Smart Grid Voltage Protection Using Digital Meters

1st Ahsan Iqbal
Department of Electrical and Electronic Engineering
132KV Grid Station Kasur New
Lahore, Pakistan
ahsaniqbalkas@gmail.com

2nd Talha Imtiaz Baig
School of Life Science & Technology
University of Electronic Science & Technology of China, UESTC, CN
talhaimbaig@gmail.com

***Abstract*— This paper presents an innovative method for protecting electrical systems from overvoltage and undervoltage faults using a digital meter, Arduino modules, and wireless communication. The system detects voltage variations on a 220V AC single-phase line, cutting off the power supply if the voltage exceeds 250V or drops below 180V. Wireless communication is achieved using the nRF24L01 module to transmit real-time data to a host computer, while a memory card attached to the digital meters stores second-by-second voltage readings. Renewable energy sources are integrated for fault recovery. The microprocessor analyzes the data and restores the main power supply once voltage conditions stabilize. This research highlights the potential for combining fault protection, renewable energy utilization, and wireless communication to enhance electrical grid reliability and efficiency.**

Keywords*— Smart Grid; Transmission and Distribution; Renewable energy resources (RES); Digital meters; Over Voltages

1. INTRODUCTION

Voltage fluctuations are a critical vulnerability in power systems, particularly when exposed to high voltages from lightning, faults, or line energization. These overvoltages have long challenged electric grids, often resulting in insulation failures and equipment damage. Voltage fluctuations, caused by poor regulation from power utilities, generate brief oscillations that can lead to serious issues, such as resonance [1]. Resonance occurs when the inductive and capacitive resistances in the system equalize, commonly during switching operations or network faults. Modern smart grids incorporate advanced monitoring and protection technologies to address these challenges. This research explores a smart grid solution that uses real-time data sensors collected to monitor energy production, consumption, and environmental conditions. The data is transmitted wirelessly to a central system for analysis and control, enabling more efficient energy management and improving grid reliability and consumer energy efficiency. Key innovations in smart grid technology include integrating renewable energy, distributed generation, and dynamic lightning protection (DLP) systems [2]. DLP helps safeguard the grid by maintaining dynamic balance and reducing disruptions caused by lightning. Another essential feature is the self-healing capability of smart grids, allowing them to automatically detect, diagnose, and correct faults in real time [3]. Overvoltage monitoring and suppression systems play a crucial role in maintaining grid stability, especially as modern equipment requires higher levels of reliability. The smart grid system begins with the isolator, a manual switch used to disconnect the power system for safety during maintenance or emergencies. This ensures that the system can be safely isolated from live electrical parts. After the isolator, a potential transformer (PT) is used to step down the high transmission voltage to a safer, lower level that can be monitored and controlled. This allows for accurate voltage measurement without exposing sensitive equipment to high voltage, ensuring the system's protection [4-8]. Next, a circuit breaker is integrated into the system as a protective device. In the event of a fault, such as an overvoltage or short circuit, the circuit breaker automatically disconnects the electrical supply, preventing damage to the grid infrastructure and connected devices. Following the circuit breaker, the step-down transformer reduces the high transmission voltage further to a lower voltage suitable for local distribution, making it usable for homes, industries, or other consumers. At the output of the step-down transformer, a digital meter is installed [9]. This meter continuously monitors the real-time voltage, current, and other electrical parameters, providing real-time data on the system's performance. The digital meter not only displays critical information on voltage levels but also transmits this data to a central host computer for real-time monitoring and control [10]. If faults or voltage fluctuations occur, the system can automatically adjust, ensuring stability and efficiency. Finally, after the digital meter, the power is sent to the feeders, which distribute the electricity to end-users. These feeders can be remotely operated using a mobile application, allowing grid operators to manage power distribution more effectively. The real-time data from the digital meters helps ensure that the grid operates efficiently, with quick responses to any fluctuations or faults, thereby maintaining the grid's stability and reliability. The schematic diagram which show in Figure 1 demonstrates the working of the project and shows the tasks performed by different components Which protect the Smart Grid [11]. The figure 1 demonstrates the working of the project and shows the tasks performed by different components Which protect the Smart Grid. The transmission line is connected with the isolators. The isolators output going to the circuit breaker. Between the isolators and circuit breaker the single line is connected with the current transformer and voltage transformer as it is current transformer is connected with the current meter and voltage transformer connected with the voltage meter. Circuit breaker output going to the stepdown transformer. Stepdown transformer converts the high voltage (HV) and low current from the primary side to the low voltage (LV) and high current value on the secondary side [12]. Feeders incoming line connected with the output transformer. In our project All readings must be shown on digital meters. We shall use two supply one from Water and Power Development Authority (WAPDA) and second from solar panel. Solar panel supply is connected with the feeders. To operate the stations feeders by using mobile app. Smart grid will be protected from over voltage [13].

