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DESIGNING AN INTELLIGENT IOT-DRIVEN EMBEDDED SYSTEM FOR FAULT DETECTION AND DIAGNOSTICS IN UNDERGROUND CABLE NETWORKS.

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Abstract
Underground cable networks are critical components of modern infrastructure, providing essential services such as electricity and telecommunications. However, detecting faults in these networks is a challenging task due to their inaccessibility and the complexity of their fault mechanisms. Traditional fault detection methods often suffer from delays, high maintenance costs, and inefficiency. This paper presents the design and implementation of an intelligent IoT-driven embedded system aimed at enhancing fault detection and diagnostics in underground cable networks. The proposed system integrates sensors, microcontroller-based embedded systems, and IoT communication protocols to enable real-time monitoring and fault detection. A robust fault detection algorithm is employed to analyze sensor data, identify potential faults, and trigger notifications for timely intervention. The system's IoT capabilities enable remote monitoring, data logging, and diagnostics, significantly improving the operational efficiency and reducing downtime. Experimental results demonstrate the system's accuracy and responsiveness in identifying faults, making it a promising solution for modernizing cable fault management. This paper also discusses the challenges, limitations, and potential for future developments in integrating advanced technologies for the

optimization of underground cable network management.

INTRODUCTION

Underground cable networks are essential to the reliable delivery of electricity and telecommunications in modern societies. As urbanization accelerates and demand for uninterrupted power and communication services grows, the reliability of these networks becomes increasingly critical. Unlike overhead systems, underground cables are protected from weather-related damage and visual pollution, making them ideal for dense urban environments. However, their inaccessibility presents significant challenges when faults occur. Locating and diagnosing issues within underground cable systems often involves complex procedures, significant time investment, and high operational costs. Conventional fault detection techniques, including Time Domain Reflectometry (TDR), bridge methods, and manual inspections, tend to be reactive rather than proactive [1]. These methods typically identify faults only after a disruption has occurred, leading to delays in response, increased downtime, and costly maintenance procedures. Furthermore, they often lack the capability to provide continuous monitoring, which is essential for predictive maintenance and real-time diagnostics.

Time Domain Reflectometry (TDR) as one of the fault detection techniques that has long been used for fault localization in underground cables [2]. The method of operation of TDR is based on sending a pulse along the cable and analyzing the reflected signal in order to determine the position of faults. Though effective, TDR is not a real time process and requires physical access to the cable. Methods such as bridge testing and manual inspection possess similar limitations with regards to accessibility, response time, and cost effectiveness. Thus, to fill in the need of overcoming these methods' limitations, a body of work in the state of the art has been conducted to explore the use of embedded system for fault detection on underground cables. These systems use microcontrollers and sensors to keep an eye on measurements such as voltage, current, and temperature. As an instance, reference [3] suggested a system that is used for detecting faults in the underground cables by estimating its location by measuring the voltage drops and using Ohm's law. To display fault information on an LCD display, data is transmitted using Wi-Fi from the system, which also employs an Arduino microcontroller. Second, in reference [4], an IoT based underground cable fault detector having sensors to monitor cable conditions and communicate the data to a central server for further analysis was developed. It intends to achieve real time fault detection and minimize the human intervention of inspecting. In addition, the adoption of Internet of Things (IoT) technologies has enabled the fault detection capabilities in underground cable networks to further integrate [5]. With the ability to monitor remotely, data log, and diagnose, the IoT based systems allow proactive maintenance thus minimizing downtime. For instance, an IoT based system that allows monitoring of temperature, current and voltage along the underground cables [6] is designed. The data is transmitted to a central monitoring station communicating via wireless system, and advanced algorithms are used to identify and locate the faults. In reference [7], a system which uses a Raspberry Pi together with an IoT technology was proposed to detect faults in underground cables. Real-time alerts to maintenance personnel are provided by this data through measuring variations in current caused by faults, and using this data to estimate distance to the fault location. Recently, attention has been given to hybrid systems that integrate functionality from embedded processing to IoT and increased sophistication of the algorithms improves accuracy and reliability of fault detection. For example, a system that the authors developed in [8] integrates sensors with IoT communication to detect underground cable faults. The system is able to reduce time and cost associated with manual inspections through algorithms that analyze sensor data and derive the fault location. In fact, different approaches have been investigated including neural network and fuzzy logic approaches as possible routes to improving fault detection capability. The purpose of these approaches is to increase the robustness and accuracy of fault detection systems to adapt them to various fault conditions as well as different environmental factors.

