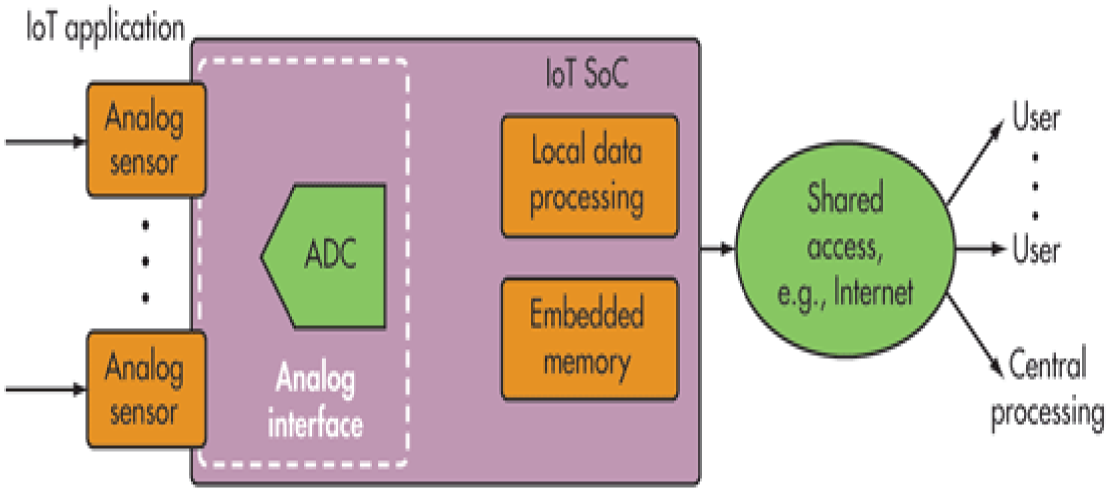

Fig. 5.10 IoT Block Diagram

Device may be run mostly via their own embedded software or firmware, but they can also offload a lot of the processing to cloud-based software via the Internet, where they can crunch more data. Some use advanced algorithms that let them learn from and adjust to various stimuli and patterns (letting them program themselves, to an extent). This sending and processing of the sensor data is often nearly instantaneous (thanks to the usually lightning-fast speeds of Internet communication), allowing the devices to react in real-time. Internet, things, Internet of things, Internet of Everything. These are some of the buzzwords you may have been hearing, reading & very likely talking about endlessly.

These are more than just keywords; IoT (Internet of Things) is a technology concept and/or an architecture which is an aggregation of already available technologies. Similar to the way in which Internet has changed the way we work & communicate by connecting us (humans) through World Wide Web, IoT aims to take this connectivity to next level by connecting various devices to the internet – facilitating human-machine, machine-machine interactions also. The visionaries have also realized that this IoT ecosystem has business applications in areas of Home Automation, Automotive, Factory/assembly line automation, Retail, Medical/Preventive healthcare and more.

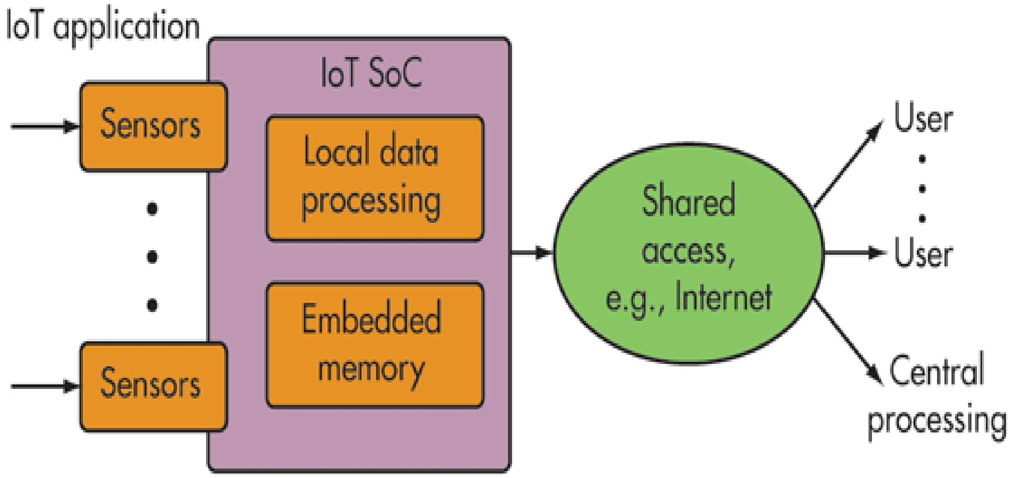

Fig. 5.11 IOT Sensor Interface

Digital sensor outputs data in a digital format. It may already take care of some of the data processing, like calibration and other functions. Also, it may implement sensor fusion techniques by including several different sensors and combining them to derive meaningful information, as in motion detection. The analog sensor outputs raw data in analog format. There is a significant range of analog sensors such as temperature whose output is delivered in the analog domain. The application SoC needs to collect the output in raw format and convert it to digital for processing. When connecting with a digital sensor device, the IoT SoC needs to include a digital interface that complies with the one the sensor chip is using to drive the sensor signals into the processor in the SoC. When connecting with an analog sensor, the IoT SoC needs to convert the sensor signal into the digital domain by means of an analog-to-digital converter (ADC). Now that we all understand the IoT concept, it would be worthwhile to deep dive in order to get familiar with the building blocks of IoT:

1. Sensors & Sensor technology – They will sniff a wide variety of information ranging from Location, Weather/Environment conditions, Grid parameters, Movement on assembly lines, Jet engine maintenance data to Health essentials of a patient

2.IoT Gateways – IoT Gateways, as the name rightly suggests, are the gateways to internet for all the things/devices that we want to interact with. Gateways help to bridge the internal network of sensor nodes with the external Internet or World Wide Web. They do this by collecting the data from sensor nodes & transmitting it to the internet infrastructure.

3. Cloud/server infrastructure & Big Data – The data transmitted through gateway is stored & processed securely within the cloud infrastructure using Big Data analytics engine. This processed data is then used to perform intelligent actions that make all our devices 'Smart Devices'!

4. End-user Mobile apps – The intuitive mobile apps will help end users to control & monitor their devices (ranging from room thermostat to jet engines & assembly lines) from remote locations. These apps push the important information on your hand-held devices & help to send commands to your Smart Devices!

5. IPv6 – IP addresses are the backbone to the entire IoT ecosystem. Internet is concerned about IP addresses only & not if you are a human or a toaster. With IPv4 we were running out of IP addresses, but with IPv6 (launched in 2012) we now have 3.4*10^38 IP addresses!