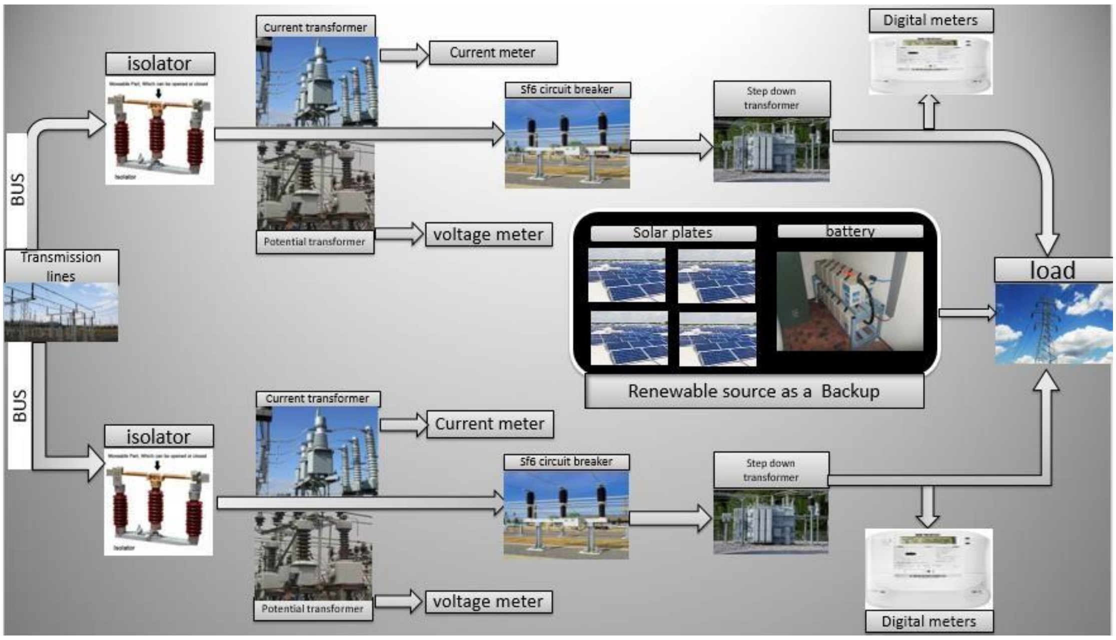

Fig. 1. Generalize block diagram of Smart Grid

2. Methodology

2.1 **System Design:** The system consists of a digital meter that monitors the voltage of a 220V AC single-phase electrical system. The system reacts to two types of faults:

- **Overvoltage:** Voltage exceeds 250V AC.
- **Undervoltage:** Voltage drops below 180V AC. Upon detecting these faults, the digital meter immediately cuts off the output transformer to prevent damage and transmits data wirelessly to a host computer.

2.2 Wireless Communication: The **nRF24L01** wireless communication module is used to transmit real-time voltage data from the digital meter to the host computer. This wireless link ensures continuous monitoring of the system and enables real-time analysis and fault detection. Voltage readings are updated every second and transmitted to the host system, providing timely alerts of any faults in the electrical system [14].

2.3 Data Storage: In addition to real-time wireless transmission, the system stores second-by-second voltage readings on a memory card attached to the digital meter. This local data storage serves as a backup in case of communication interruptions and can be used for post-event analysis or system diagnostics [15].

2.4 Fault Detection and Recovery: The Arduino microcontroller continuously monitors the voltage levels, identifies fault conditions, and automatically switches the power supply to renewable energy sources such as solar panels. The data is sent wirelessly via the nRF24L01 module, and the host computer uses a microprocessor to analyze the incoming data and determine when the voltage has stabilized [16].