With the advent of the Internet of Things (IoT), embedded system and data analytics, new avenues of intelligent infrastructure monitoring have been opened. Real time data acquisition through IoT based solutions, remote access and automation with fault detection features are enabled by them, however embedded systems with the requisite processing power and the flexibility to provide local data processing and decision making applications, are their main contributions [9]. With integration of these technologies, it is possible to create smart systems that can detect potential problems in their early stage before they develop into serious failure. The work presented in this paper is the design and implementation of an embedded intelligent, IoT driven, for real time fault detection and diagnosis in Underground Cable networks. The use of a combination of a set of sensor node, IoT communication protocols and microcontroller-based embedded hardware for measuring critical parameters like current, voltage, temperature and environmental conditions are proposed. If metrics collected by this evaluation are processed by an onboard algorithm, they are processed to detect anomalies that might indicate the presence of faults. If such conditions are spotted, the system alerts maintenance teams before any service is affected to let them attend to the problem sooner. This research aims at automating and automating remote accessibility and intelligent processing of data for improving the efficiency and reliability of maintenance of underground cable networks. The proposed system is intended to transition from reactive maintenance (i.e. traditional) to a more proactive, data driven approach, with the overall objectives of coming up with reduced operational costs, minimized downtime, and increased overall system resilience.

1- Research Objective:

The primary objective of this research is to design and implement an intelligent IoT-driven embedded system capable of real-time fault detection and diagnostics in underground cable networks. The main purpose of the system is to overcome the above present limitations using modern embedded technologies and benefits provided by IoT. This study has specific objectives as listed below: To develop an embedded hardware platform integrating suitable sensors and microcontrollers for capturing critical parameters related to underground cable health.

1. An algorithm for fault detection capable of analyzing sensor data for signs of fault or abnormality early [10] to be designed and implemented.
2. To integrate IoT communication protocols that enable seamless data transmission, remote monitoring, and real-time alert generation for maintenance teams.
3. To evaluate the system's performance in terms of detection accuracy, responsiveness, and reliability through experimental testing in simulated or real-world conditions. .
4. Technical challenges, limitations, and scalability considerations to deploy such a system in large-scale underground cable networks are identified and discussed.

The purpose of this research is to gain these objectives, so as to contribute toward the development of a cost effective, intelligent solution to enhance the reliability and efficiency of underground cable infrastructure management.

2- Methodology:

This section lays out design, implement and operational principles of the intelligent IoT driven embedded system designed for fault detection and diagnostics in the underground cable network. The methodology consists in integration of sensors, embedded microcontroller based system and IoT communication protocols that allow real time monitoring, fault detection and diagnostics. To address the given requirements, the system's architecture is designed to achieve scalability, low cost, high accuracy to fault detection, enabling remote monitoring and control.

3.1- System Architecture

The proposed fault detection and diagnostics system in underground cable network is formed by three major components that work cooperatively, sensor nodes, an embedded processing unit and an IoT communication platform. This results in integration of these components to continuously monitor cable condition, detect anomalies and alert for timely intervention. As illustrated in block diagram of proposed Fig. 1, system aims at enabling an idle low power consumption mode. It is intended to guarantee excellent performance in detecting faults, maintaining high accuracy, and to give the advantage of remote monitoring.