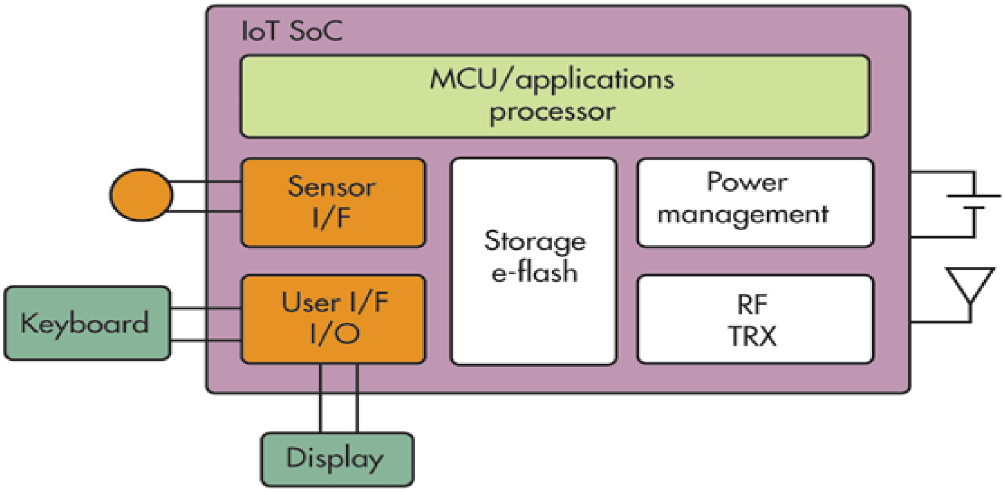

Fig. 5.12 Microcontroller of IOT

1. A temperature sensor network installed in the room will be integrated with the gateway. Gateway helps to connect the temperature sensor network (things) to the Internet through Cloud infrastructure.

2. Cloud/server possesses the detailed records about the each and every device connected to it – device id, current status of the device, who has accessed the device last time, how many times the device has been accessed and more.

3. Connection with the cloud is implemented using web services such as REST full.

4. End-users like you and me interact with Cloud (and in turn devices installed in our homes) through the mobile app. Request will be sent to the cloud with the authentication and device information. Authentication is configured to ensure cyber security.

5. Cloud will identify the device with the help of the device id and will send the corresponding request to the appropriate sensor network using gateways.

6. Then, the temperature sensor will read the current temperature in the room and will send the response back to the cloud.

7. Cloud will identify the user who has requested the data and push the requested data to the app. So, user will get the current information directly on his screen.

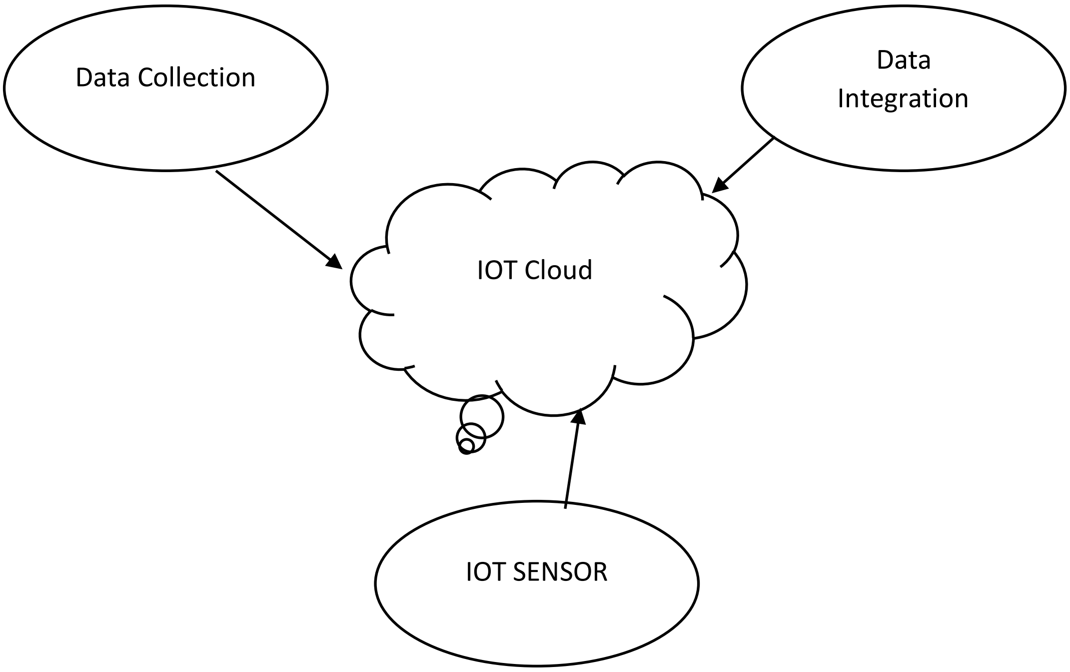

Fig. 5.13 Interference of IOT

5.11.1 DATA COLLECTION

This software manages sensing, measurements, light data filtering, light data security, and aggregation of data. It uses certain protocols to aid sensors in connecting with real-time, machine-to-machine networks. Then it collects data from multiple devices and distributes it in accordance with settings. It also works in reversedistributing data over devices. The system eventually transmits all collected data to a central server.

5.11.2 DEVICE INTEGRATION

Software supporting integration binds (dependent relationships) all system devices to create the body of the IoT system. It ensures the necessary cooperation and stable networking between devices. These applications are the defining software technology of the IoT network because without them, it is not an IoT system. They manage the various applications, protocols, and limitations of each device to allow communication.

5.11.3 IOT SENSOR

The most important hardware in IoT might be its sensors. These devices consist of energy modules, power management modules, RF modules, and sensing modules. RF modules manage communications through their signal processing, Wi-Fi, ZigBee, Bluetooth, radio transceiver, duplexer, and BAW.

5.11.4 STANDARD DEVICES

The desktop, tablet, and cell phone remain integral parts of IoT as the command centre and remotes. The desktop provides the user with the highest level of control over the system and its settings. The tablet provides access to the key features of the system in a way resembling the desktop and also acts as a remote. The cell phone allows some essential settings modification and also provides remote functionality.

5.11.5 REAL-TIME ANALYTICS

These applications take data or input from various devices and convert it into viable actions or clear patterns for human analysis. They analyse information based on various settings and designs in order to perform automation-related tasks or provide the data required by industry.

5.11.6 APPLICATION AND PROCESS EXTENSION

These applications extend the reach of existing systems and software to allow a wider, more effective system. They integrate predefined devices for specific purposes such as allowing certain mobile devices or engineering instruments access. It supports improved productivity and more accurate data collection.