3. Hardware Implementation

The hardware shown in Figure 2 illustrates the integration of a digital meter, Arduino microcontroller, NRF24L01 wireless module, and renewable energy interface for fault protection and recovery. The digital meter continuously monitors voltage levels, while the Arduino manages the real-time fault detection, switching the power supply to renewable sources (e.g., solar panels) in case of overvoltage or undervoltage conditions. The system communicates wirelessly with a host computer using the nRF24L01 module to transmit second-by-second voltage data, which is also stored locally on a memory card for backup. The relay system disconnects the main power supply during fault conditions, and the system is restored once normal voltage levels are detected [17].

- **NRF24L01 Wireless Communication Module:** The **NRF24L01** module allows seamless communication between the digital meter and the host computer. It ensures the real-time transmission of voltage data every second, providing a continuous stream of updates to the host computer for fault detection and system status monitoring.
- **Data Storage on Memory Card:** Each digital meter is equipped with a memory card for storing voltage readings at one-second intervals. This redundancy ensures that data is available even in case of wireless communication failures, allowing for later retrieval and analysis.
- **Arduino Module:** The Arduino controls both the data transmission to the host computer via the nRF24L01 and the fault response mechanism. It manages the transition to renewable energy during fault conditions and ensures the continuous operation of the system [18].

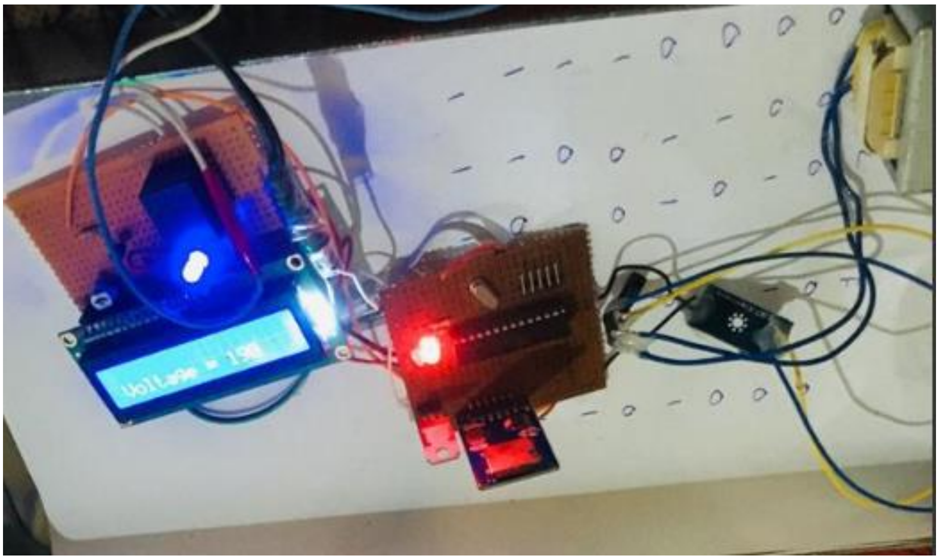

Fig. 2. Hardware of the Control System

4. Results

The experimental setup successfully demonstrated the system's response to both **overvoltage** and **undervoltage** conditions. The images provided show the system in action as it detects fault conditions, switches the power supply and communicates real-time data to the host computer.

4.1 Overvoltage Detection

Image Description: Figure 3 shows the system detecting an overvoltage condition, currently it works normally due to the stable if the voltage output voltage exceeds 250V the system will shift to the renewable energy sources. Upon detection, the digital meter cut off the power supply to the output transformer, preventing any potential damage to the connected equipment.

System Response: The relay disconnected the main power supply, and the Arduino immediately switched the supply to the solar energy source. Voltage data was transmitted wirelessly to the host computer for analysis, and readings were stored on the attached memory card for further reference [19].

Result: The system effectively mitigated the overvoltage by isolating the faulty input and providing a seamless switch to renewable energy.

Fig. 3. Stable output voltages

4.2 Undervoltage Detection

- **Image Description**: The Figure 4 system during an undervoltage scenario where the voltage dropped below 180V. Similar to the overvoltage condition, the system shut off the main power supply to protect the equipment.
- **System Response**: Upon under-voltage detection, the Arduino initiated the transition to solar power to maintain supply to the output feeder. Wireless communication via the nRF24L01 module ensured that the host computer received real-time data, and the memory card module continuously logged the voltage changes for future analysis.
- **Result**: The system successfully managed the Undervoltage condition, ensuring continuous power supply and preventing any disruptions.