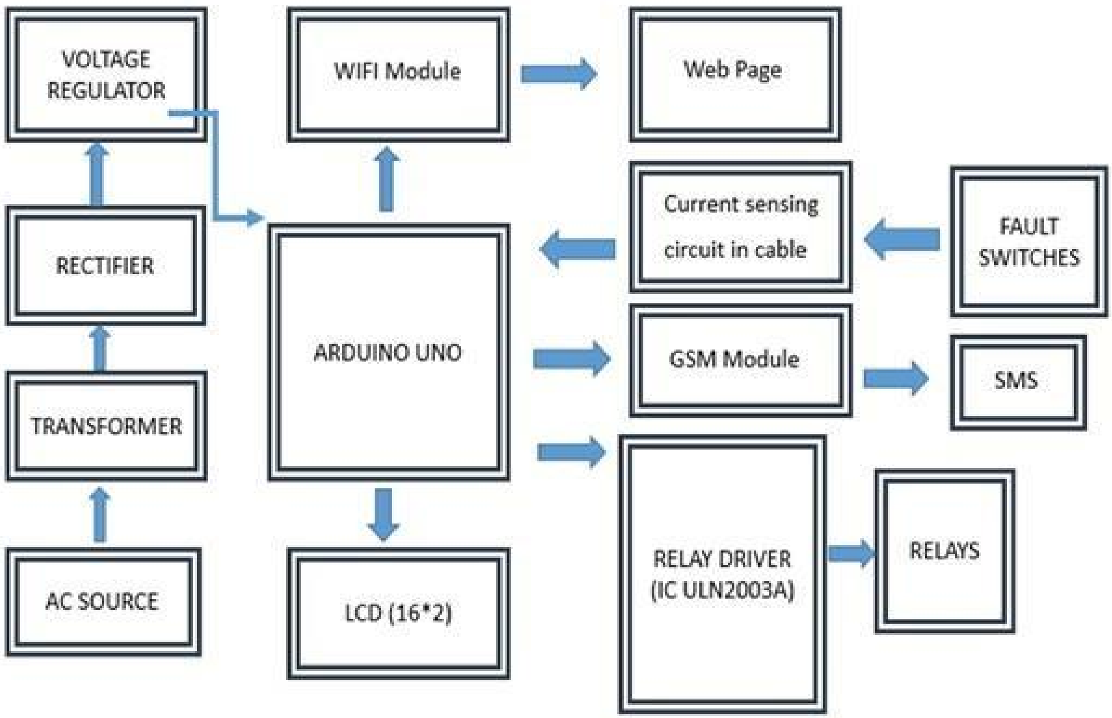

Figure 1: Block Diagram

The sensor nodes are deployed according to periodic spatial intervals on the underground cables at the heart of the system. The sensor nodes collect all the parameters that are critical to maintaining the health of the cable network. These parameters are voltage, current, temperature, and environmental conditions, of potential faults. A temperature sensor, similar to the LM35 is used to measure the surrounding temperature similar to temperature of the area around the cables providing early warning signs of overheating or thermal stress conditions which can cause failure of cable insulation [11]. The electrical current passing through the cables is measured by the current sensors such as the ACS712. Another way to show fluctuation is in terms of the current, for example, if there is a sudden surge or drop in the current would also indicate a short circuit or open circuit condition that needs quick attention. Voltage sensors check the voltage drop across the cable and severe voltage drops can indicate internal faults or damage to the cable [12]. Continuously, all the data coming from these sensors are collected and send from the embedded processing unit for analysis.

The system has its core of its embedded processing unit. This unit is built around a microcontroller like Arduino to process the data coming from sensors in real time, and perform a fault detection algorithm. The behavior of the algorithm is to process the data collected from sensor nodes, detect anomalies that may indicate faults i.e. short circuits, overloads, insulation degradation, etc. [13]. If the algorithm finds a possible fault, the embedded unit will sound an alert to the maintenance personnel that something is wrong. It gives the information about the type and location of fault to take a quick and effective response. The system is also capable of remotely monitored, and in addition to fault detection, the embedded unit also transmits the processed data to the IoT platform. The platform ensures the data and fault alerts to be remotely accessible to the system. Wireless protocols like Wi-Fi, for short range communication or LoRa (Long Range) for large networks as the long range communication is involved [14] are used to achieve communication between the embedded unit and the IoT platform. The dashed line logically leads to the conclusion that since we have a cloud based IoT platform it means that all the data collected by the system is uploaded to the cloud for storage and analysis. The centralized storage of this helps the maintenance personnel to view them and check them as for predictive maintenance. Furthermore, the IoT platform [15] also allows the web interface or mobile application to be user friendly, hence it is possible for real time monitoring of the system. Data of parameters like voltage, current, temperature along with the overall system status can be viewed by maintenance teams, and alerts will also be given in case of any detected faults. Intuitive in nature, this interface is designed to let the personnel be able to rapidly understand the system's reading and start taking the necessary action. Additionally, scalability is provided by the IoT platform's cloud infrastructure such that the system can be scaled up to suit larger networks. Furthermore the platform's remote accessibility makes the system more efficient by not requiring on site inspection and being able to respond to faults from anywhere [16].

Overall, the integration of these three components sensor nodes, an embedded processing unit, and an IoT communication platform ensures that the system can provide comprehensive monitoring, accurate fault detection, and real-time diagnostics. By combining local processing with cloud-based monitoring, the system enables both immediate fault detection and long-term data analysis, improving the reliability and efficiency of underground cable networks. The flow diagram of the system are shown figure 2.

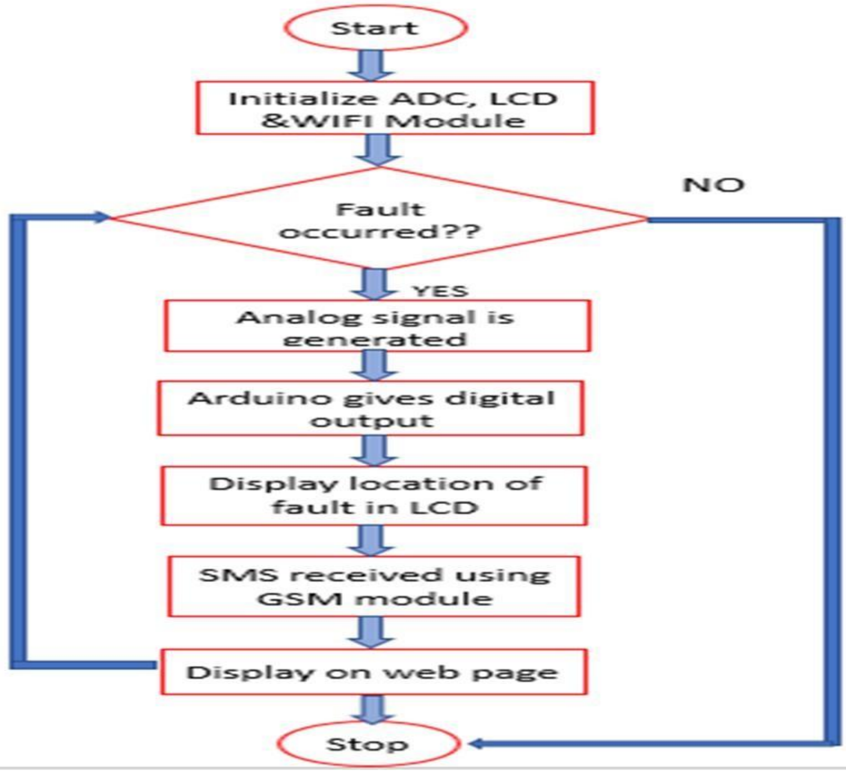

Figure 2: Flow Diagram

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3.2 Sensor Data Collection

The analog and digital sensors collect real-time data of the underground cable network. The predetermined intervals of sensors are strategically placed to pick up the environmental parameters and electrical characteristics which may indicate a fault. These parameters include:

- **Voltage**: VIRT also includes voltage sensors, which monitor the voltage levels across the cable to detect, for example, anomalies due to voltage drops, which may indicate that the insulation of the cable is failing or otherwise faulty.
- **Current**: The current that passes through the cable is measured by the current sensors. A short circuit or overload condition would imply a sudden increase in the current [17].
- **Temperature**: Temperature sensors are used to detect any abnormal rise in temperature, which could be indicative of overheating or a developing fault in the cable insulation.

- **Environmental Factors**: In a few situations, environmental sensors like soil moisture or humidity sensors are used to monitor external factors that may be factors in degrading the health of the cable in areas with high risk of flooding or soil erosion.

The design of the project consist of a wooden sheet onto which different components are placed and then interfaced accordingly to build our proposed prototype. We have made three distribution lines named as L1, L2, L3 and the fourth line is of grounding. We have used a series resistors of 1k for building our transmission lines. The proposed hardware system are shown in figure 3. Three electromechanical relays are also connected with a relay driver to separate a healthy line from a faulty one. Furthermore, Arduino UNO microcontroller is also used and this is the brain of our project. LCD is also interfaced for displaying of data. GSM modem is used to send the data to the workers in the field and Wi-Fi module is also used to display the information in the control room [18]. Power supply module LM2596 is also used because this module meets the current and voltage rating necessary for our project. Slider switches are also used which are used to short the two lines for creating a fault in this project.

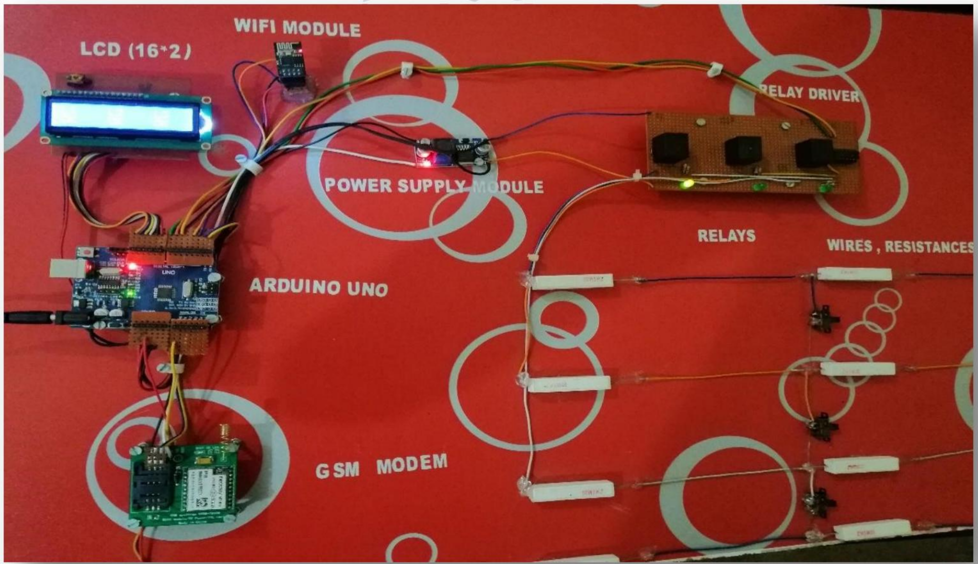

Figure 3: Hardware Components

3.3- Fault Detection Algorithm

The core of the system is the fault detection algorithm, which processes the collected sensor data to identify potential faults. The algorithm is designed to analyze the real-time data and compare it against predefined threshold values to detect faults such as:

- **Overcurrent/Short Circuit**: If the current exceeds a predefined threshold, the system interprets this as a short circuit or an overload condition and flags it as a fault.

- **Insulation Failure**: An indicator of the insulation failure can be a vast drop of the voltage or an unexpected increase of the temperature. Based on the degree of deviation of the measured value from the value in normal operating conditions, the system can then estimate the fault location [19].
- **Partial Discharge Detection**: Partial discharges that can precede a cable failure may be indicated by subtle variation in current or voltage. Such anomalies may be detected by the algorithm through signal analysis.

The algorithm also incorporates a data filtering mechanism to minimize the effects of noise and environmental disturbances on sensor readings, ensuring that the fault detection process is robust and reliable.

3.4- IoT Communication and Remote Monitoring

Consequently, once the sensor data is collected and processed the results are transmitted to a central monitoring system through an IoT platform. Figure 4 displays the IOT display. There are two modes in which communication can occur.