5.12 IOT − KEY FEATURES

The most important features of IoT include artificial intelligence, connectivity, sensors, active engagement, and small device use. A brief review of these features is given below. IoT essentially makes virtually anything “smart”, meaning it enhances every aspect of life with the power of data collection, artificial intelligence algorithms, and networks. This can mean something as simple as enhancing your refrigerator and cabinets to detect when milk and your favourite cereal run low, and to then place an order with your preferred grocer. Connectivity. New enabling technologies for networking, and specifically IoT networking, mean networks are no longer exclusively tied to major providers. Networks can exist on a much smaller and cheaper scale while still being practical. IoT creates these small networks between its system devices. Sensors. IoT loses its distinction without sensors. They act as defining instruments which transform IoT from a standard passive network of devices into an active system capable of real-world integration. Active Engagement much of today's interaction with connected technology happens through passive engagement. IoT introduces a new paradigm for active content, product, or service engagement. Small Devices − Devices, as predicted, have become smaller, cheaper, and more powerful over time. IoT exploits purpose-built small devices to deliver its precision, scalability, and versatility.

5.13 IOT – ADVANTAGES

The advantages of IoT span across every area of lifestyle and business. Here is a list of some of the advantages that IoT has to offer. It Improved Customer Engagement. Current analytics suffer from blind. spots and significant flaws in accuracy.

IoT completely transforms this to achieve richer and more effective engagement with audiences. Technology Optimization. The same technologies and data which improve the customer experience also improve device use, and aid in more potent improvements to technology. IoT unlocks a world of critical functional and field data. Reduced Waste. I.T makes areas of improvement clear. Current analytics give us superficial insight, but IoT provides real-world information leading to more effective management of resources. Enhanced Data Collection. Modern data collection suffers from its limitations and its design for passive use. IoT breaks it out of those spaces, and places it exactly where humans really want to go to analyse our world. It allows an accurate picture of everything.

4.14 IOT – DISADVANTAGES

Though IoT delivers an impressive set of benefits, it also presents a significant set of challenges. Here is a list of some its major issues. IoT creates an ecosystem of constantly connected devices communicating over networks. The system offers little control despite any security measures. This leaves users exposed to various kinds of attackers. Privacy. The sophistication of IoT provides substantial personal data in extreme detail without the user's active participation.

CHAPTER 6

SOFTWARE MODULE

6.1 SOFTWARE TOOL

Arduino is an open source, computer hardware and software company, project, and user community that designs and manufactures microcontroller kits for building digital devices and interactive objects that can sense and control objects in the physical world. The project's products are distributed as open-source hardware and software, which are licensed under the GNU Lesser General Public License (LGPL) or the GNU General Public License (GPL),[1] permitting the manufacture of Arduino boards and software distribution by anyone. Arduino boards are available commercially in preassembled form, or as do-it-yourself kits. Arduino board designs use a variety of microprocessors and controllers. The boards are equipped with sets of digital and analog input/output (I/O) pins that may be interfaced to various expansion boards (*shields*) and other circuits. The boards feature serial communications interfaces, including Universal Serial Bus (USB) on some models, which are also used for loading programs from personal computers. The microcontrollers are typically programmed using a dialect of features from the programming languages C and C++. In addition to using traditional compiler toolchains, the Arduino project provides an integrated development environment (IDE) based on the Processing language project. The Arduino project started in 2003 as a program for students at the Interaction Design Institute Ivrea in Ivrea, Italy,[2] aiming to provide a low-cost and easy way for novices and professionals to create devices that interact with their environment using sensors and actuators. Common examples of such devices intended for beginner hobbyists include simple robots, thermostats, and detectors. Over the years Arduino has been the brain of thousands of projects, from everyday objects to complex scientific instruments.

A worldwide community of makers - students, hobbyists, artists, programmers, and professionals - has gathered around this open-source platform, their contributions have added up to an incredible amount of accessible knowledge that can be of great help to novices and experts alike. Arduino was born at the Ivrea Interaction Design Institute as an easy tool for fast prototyping, aimed at students without a background in electronics and programming. As soon as it reached a wider community, the Arduino board started changing to adapt to new needs and challenges, differentiating its offer from simple 8-bit boards to products for IoT applications, wearable, 3D printing, and embedded environments. All Arduino boards are completely open-source, empowering users to build them independently and eventually adapt them to their particular needs. The software, too, is open-source, and it is growing through the contributions of users worldwide. There are many other microcontrollers and microcontroller platforms available for physical computing. Parallax Basic Stamp, Net media's BX-24, Phi gets, MIT's Handy board, and many others offer similar functionality. All of these tools take the messy details of microcontroller programming and wrap it up in an easy-to-use package. Arduino also simplifies the process of working with microcontrollers, but it offers some advantage for teachers, students, and interested amateurs over other systems:

- Inexpensive - Arduino boards are relatively inexpensive compared to other microcontroller platforms. The least expensive version of the Arduino module can be assembled by hand, and even the pre-assembled Arduino modules cost less than $50
- Cross-platform - The Arduino Software (IDE) runs on Windows, Macintosh OSX, and Linux operating systems. Most microcontroller systems are limited to Windows.
- Simple, clear programming environment - The Arduino Software (IDE) is easy-to-use for beginners, yet flexible enough for advanced users to take advantage of as well. For teachers, it's conveniently based on the Processing programming environment.
- Open source and extensible software - The Arduino software is published as open-source tools, available for extension by experienced programmers.
- The language can be expanded through C++ libraries, and people wanting to understand the technical details can make the leap from Arduino to the AVR C programming language on

which it's based. Similarly, you can add AVR-C code directly into your Arduino programs if you want to.

- Open source and extensible hardware - The plans of the Arduino boards are published under a Creative Commons license, so experienced circuit designers can make their own version of the module, extending it and improving it. Even relatively inexperienced users can build the breadboard version of the module in order to understand how it works and save money.

6.2 VARIABLES

A *variable* is a place for storing a piece of data. It has a name, a type, and a value. For example, the line from the Blink sketch above declares a variable with the name led Pin, the type int, and an initial value of 13. It's being used to indicate which Arduino pin the LED is connected to. Every time the name led Pin appears in the code, its value will be retrieved. In this case, the person writing the program could have chosen not to bother creating the led Pin variable and instead have simply written 13 everywhere they needed to specify a pin number. The advantage of using a variable is that it's easier to move the LED to a different pin: you only need to edit the one line that assigns the initial value to the variable.