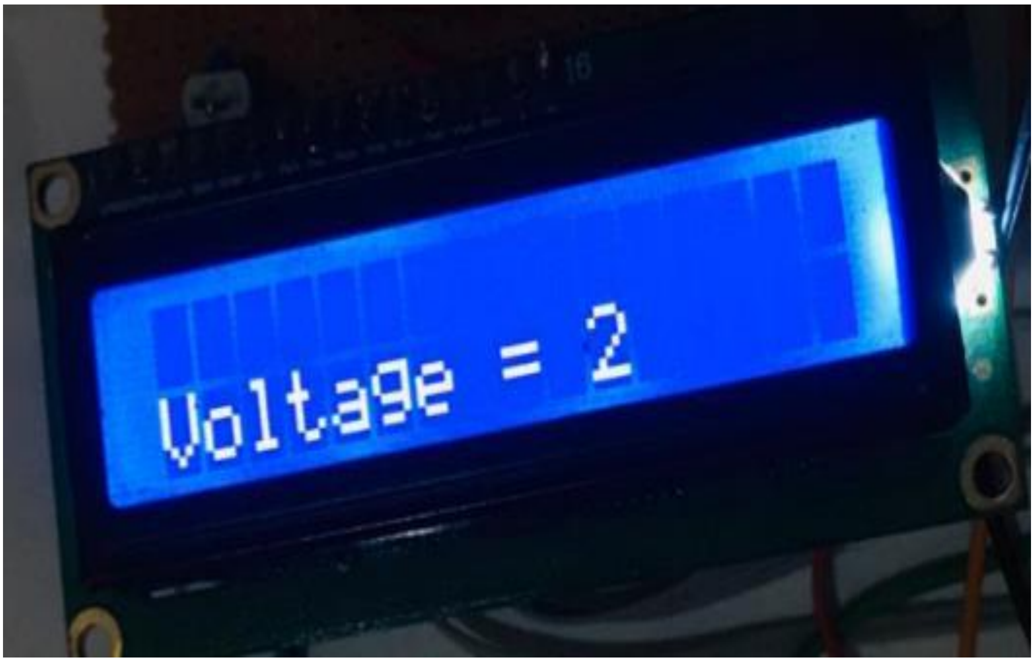

Fig. 4. undervoltage condition

5. Software Implementation

Following the hardware setup, the software plays a crucial role in controlling and monitoring the entire system. The control algorithm was developed using the Arduino Integrated Development Environment (IDE) to manage the fault detection and response mechanism. The code was uploaded to the Arduino microcontroller to ensure seamless integration with the hardware components, including the digital meter, relay, and wireless communication module. In the figure shows the circuit diagram on the Porteous [20].

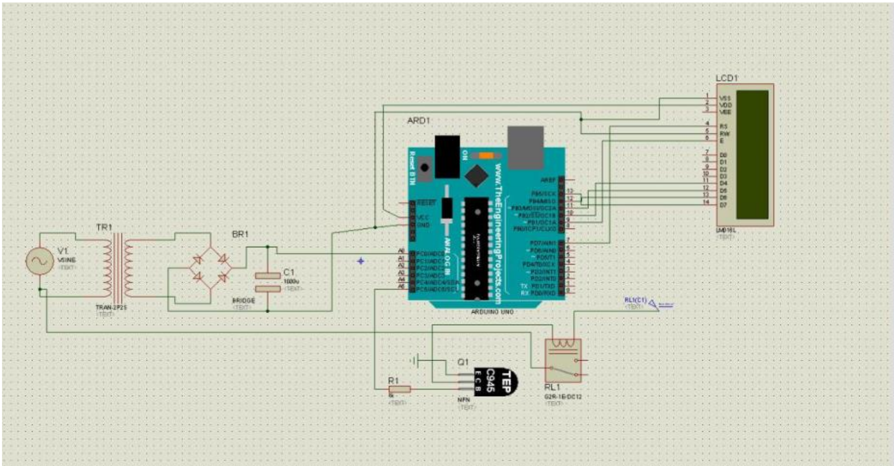

Fig. 5. Circuit Diagram

6. Implementation on a 132kV Grid Station

The same fault protection system was successfully implemented at a **132kV grid station**, demonstrating its scalability and effectiveness in a high-voltage environment. This adaptation involved monitoring the overvoltage and undervoltage conditions of the 132kV power line, with the same principles of fault detection, data transmission, and renewable energy integration applied.