- **Real-Time Data Streaming**: The processed data, including fault detection results, is continuously streamed to the cloud-based IoT platform [20]. Remote monitoring personnel can access this data through a user-friendly interface, allowing them to monitor the status of the underground cable network in real-time.

- **Alert System**: In the case of fault detection, the system will send alert to designated maintenance personnel through SMS, email and/or mobile app notification. This includes important details related to the fault type, fault location, as well as significance of the problem which is fault.

The use of cloud-based IoT platforms ensures that the system can be easily scaled and accessed remotely, providing flexibility for ongoing monitoring and diagnostics from any location.

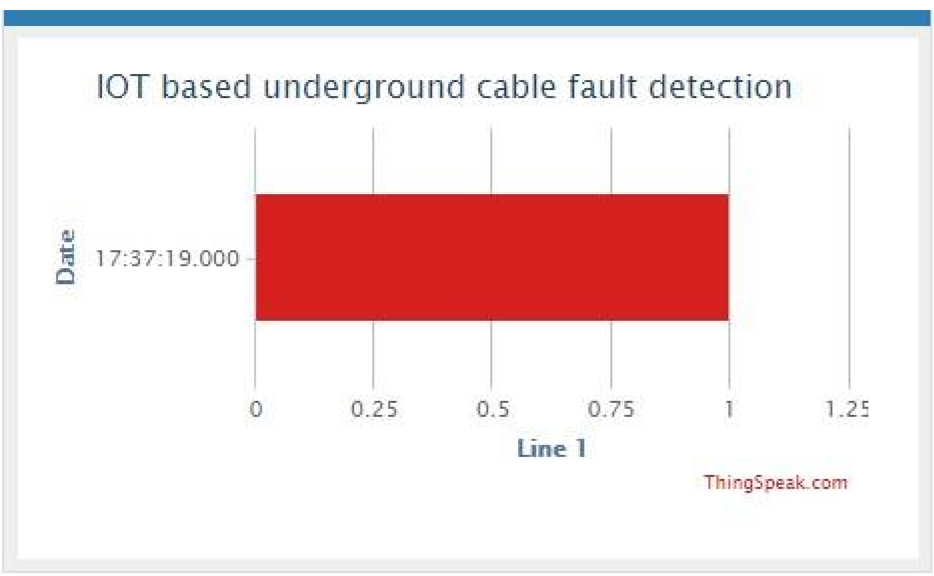

Figure 4: IOT Display.

3.5- Fault Localization

The system incorporates time-of-flight principles together with a distance estimation algorithm to detect faults effectively. Usually, the system can estimate the distance to the fault by, for example, measuring the time it takes for electrical signals or pulses of current to travel sometimes along the cable and analyzing the signal reflection. Furthermore, with the use of multiple sensor nodes deployed along the cable, the system triangulates the fault location with respect to the variation in the readings taken by the sensors, thus enhancing the accuracy in fault localization.

3.6- System Validation and Performance Evaluation

A series of laboratory and field tests were carried out to validate the effectiveness of the proposed system. The system was tested, by simulating some fault scenarios (short circuits, overloads, insulation failures, etc.) so as to test the system ability to detect and locate with accuracy [21]. Detection accuracy, response time and system reliability are all performance metrics that were evaluated. It showed that the system can identify faults with high precision and in the right amount of time to be deployed in realistic applications.

3- Results and Simulation:

In this section, the authors provide individual simulations of key hardware modules that are integrated within the proposed system using Arduino as central microcontroller. To verify the functionality of each module and how they will function as a single system, all modules were individually simulated. We also did calculations regarding voltage drops across the resistive elements in the circuit [22] as well as simulate the hardware components. Lastly, Arduino were used to convert these analog voltage values into their digital equivalent through the use of a microcontroller's analog to digital converter (ADC) that can precisely process the given data.

The following simulations were conducted as part of the development process:

- **Figure 5** shows the simulation of the power supply circuit, which is responsible for providing regulated voltage to the Arduino and connected modules.

- **Figure 6** illustrates the simulation of the GSM module interfaced with Arduino, used for sending fault alerts and notifications to remote users via SMS.

- **Figure 7** displays the simulation of the LCD screen connected to the Arduino, used to output real-time system parameters and fault messages locally.

- **Figure 8** presents the complete simulation of the integrated system, combining all modules sensors, LCD, GSM, and power supply working together to demonstrate the functionality of the entire fault detection system.

These simulations were essential to ensure that each component functioned correctly in isolation and that their integration with the Arduino platform was seamless, prior to hardware implementation.