6.3 FUNCTIONS

A *function* (otherwise known as a *procedure* or *sub-routine*) is a named piece of code that can be used from elsewhere in a sketch. For example, here's the definition of the setup () function from the Blink example:

```
void setup ()
{
        pin Mode (led Pin, OUTPUT);
}
```

The first line provides information about the function, like its name, "setup". The text before and after the name specify its return type and parameters: these will be explained later. The code between the {and} is called the *body* of the function: what the function does.

pin Mode (), digital Write (), and delay ()

The pin Mode () function configures a pin as either an input or an output. To use it, you pass it the number of the pin to configure and the constant INPUT or OUTPUT. When configured as an input, a pin can detect the state of a sensor like a pushbutton; As an output, it can drive an actuator like an LED.

The digital Write () functions outputs a value on a pin.

For example, the line:

digital Write (led Pin, HIGH);

The delay () causes the Arduino to wait for the specified number of milliseconds before continuing on to the next line. There are 1000 milliseconds in a second, so the line:

delay (1000);

setup () and loop ()

There are two special functions that are a part of every Arduino sketch: setup () and loop (). The setup () is called once, when the sketch starts.

It's a good place to do setup tasks like setting pin modes or initializing libraries. The loop () function is called over and over and is heart of most sketches. You need to include both functions in your sketch, even if you don't need them for anything. Everything between the /* and */ is ignored by the Arduino when it runs the sketch (the * at the start of each line is only there to make the comment look pretty and isn't required). It's there for people reading the code: to explain what the program does, how it works, or why it's written the way it is. It's good practice to comment on your sketches, and to keep the comments up to date when you modify the code. This helps other people to learn from or modify your code.

6.4 ATMEL STUDIO 7

ATMEL Studio is an Integrated Development Environment (IDE) for writing and debugging applications for AVR/ARM platforms. Currently as a code writing environment, it supports the included AVR Assembler and any external AVRGCC/ARMGCC compiler in a complete IDE environment. Using ATMEL Studio as an IDE gives you several advantages:

1. Editing and debugging in the same application window allow for a faster error tracking.

2. Breakpoints are saved and restored between sessions, even if the code was edited in the meantime. 3. Project item management is made convenient and portable.

6.5 PROGRAMMING FOR ATMEGA IC

1. Go to the ATMEL website and download ATMEL studio 7. The download link is below, and it can be download and install either the web installer or the offline installer.

2. The second step to program ARDUINO using ATMEL Studio 7 is to add AVR dude as an external tool. To do this, open ATMEL studio and go to Tool > External Tools. There you will see a form for specifying external tool. Here we have to setup the AVRdude.exe that ARDUINO uses as our external tool so that ATMEL studio can use it.

3. The final step to program ARDUINO using ATMEL Studio 7 is to write, compile and upload the program into the Microcontroller via USB. As we said we will use C program to write the code. Start a new GCC C Executable Project, provide some name and finally select the ATMEGA328P as your device. This also works if you want to use C++ programming language.

4. The External Tool ARDUINO UNO Programmer that we created in the earlier step. But before that you have to connect the ARDUINO to your PC.

5. To do this, go to Tools menu in the toolbar and select/click ARDUINO UNO Programmer. The hex code will be burned into the microcontroller, and you should see a message “avrdude.exe done. Thank you.” in the output window.

To use ARDUINO Uno (with ATMEGA328P device) outside of the ARDUINO software environment. We will use ATMEL Studio 7 for programming the ARDUINO Uno in C. The use of ATMEL Studio gives you complete flexibility and control over microcontroller and will help you to create interesting ARDUINO Uno Projects. The board used in this tutorial is ARDUINO Uno R3. Moving from the standard Arduino IDE to Microchip Studio (formerly Atmel Studio 7) represents a transition from a simplified abstraction layer to a professional-grade Integrated Development Environment (IDE). This approach provides a deeper understanding of the AVR architecture and allows for more efficient code execution.