6.1 Key Features of the 132kV Implementation:

Voltage Monitoring: The system monitored the grid's high-voltage lines, detecting faults when voltage exceeded the operational limits set for the 132kV system. This protection mechanism ensured that overvoltage or undervoltage scenarios did not result in system damage or outages.

Real-Time Fault Detection: When fault conditions were detected, the system immediately isolated the affected part of the grid, preventing potential blackouts and ensuring safety across the network. The system was designed to switch to renewable energy sources for critical loads during fault conditions [21].

MATLAB Simulation Results: MATLAB simulations were conducted to verify the system's response under various fault conditions, including both overvoltage and undervoltage scenarios. The simulation results aligned with the experimental data from the grid station, showing the successful disconnection of faulty lines and automatic recovery once the voltage stabilized. MATLAB graphs demonstrated the real-time response of the system, visualizing voltage changes and relay action.

6.2 Calculations and Results

In the schematic diagram (Figure 6) for the MATLAB simulation of a three-phase fault in a Smart Grid, the output is derived from a 20/26 MVA transformer, which is used as the distribution transformer. The simulation source operates at 11 kV, with the base voltages remaining constant throughout.

The simulation involves four inputs and three outputs. Three of the inputs are connected to a phase circuit breaker, which is initially in a closed state. The switching time of the circuit breaker is controlled by an external source. One important parameter in the setup is the Three-Phase Voltage-Current (V-I) Measurement.

This component measures the current passing through the system when a fault occurs.

A fault is induced at the output terminals of the Three-Phase V-I Measurement, which is also connected to a Three-Phase Series RLC Load. The fault mechanism is activated by a step function with a step time of 0.1 seconds, generating a pulse that triggers the fault condition. This setup helps analyze how the system responds during a fault and the behavior of current and voltage in the grid during such an event.

In Figure 7, the subsystem represents a phase fault relay. Within this subsystem, a rational operator is used to compare three input values, converting them into a Boolean expression since the output needs to be in binary format. These three inputs are then fed into an AND gate, which processes them before passing the result to an S-R Flip-Flop.

The output from the AND gate is digital, and since the subsequent system requires the data type to be double, we perform the necessary conversion. The output signal is then sent to the circuit breaker. If the current exceeds the predefined safety threshold, the circuit breaker is triggered to actuate.

The simulation runs for 0.3 seconds, with the fault introduced at the 0.1-second mark.