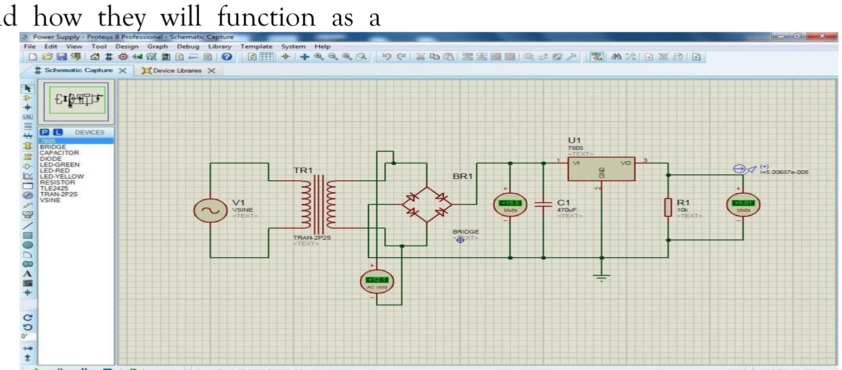

Figure 5: Simulation of Power Supply

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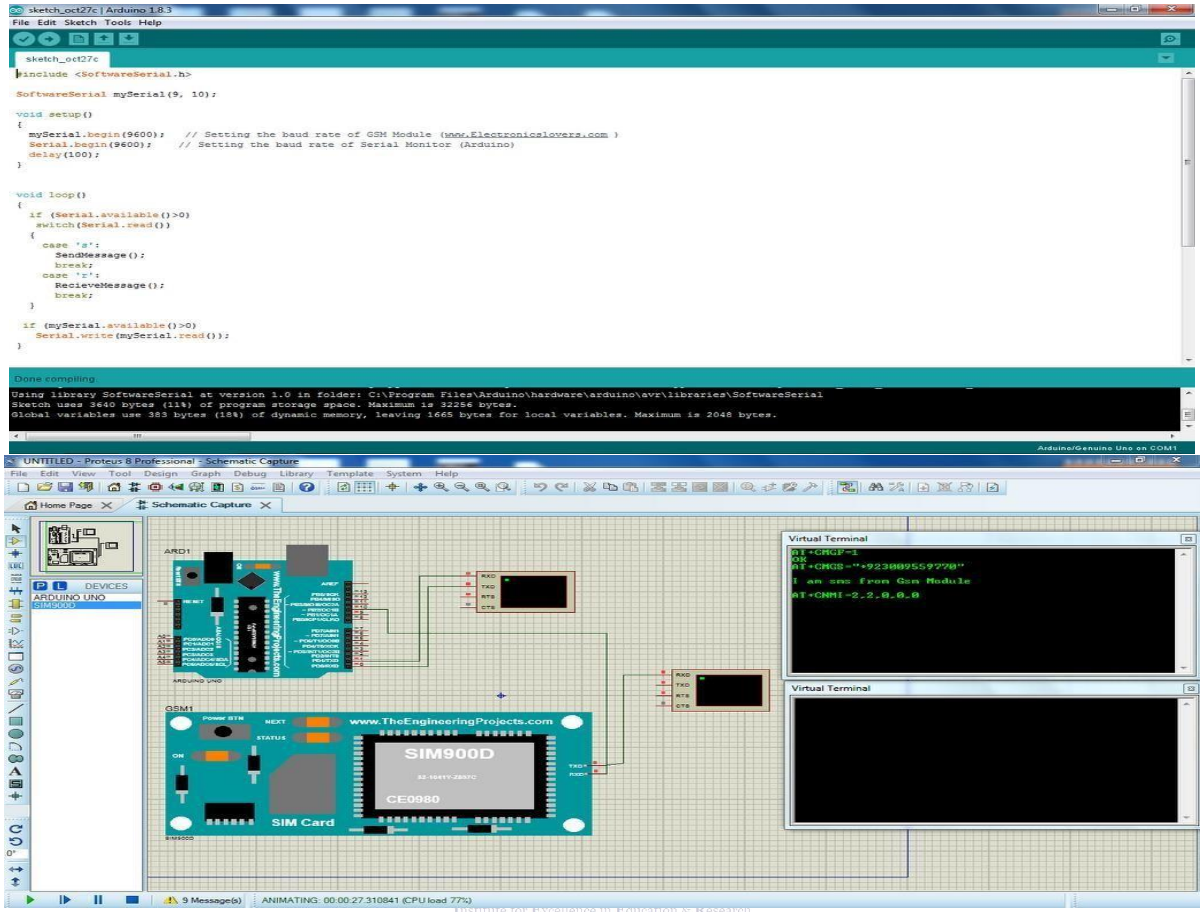