6.6 FLOW CHART

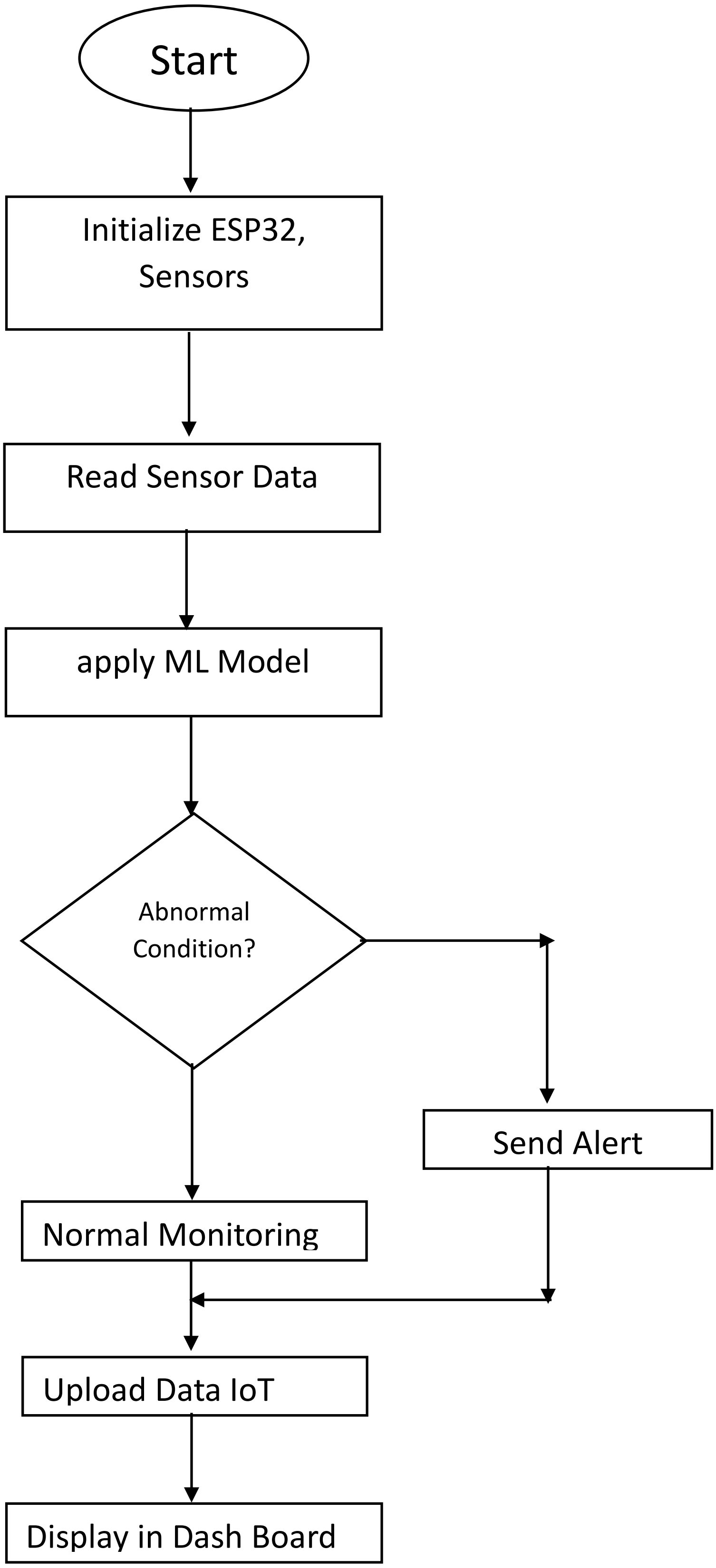

Fig. 6.1 Flow Chart

The Fig.6.1 illustrates the step-by-step operation of the proposed smart transformer monitoring system integrated with machine learning. The process begins with the start condition, where the system is powered ON and all components are initialized. This includes the initialization of the ESP32 module and all connected sensors, ensuring that the system is ready to perform monitoring and data processing tasks. Once initialization is completed, the system enters the data acquisition stage, where sensor data is continuously read. The sensors measure key transformer parameters such as voltage, current, temperature, humidity, and oil level. These values provide real-time information about the operating condition of the transformer and are essential for detecting any abnormalities. After collecting the sensor data, the system proceeds to the machine learning analysis stage. In this stage, the ESP32 applies a trained machine learning model to the incoming data. The ML model has been trained using historical data representing both normal and faulty transformer conditions. It analyses multiple parameters simultaneously and identifies patterns that indicate whether the system is operating normally or approaching a fault condition.

This approach improves accuracy compared to traditional threshold-based systems. If the machine learning model detects any abnormality or predicts a potential fault, the system immediately triggers an alert. A notification is sent to the user or maintenance personnel through communication modules such as GSM or IoT-based services, ensuring timely response and preventive action. If no abnormal condition is detected, the system continues with normal monitoring operation, where it keeps collecting and analysing sensor data in real time without generating any alerts. This ensures continuous supervision of transformer performance under safe operating conditions. Following this, the system proceeds to the data transmission stage, where all collected data is uploaded to an IoT platform. This allows remote monitoring and storage of historical data for further analysis and decision-making. The data is then displayed on a dashboard, enabling users to view real-time transformer parameters and system status from any location.

6.7 ML IMPLEMENTATION

Machine Learning (ML) is an advanced computational approach that enables systems to learn patterns from data and make intelligent decisions without being explicitly programmed for every condition. In the proposed transformer monitoring system, ML is integrated to enhance the accuracy, reliability, and predictive capability of fault detection. Unlike traditional monitoring systems that rely on fixed threshold values for each parameter, the ML-based approach considers multiple parameters simultaneously and identifies complex relationships among them to determine the actual condition of the transformer. The implementation of machine learning in this system begins with data acquisition, where multiple sensors continuously measure transformer parameters such as voltage, current, temperature, humidity, and oil level. These parameters serve as the input features for the ML model. Each parameter plays a critical role in determining transformer health. For instance, voltage and current indicate electrical loading conditions, temperature reflects thermal stress, humidity affects insulation quality, and oil level indicates cooling efficiency.

The collected data is then subjected to data preprocessing, which is a crucial step in machine learning. Sensor data in real-world environments often contains noise, fluctuations, and inconsistencies. To improve data quality, preprocessing techniques such as filtering, normalization, and scaling are applied. Normalization ensures that all input parameters are within a common range, preventing any single parameter from dominating the model. This step is essential for improving the performance and accuracy of the ML algorithm. Once the data is pre-processed, it is used to train the machine learning model. In this project, a lightweight classification model is used, suitable for implementation on embedded systems like the ESP32. Algorithms such as logistic regression, decision trees, or simple neural networks are ideal choices due to their low computational requirements. The training process involves feeding labelled data into the model, where each data sample is associated with an output label indicating whether the transformer condition is normal or faulty.

The model learns patterns by adjusting its internal parameters, such as weights and biases, to minimize prediction errors. Mathematically, the machine learning model can be represented as a function that maps input features to an output prediction. For example, in logistic regression, the model computes a weighted sum of input parameters and applies a sigmoid activation function to produce a probability value between 0 and 1. This can be expressed as:

$$y = \frac{1}{1 + e^{-(w_1x_1+w_2x_2+w_3x_3+w_4x_4+w_5x_5+b)}}$$

Eq.6.1

where x_1, x_2, x_3, x_4, x_5 represent voltage, current, temperature, humidity, and oil level respectively, w_1, w_2, w_3, w_4, w_5 are the model weights, b is the bias, and y is the predicted output. If the value of y exceeds a predefined threshold (typically 0.5), the system classifies the condition as faulty; otherwise, it is considered normal. After training, the model is deployed on the ESP32 for real-time inference. During operation, the ESP32 receives live sensor data from the microcontroller and applies the trained model to predict the current state of the transformer. This process is fast and efficient, enabling immediate detection of abnormal conditions. The use of edge computing ensures that data processing occurs locally, reducing latency and dependence on cloud infrastructure. One of the key advantages of using machine learning in this system is its ability to perform multi-parameter analysis. Traditional systems evaluate each parameter independently, which can lead to incorrect conclusions. For example, a high temperature reading alone may not indicate a fault if the load is within safe limits. However, if high temperature is combined with high current and low oil level, it may indicate a serious issue such as overheating or cooling failure. The ML model effectively captures such relationships, leading to more accurate and reliable fault detection. Another important feature of the ML-based system is its capability for predictive maintenance

This allows maintenance actions to be scheduled in advance, reducing downtime and preventing costly repairs. Predictive maintenance also extends the lifespan of the transformer by ensuring that it operates within safe limits. The implementation of ML on the ESP32 requires careful consideration of hardware limitations. Since the ESP32 has limited memory and processing power, the model must be optimized for efficient execution. Techniques such as model simplification, parameter reduction, and quantization can be used to reduce computational load without significantly affecting accuracy. This ensures that the system operates smoothly in real-time conditions This information can be used to prioritize maintenance actions and improve decision-making. For example, a prediction with a high probability of failure may trigger immediate shutdown, while a lower probability may generate a warning for observation.