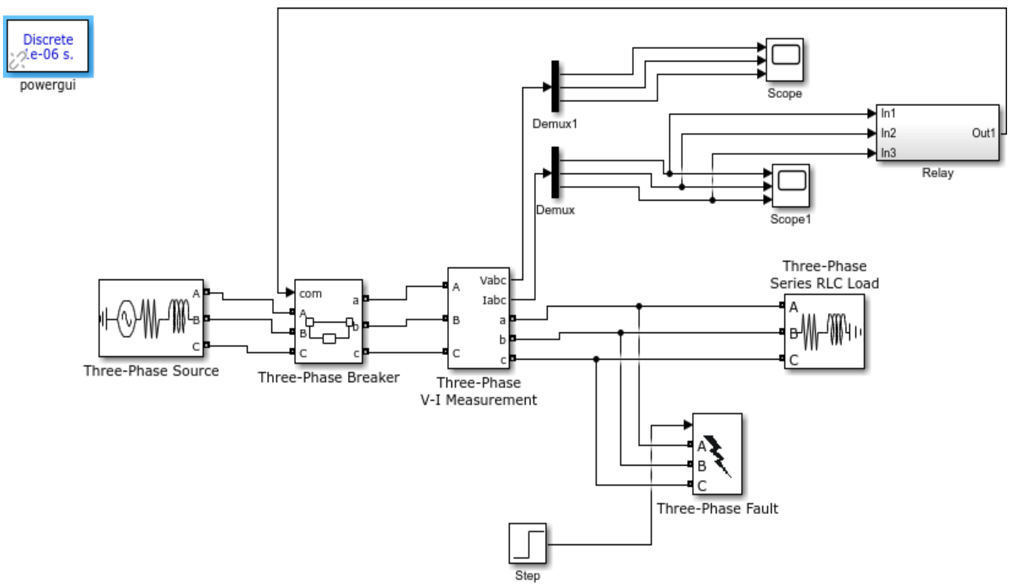

Fig. 6. Circuit model for three-phase fault in the power system of Smart Grid

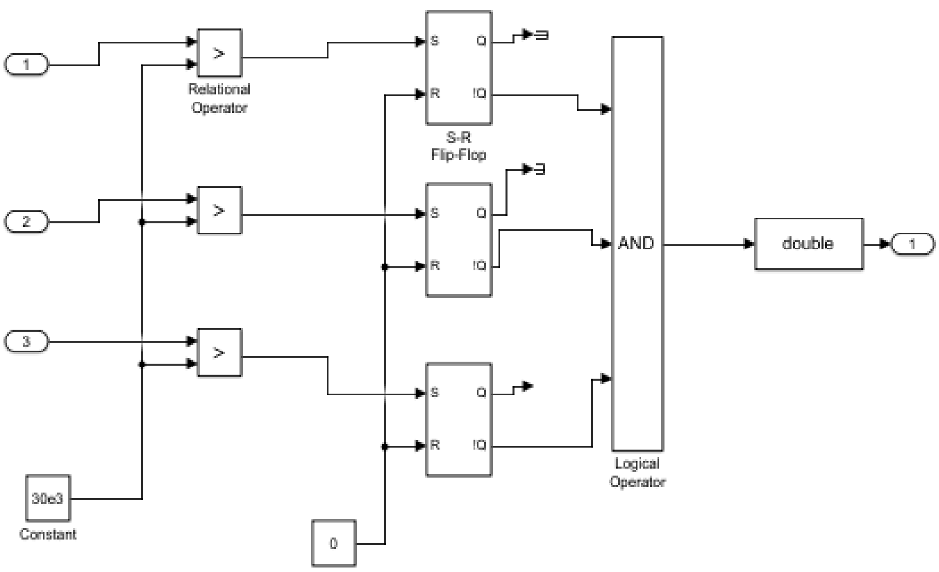

Fig. 7. Subsystem of three-phase fault relay

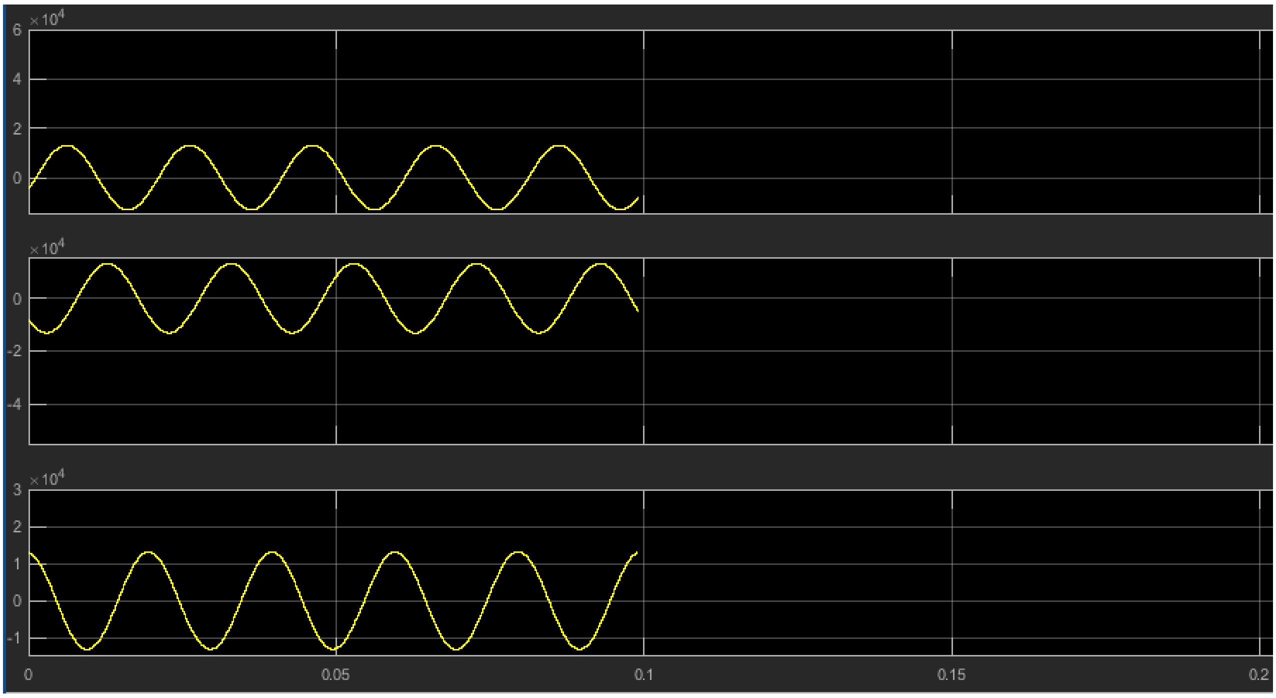

Fig. 8. Output waveform normal current situation

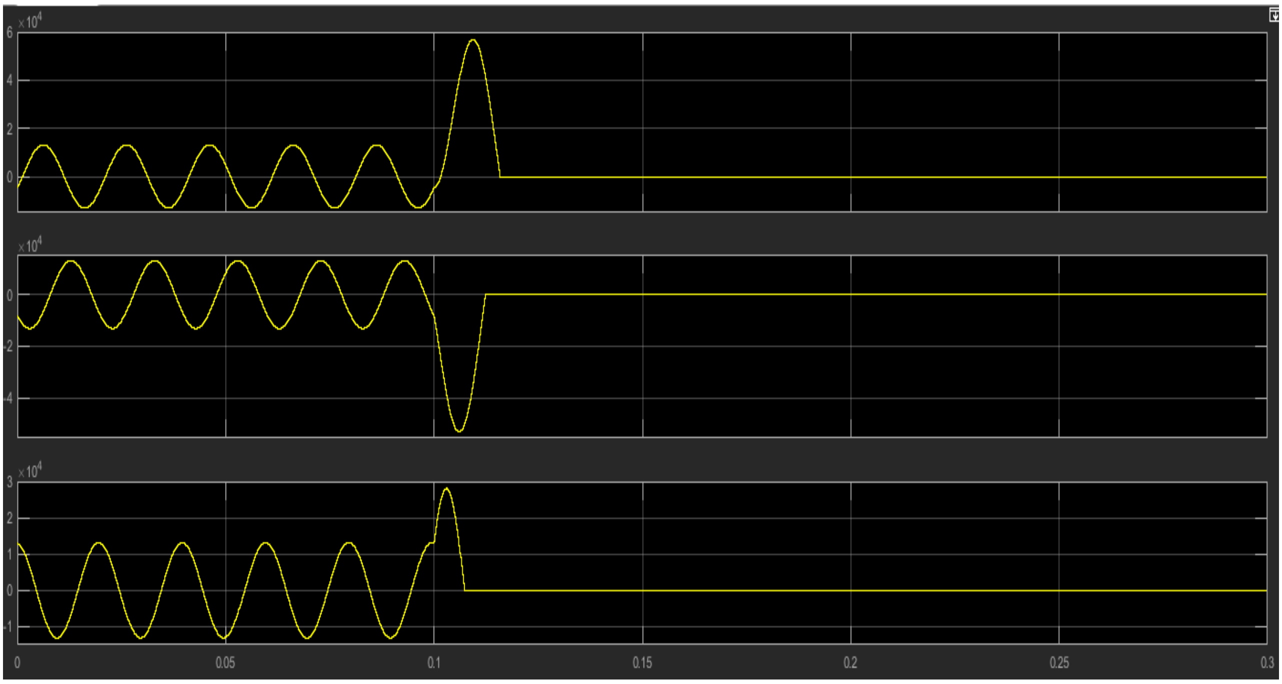

Fig. 9. Output waveform when a fault occurs

Initially, the current flows normally at approximately 1.8 × 10^4 A. However, when the fault occurs at 0.1 seconds, a surge of current, around 6 × 10^4 A, is observed, which exceeds the comparison threshold. As a result, the current drops to nearly zero.

In this scenario, the distribution system model simulates a three-phase-to-ground fault. The simulation is run for 1 second to observe the waveforms. A sampling frequency of 10 kHz is used, with the system voltage set at 33 kV and the line length at 10 km. The fault occurs 5 km along the line, starting at 0.2 seconds and clearing at 0.7 seconds, as shown in Figure 9.

7. Conclusion

This research presents a robust solution for voltage protection in smart grids, effectively addressing the challenges posed by overvoltage and under-voltage conditions. By integrating digital meters, Arduino modules, and wireless communication, the system ensures real-time monitoring and rapid fault response, enhancing grid reliability. The incorporation of renewable energy sources for fault recovery further demonstrates the system's adaptability and sustainability. The successful implementation and testing at a 132kV grid station validate the approach's scalability and effectiveness, highlighting its potential for improving the overall stability and efficiency of modern electrical grids. Future work can explore further optimizations and the integration of additional renewable energy technologies to enhance resilience against voltage fluctuations.