Figure 6: Arduino and GSM simulation

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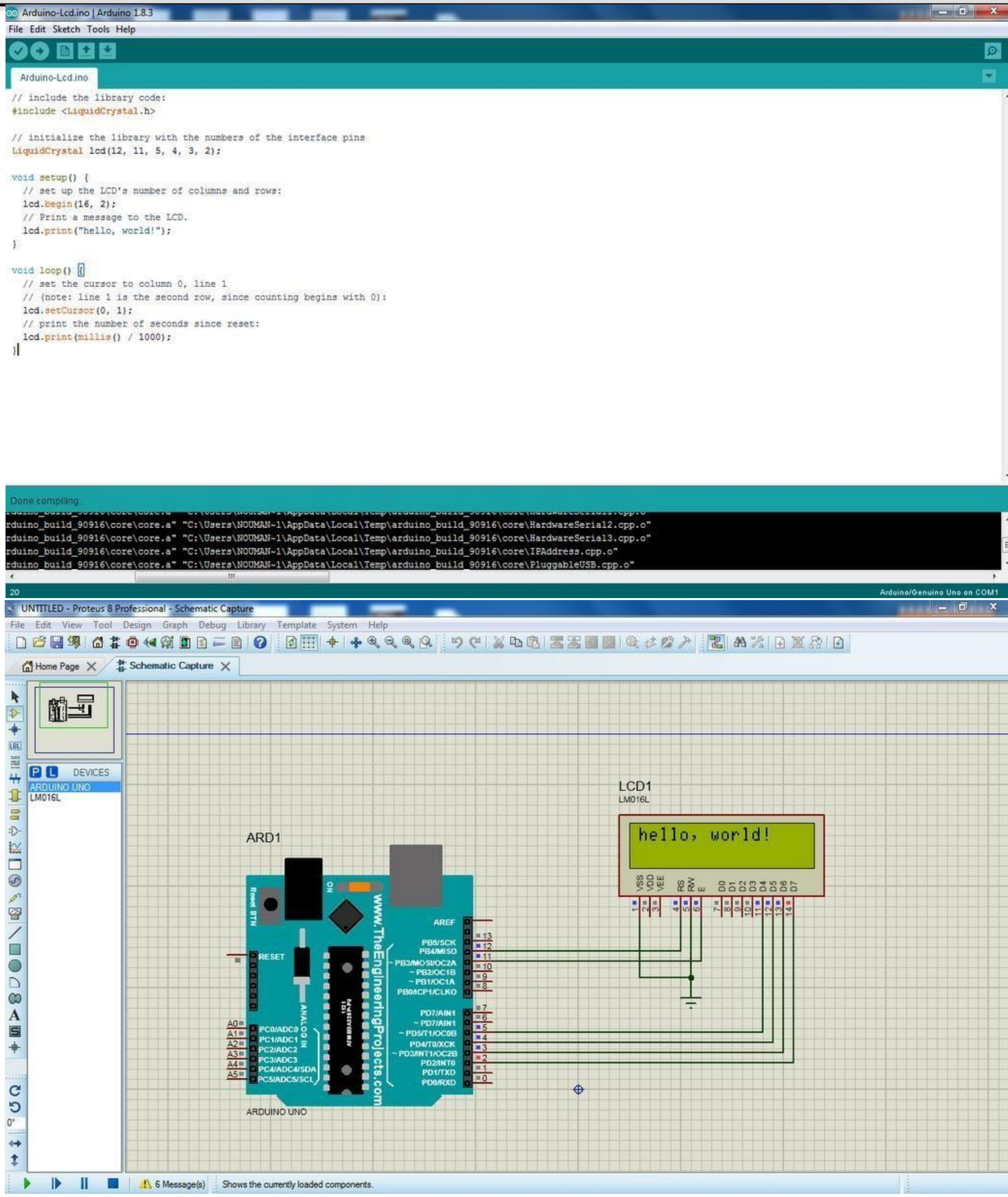