The integration of machine learning also enables the system to improve over time. As more data is collected during operation, the dataset can be updated and used to retrain the model, enhancing its accuracy and adaptability. This continuous learning capability makes the system more robust and capable of handling diverse operating conditions. In conclusion, the use of machine learning in the proposed transformer monitoring system significantly enhances its performance by enabling intelligent data analysis, accurate fault detection, and predictive maintenance. By leveraging real-time sensor data and embedded processing through the ESP32, the system achieves a high level of automation and reliability

6.8 TINY ML MODEL IMPLEMENTATION

Tiny Machine Learning (Tiny ML) refers to the deployment of machine learning models on low-power embedded devices such as microcontrollers. In this project, Tiny ML is implemented on the ESP32 to enable real-time transformer monitoring and fault prediction directly at the edge. This approach eliminates the need for continuous cloud processing and allows faster decision-making with reduced latency and improved reliability.

The Tiny ML implementation begins with data collection, where sensor readings from voltage, current, temperature, humidity, and oil level are gathered over a period of time. These readings form the dataset required to train the machine learning model. The dataset must include both normal operating conditions and fault conditions such as overload, overheating, or low oil levels. Each data sample is labelled accordingly, which enables supervised learning. Once the dataset is prepared, the next step is model training, which is typically performed on a computer using tools such as Python with TensorFlow or Edge Impulse. The collected data is first pre-processed by normalizing values and removing noise. A lightweight model is then created, usually a small neural network or logistic regression model, due to the limited computational resources of the ESP32.A simple neural network model used in this project may consist of an input layer corresponding to the five sensor parameters, one or two hidden layers, and an output layer representing the classification result (normal or fault). During training, the model learns the relationship between input features and output labels by adjusting weights using optimization techniques such as gradient descent.

The performance of the model is evaluated using metrics such as accuracy and loss, and the model is refined until satisfactory results are achieved. After training, the model is converted into a format suitable for embedded deployment using TensorFlow Lite for Microcontrollers (Flite Micro). This conversion process reduces the model size and optimizes it for execution on devices with limited memory. The trained model is then converted into a C array file (usually a .h file), which can be included directly in the ESP32 firmware. In the ESP32, the Tiny model is integrated into the system code The model processes the input and produces an output indicating the condition of the transformer. A simplified implementation flow on ESP32 includes initializing the model, loading input data into an input tensor, running inference, and reading the output result. The output is typically a probability value indicating whether the system is in a normal or fault condition. Based on this result, the system can trigger alerts or control actions.

CHAPTER 7

HARDWARE MODULE

7.1 HARDWARE SETUP

A hardware setup refers to the physical components, devices, and wiring arranged to perform a specific task or run a particular system. It is the tangible foundation of any computing or engineering project, ranging from a simple desktop computer to complex embedded systems. The hardware setup integrates a multi-layered sensor network.