References

[1] Fan, Dongming, et al. "Restoration of smart grids: Current status, challenges, and opportunities." Renewable and Sustainable Energy Reviews 143 (2021): 110909.

[2] Souto, Laiz, Philip C. Taylor, and Jonathan Wilkinson. "Probabilistic impact assessment of lightning strikes on power systems incorporating lightning protection design and asset condition." International Journal of Electrical Power & Energy Systems 148 (2023): 108974.

[3] Sarathkumar, D., et al. "A technical review on classification of various faults in smart grid systems." *IOP conference series: Materials science and engineering*. Vol. 1055. No. 1. IOP Publishing, 2021.

[4] Dabou, Rachid, et al. "Development of autonomous monitoring and performance evaluation system of grid-tied photovoltaic station." International Journal of Hydrogen Energy 46.59 (2021): 30267-30287.

[5] Pang, Yi, et al. "Integrated sizing and scheduling of an off-grid integrated energy system for an isolated renewable energy hydrogen refueling station." Applied Energy 323 (2022): 119573.

[6] Pourmirasghariyan, Mirsajed, et al. "A power routing-based fault detection strategy for multi-terminal VSC-HVDC grids." IEEE Transactions on Power Delivery 38.1 (2022): 528-540.

[7] Eikeland, Odin Foldvik, et al. "Uncovering contributing factors to interruptions in the power grid: An Arctic case." Energies 15.1 (2022): 305.

[8] Rind, Yousaf Murtaza, et al. "Smart energy meters for smart grids, an internet of things perspective." Energies 16.4 (2023): 1974.

[9] Cheikh-Mohamad, Saleh, Manuela Sechilariu, and Fabrice Locment. "Real-time power management including an optimization problem for PV-powered electric vehicle charging stations." Applied Sciences 12.9 (2022): 4323.

[10] Malozyomov, Boris V., et al. "Designing the Optimal Configuration of a Small Power System for Autonomous Power Supply of Weather Station Equipment." Energies 16.13 (2023): 5046.

[11] Prajwal, K. S., et al. "Wireless communication network-based smart grid system." Pervasive Computing and Social Networking: Proceedings of ICPCSN 2021. Springer Singapore, 2022.

[12] Souhe, Felix Ghislain Yem, et al. "Fault detection, classification and location in power distribution smart grid using smart meters data." Journal of Applied Science and Engineering 26.1 (2022): 23-34.

[13] Kabalcı, Ersan, Yasin Kabalcı, and Pierluigi Siano. "Design and implementation of a smart metering infrastructure for low voltage microgrids." International Journal of Electrical Power & Energy Systems 134 (2022): 107375.

[14] Singh, S. Vikram, Aizad Khursheed, and Zahoor Alam. "Wired communication technologies and networks for smart grid—a review." Cyber Security in Intelligent Computing and Communications (2022): 183-195.

[15] Souhe, Felix Ghislain Yem, et al. "Fault detection, classification and location in power distribution smart grid using smart meters data." *Journal of Applied Science and Engineering* 26.1 (2022): 23-34.

[16] Goudarzi, Arman, et al. "A survey on IoT-enabled smart grids: emerging, applications, challenges, and outlook." Energies 15.19 (2022): 6984.

[17] Liyakat, Kazi Sultanabanu Sayyad, and Kazi Kutubuddin Sayyad Liyakat. "IoT Based Arduino-Powered Weather Monitoring System." Journal of Telecommunication Study 8.3 (2023): 25-31.

[18] Wondimu, Aneley, et al. "Design and Implementation of Digital Automation System for the Protection of Equipment and Machineries in Ethio Telecom." (2023).

[19] Dhanapal, M., K. Vijaya Kumar, and R. Prabhu. "ESTIMATION OF AN UNSTABLE MICROGRID USING PROTEUS ADAPTIVE SLIDE MODE CONTROL." CURRENT APPROACHES IN SCIENCE, ENGINEERING AND TECHNOLOGY: 19.

[20] Bakkar, Mostafa, et al. "Multi-layer smart fault protection for secure smart grids." IEEE Transactions on Smart Grid 14.4 (2022): 3125-3135.

[21] Hajji, Mansour, et al. "Fault detection and diagnosis in grid-connected PV systems under irradiance variations." Energy Reports 9 (2023): 4005-4017.