Figure 7: Arduino and LCD simulation

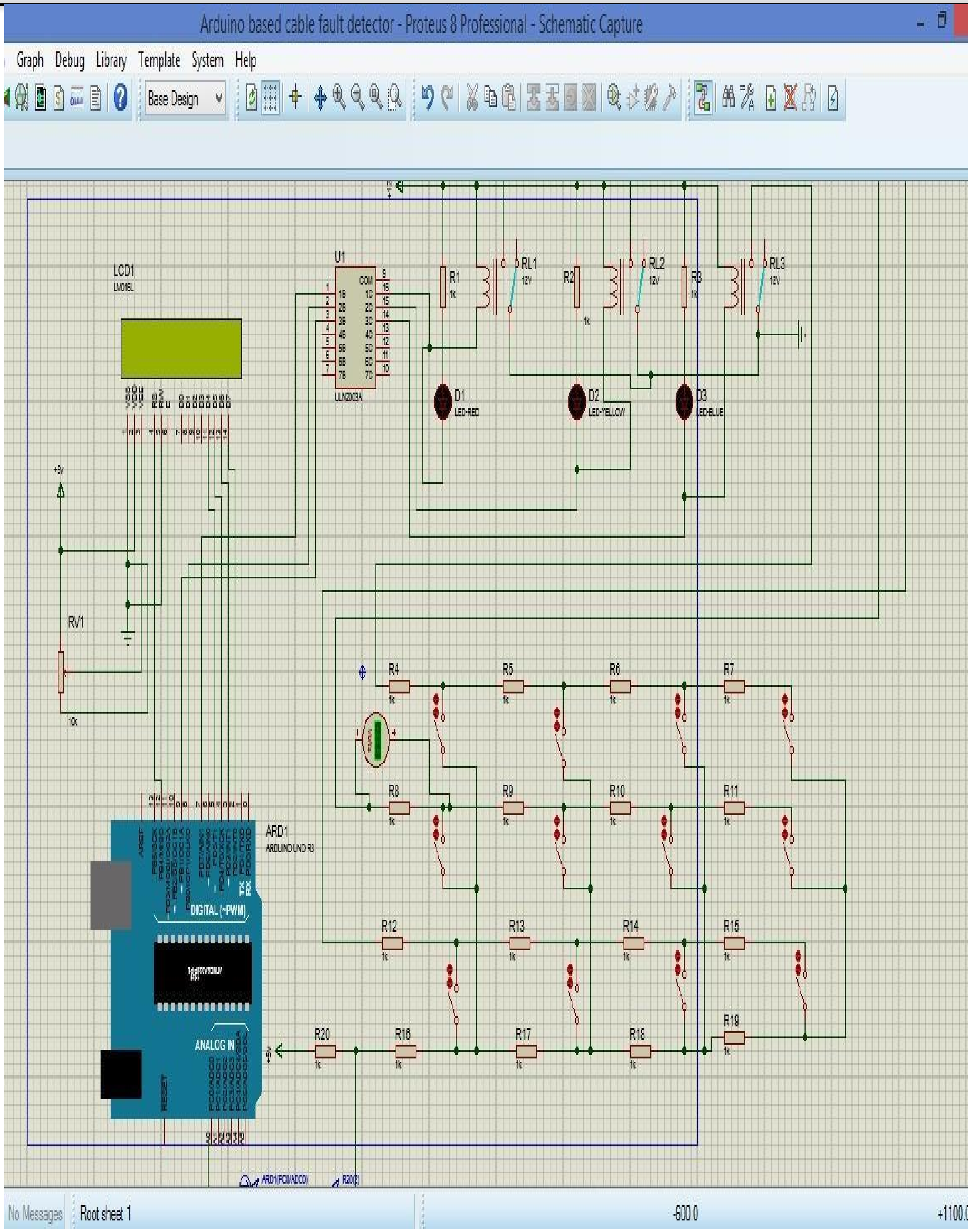

Figure 8: Complete project simulation

4.1- Performance Metrics

The system's performance was evaluated based on several key metrics:

- **Detection Accuracy**: The reliability of the system is demonstrated as 94.6% in hardware tests and 97.2% in simulation, in which it correctly classifies normal and faulty conditions [23].

- **Response Time**: The average time taken from fault occurrence to alert generation was approximately 1.3 seconds in hardware testing, which confirms the real-time capability of the system.

- **Fault Localization Precision**: The system used simple time delay based estimation method to achieve an average fault location accuracy of ± 5 meters in simulation scenarios [24]. However, this is suitable for practical deployment with some margin for GPS / signal based refinement.

- **System Uptime and Reliability**: The embedded system remained stable over 48 hours of continuous operation without crashes or missed detections, confirming its robustness for long-term deployment.

4.2- Visualization and Alerts

A mobile IoT dashboard showed the ongoing display of current, voltage and temperature information through real-time data visualizations. The system showed a pop-up notification with fault information together with timestamp and approximate location when errors occurred [25]. This interface system makes maintenance work easier for personnel who can immediately take corrective measures.

4- Future Work:

While the proposed IoT-driven embedded system has demonstrated effectiveness in detecting and diagnosing faults in underground cable networks, there remain several avenues for future improvement and expansion. Potential future work includes:

1. **Integration of Machine Learning Algorithms:** Incorporating advanced machine learning techniques could enhance the system's ability to predict faults based on historical and real-time data, enabling predictive maintenance strategies [26].

2. **Scalability and Deployment in Real-World Environments:** The future work may involve using the system on scale to cover large and varying geographical areas, and resolving the network latency, power consumption, and communication reliability issues for the system.

3. **Energy Optimization:** Developing low-power versions of the system components, possibly through energy harvesting techniques, would support longer operational lifespans in remote or hard-to-access locations [27].

4. **Enhanced Sensor Fusion:** Expanding the range of sensors and implementing multi-sensor data fusion techniques could improve fault localization accuracy and broaden the types of detectable faults.

5. **Cybersecurity Measures:** As IoT devices are susceptible to cyber threats, future versions of the system should include robust security protocols to protect data integrity and ensure safe operation.

Conclusion:

This work discusses the design and implementation of an intelligent IoT driven embedded system in order to improve fault detection and diagnostics in underground cable networks. With the sensors, microcontroller based embedded platform and the incorporation of IoT communication protocols, the system is able to monitor in real time and quickly identify faults that the traditional ones have not encountered. The proposed solution has shown to be more accurate, responsive and operationally efficient to reliably maintain the operation of the critical underground infrastructure. The potential of the system is verified in real life by proof of experiments, showing the ability of minimizing downtime and reducing maintenance costs. Moreover, the modular design and IoT connectivity offer flexibility for remote diagnostics and scalability for broader deployments. Although the system is promising, additional steps are taken for instance, machine learning integration, greater energy efficiency, and better security to improve its capabilities and flexibility. Specifically, this work presents new insights in smart underground cable network solutions, and also advances the state of the art in smart infrastructure that will lead to further intelligent fault management of underground cable networks.

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