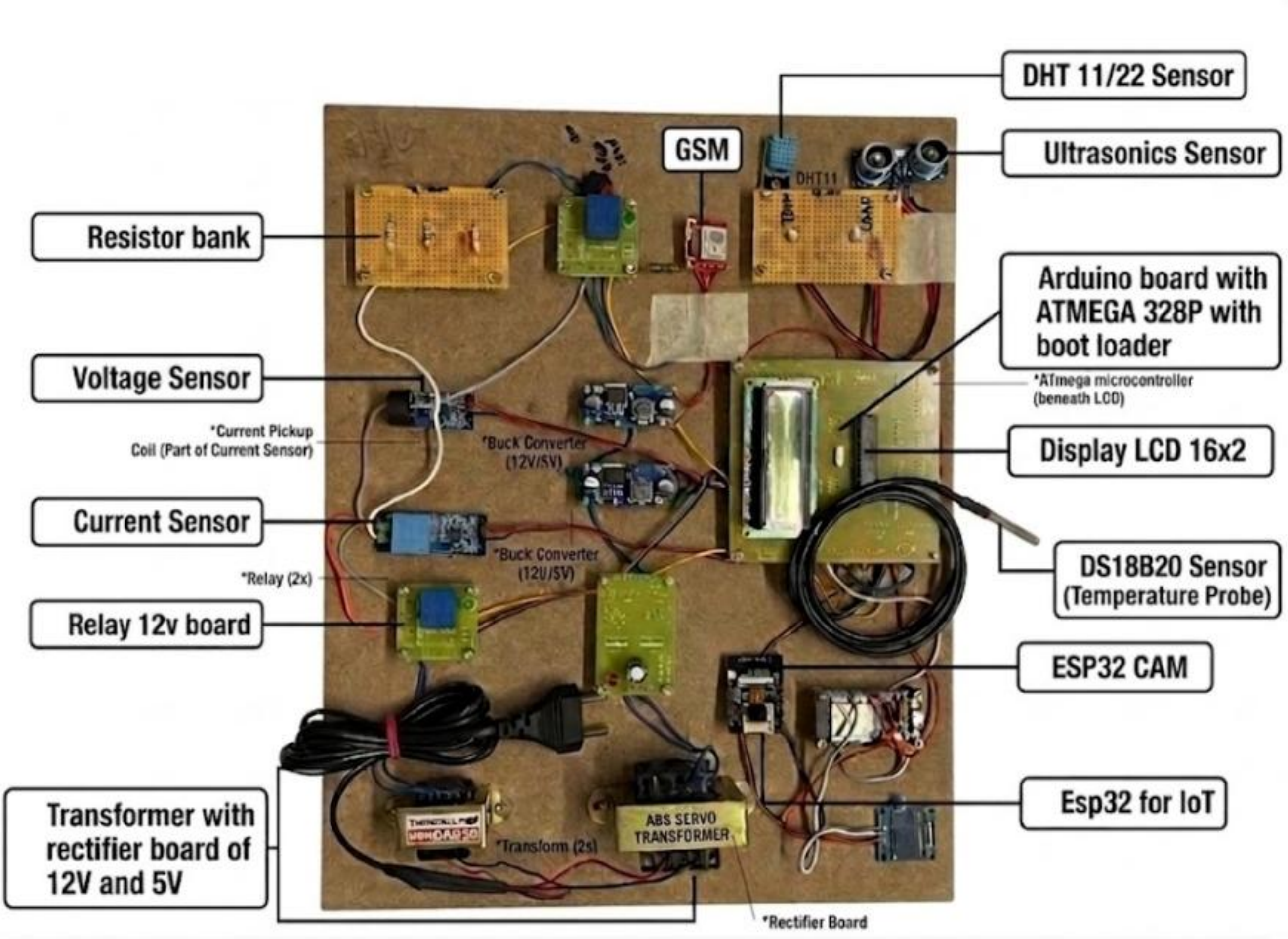

Fig. 7.1 Hardware Setup

The Fig. 7.1 illustrates the hardware setup integrates a multi-layered sensor network with dual-processing units to enable real-time health assessment and automated management of a distribution transformer. At the sensing layer, voltage and current sensors capture the primary electrical characteristics, while specialized probes like the DS18B20 monitor oil temperature and the ultrasonic sensor tracks oil levels to detect leaks. Environmental variables are factored in using DHT11/22 sensors, ensuring the Machine Learning (ML) model can distinguish between ambient heat and internal transformer stress. These signals are first aggregated by an Arduino (ATmega328P) for edge-level processing and local visualization on a 16x2 LCD, providing immediate feedback on the hardware's status. The system then leverages an ESP32 for IoT connectivity, transmitting the processed datasets to a cloud platform where the ML approach is applied. By analysing historical and real-time data, the ML model can perform anomaly detection to identify early signs of insulation failure or load forecasting to prevent transformer burnouts during peak demand.

The ESP32 CAM adds a visual verification layer, allowing operators to inspect the physical condition of the unit remotely. In the event of a predicted fault or an immediate overload—simulated here by the resistor bank the system autonomously triggers a 12V relay board to isolate the load. As a fail-safe, a GSM module ensures that critical alerts are sent via SMS to utility personnel even if local Wi-Fi connectivity is lost, completing a robust loop of monitoring, prediction, and protection. The hardware setup determines the capability and performance of a system. For instance, in electrical engineering, a setup might be designed specifically to monitor power system protection or renewable energy technologies, requiring specialized sensors and protective relays. One critical point regarding a hardware setup is the integration of control and power stages, which allows a low-power microcontroller to safely manage high-power electrical components.

7.2 OUTPUT INTERFACE

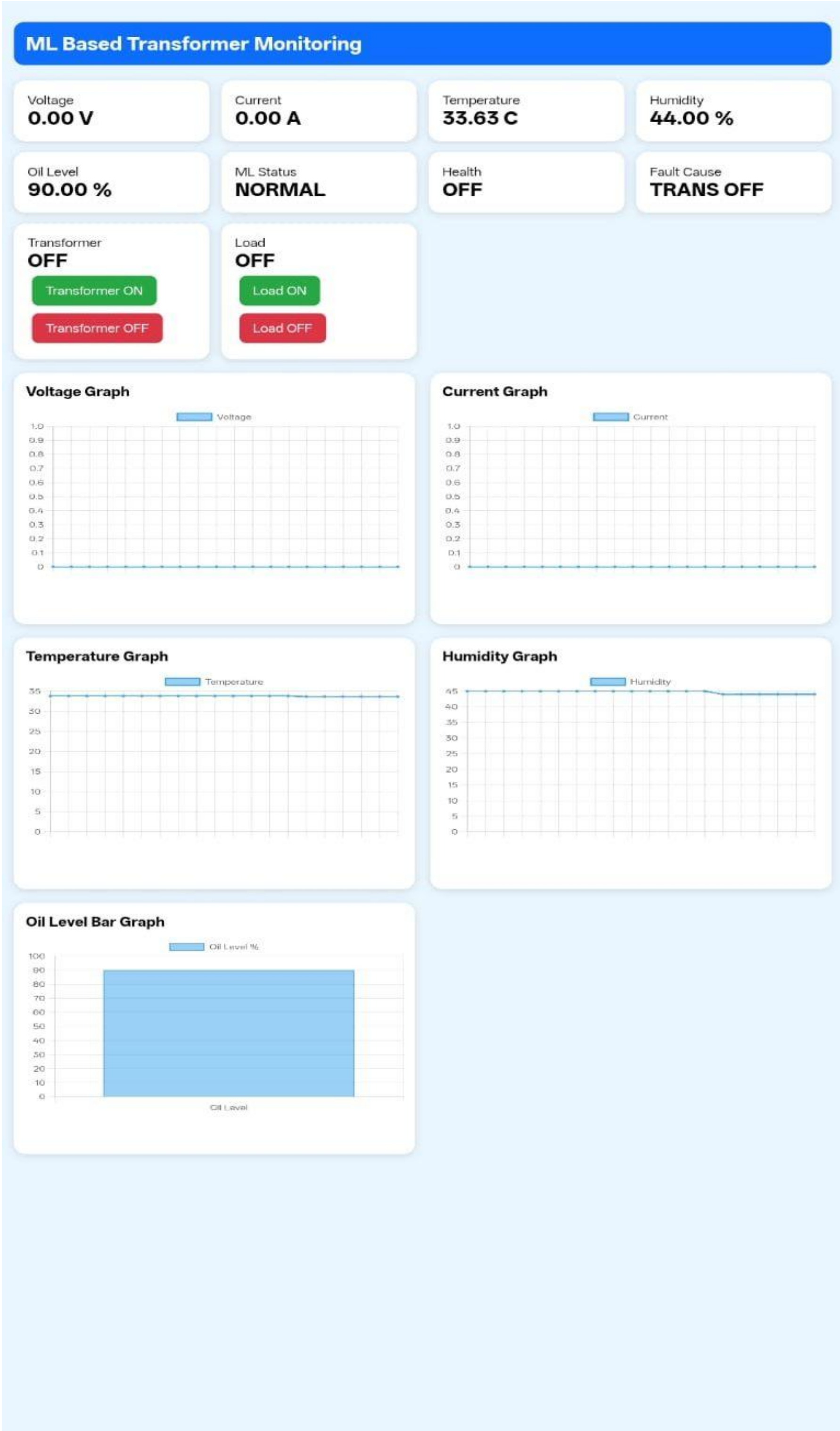

Fig. 7.2 Output Interface OFF Condition

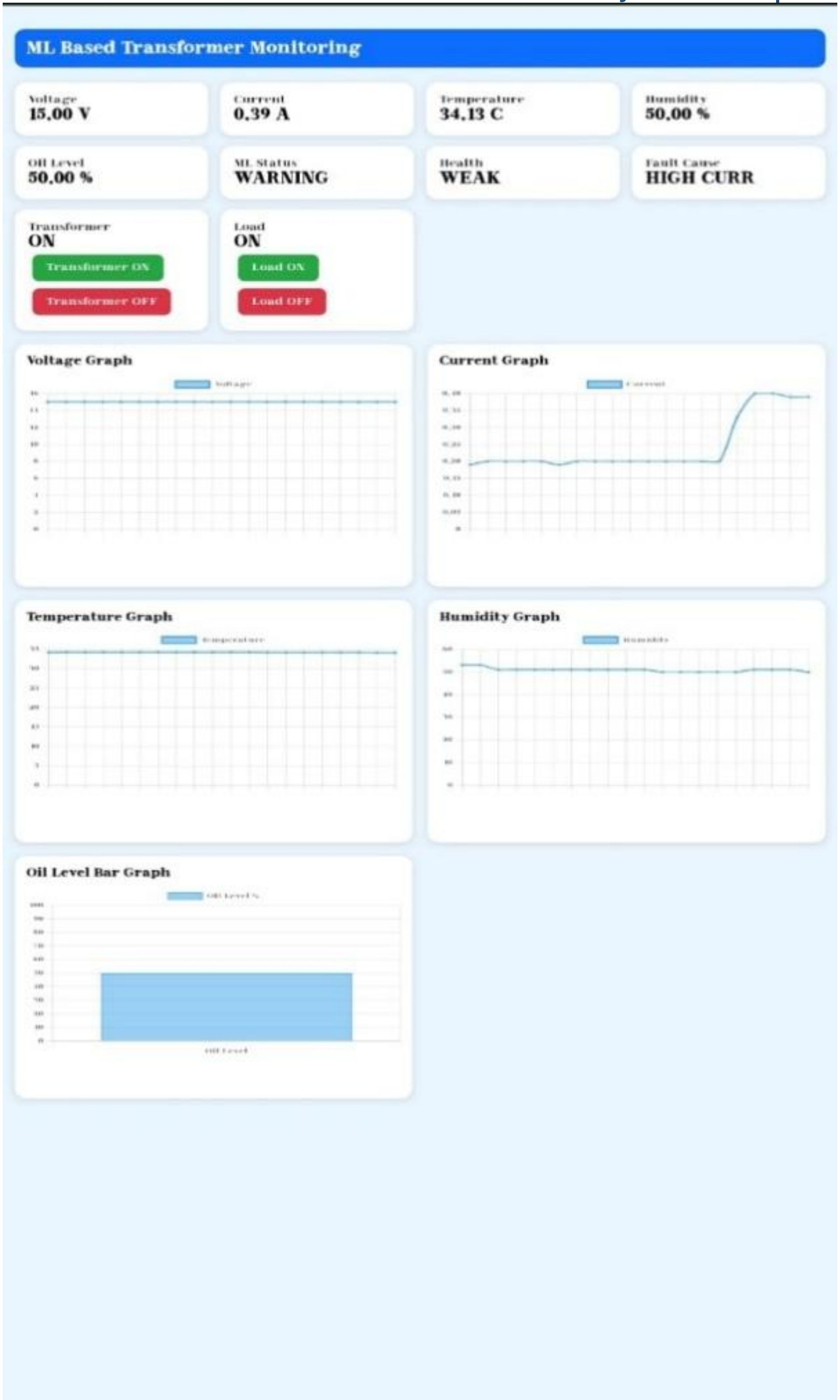

Fig. 7.3 Output Interface ON Condition

The Fig.7.2 and Fig.7.3 showcase a web-based dashboard for ML Based Transformer Monitoring, designed to track real-time electrical and environmental data. The interface is organized into a top row of numerical status cards, a control section with toggle buttons, and a series of detailed line and bar graphs for historical tracking. In the first image, the system is essentially inactive: the transformer and load are both OFF, showing 0.00 V and 0.00 A, while the ML status is NORMAL. In contrast. In second image displays a system under stress; the transformer is ON, but the ML status has shifted to WARNING with a "WEAK" health rating. This alert is triggered by a HIGH CURR (high current) fault cause, as the current has spiked to 0.39 A. Key differences between the two states also include the oil level dropping from 90% to 50% and the humidity rising from 44% to 50%, all of which are reflected in the corresponding real-time graphs.

The dashboard provides a clear visual narrative of how environmental factors and electrical loads directly impact the machine's longevity. By comparing the two states, it becomes evident that the integrated machine learning model is actively correlating the drop in oil levels and the spike in current to provide an early warning before a total system failure occurs. This proactive monitoring allows operators to intervene and perform maintenance while the transformer is still operational, rather than reacting after a breakdown.

CHAPTER 8

CONCLUSION

The proposed Smart Transformer Monitoring System using IoT and Machine Learning provides an effective and intelligent solution for improving the reliability and safety of power distribution systems. By integrating multiple sensors such as voltage, current, temperature, humidity, and oil level, the system enables continuous real-time monitoring of transformer operating conditions. The use of a microcontroller ensures efficient data acquisition and coordination among all system components. A key highlight of this project is the implementation of Machine Learning using Tiny ML on the ESP32, which significantly enhances the system’s capability compared to traditional monitoring methods. Unlike conventional threshold-based systems, the ML model analyses multiple parameters simultaneously and identifies complex patterns that indicate potential faults. This allows the system to perform accurate fault detection and predictive maintenance, reducing the risk of unexpected transformer failures.

The deployment of the ML model on the ESP32 enables edge computing, where data processing and decision-making are performed locally. This reduces latency, minimizes dependency on cloud infrastructure, and ensures system operation even in areas with limited connectivity. The integration of communication modules such as GSM further enhances the system by providing real-time alerts to users, enabling quick response to abnormal conditions.

Additionally, the system includes automatic control mechanisms, allowing it to take immediate action, such as disconnecting the load or switching OFF the transformer during critical conditions. This improves system safety and prevents severe damage to equipment. The project successfully demonstrates how embedded machine learning can be used to enhance traditional electrical systems, leading to improved efficiency, reduced maintenance costs, and increased operational reliability. This approach aligns with the advancement of smart grid technologies and represents a significant step toward intelligent power system management.

FUTURE SCOPE

The future scope of this project involves transitioning from a localized ESP32-based machine learning model to a comprehensive, grid-wide intelligent ecosystem. While the current system focuses on monitoring core parameters like voltage, current, and oil levels, future iterations could integrate advanced biochemical sensors for Dissolved Gas Analysis (DGA) to detect internal insulation failure before electrical anomalies occur. The predictive maintenance capabilities can be further enhanced by developing a Digital Twin, allowing engineers to simulate transformer stress under extreme weather or high-demand scenarios such as Electric Vehicle (EV) charging. Additionally, to strengthen the remote monitoring and alert mechanisms, the integration of Blockchain technology would ensure data integrity and protect the automatic control features from cyber-physical tampering.

Ultimately, this scalable solution can evolve into an Edge-AI network where multiple smart transformers communicate with each other to perform autonomous load balancing, significantly reducing downtime and further extending the lifespan of power transformers in both urban and rural environments.

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