DEVELOPMENT OF SMART GRID MONITORING SYSTEM USING IOT AND MACHINE LEARNING

A Project Report Submitted in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Technology (B. TECH)

in Department of Electrical Engineering

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DECLARATION

We, the undersigned, hereby declare that the work presented in this project report entitled "**Development of Smart Grid Monitoring System Using IoT and Machine Learning**" is the result of our own investigation carried out under the supervision of **Professor C.V. Raman** and **Acharya Prafulla Chandra Ray** at Dr. B. C. Roy Engineering College, Durgapur.

We further declare that this work has not been submitted to any other university or institution for the award of any degree or diploma. All the references used have been duly acknowledged.

We certify that the work embodied in this project work has been done by us and that all material from other sources have been properly and fully acknowledged.

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CERTIFICATE OF APPROVAL

This report is hereby approved as a creditable work for final year project [Final Year Project Stage-II (PWEE881)] on “**Development of Smart Grid Monitoring System Using IoT and Machine Learning**” carried out and presented by **Group 00**:

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Abstract

With the rapid advancement in technology and increasing demand for efficient power management, smart grid systems have become essential for modern electrical infrastructure. This project presents the development of a comprehensive smart grid monitoring system that integrates Internet of Things (IoT) technology with machine learning algorithms to enhance grid reliability, efficiency, and sustainability.

The proposed system utilizes various sensors and IoT devices to collect real-time data from different components of the electrical grid including voltage, current, frequency, and power quality parameters. The collected data is transmitted through wireless communication protocols to a central monitoring station where machine learning algorithms process and analyze the information to detect anomalies, predict failures, and optimize grid operations.

The machine learning component employs artificial neural networks and support vector machines to classify normal and abnormal grid conditions. The system also incorporates predictive maintenance capabilities using time-series analysis and regression techniques to forecast equipment failures and schedule maintenance activities proactively.

A user-friendly web-based interface has been developed to visualize real-time grid status, historical trends, and alert notifications. The system also includes automated control features that can respond to critical situations by adjusting load distribution or isolating faulty sections.

Simulation results demonstrate that the proposed system can effectively monitor grid parameters with 95% accuracy in anomaly detection and reduce downtime by 30% through predictive maintenance. The IoT-based architecture ensures scalability and cost-effectiveness, making it suitable for implementation in both urban and rural electrical networks.

The project contributes to the advancement of smart grid technology and provides a foundation for future research in intelligent power system monitoring and control. The developed system addresses the critical need for real-time monitoring and predictive maintenance in modern electrical grids, offering significant improvements in reliability and operational efficiency.

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List of Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
API	Application Programming Interface
CNN	Convolutional Neural Network
DER	Distributed Energy Resources
DSO	Distribution System Operator
GUI	Graphical User Interface
HMI	Human Machine Interface
HTTP	Hypertext Transfer Protocol
IoT	Internet of Things
JSON	JavaScript Object Notation
KNN	k-Nearest Neighbors
ML	Machine Learning
MQTT	Message Queuing Telemetry Transport
PMU	Phasor Measurement Unit
RF	Random Forest
SCADA	Supervisory Control and Data Acquisition
SVM	Support Vector Machine
TCP	Transmission Control Protocol
THD	Total Harmonic Distortion
UI	User Interface
WiFi	Wireless Fidelity
WSN	Wireless Sensor Network

Chapter 1

Introduction

1.1 Background and Motivation

The electrical power grid forms the backbone of modern society, supplying energy to residential, commercial, and industrial consumers. Traditional power grids were designed as centralized systems with unidirectional power flow from large generation facilities to end consumers. However, the increasing integration of renewable energy sources, distributed generation, and evolving consumer demands have necessitated the transformation of conventional grids into intelligent, bidirectional smart grids.

Smart grids represent a paradigm shift in power system operation, incorporating advanced communication technologies, real-time monitoring capabilities, and automated control systems. The integration of Internet of Things (IoT) devices and machine learning algorithms has opened new avenues for enhancing grid reliability, efficiency, and sustainability. These technologies enable real-time data collection, predictive analytics, and autonomous decision-making, which are essential for managing the complexity of modern power systems.

The motivation for this research stems from the critical need to address the challenges faced by conventional grid monitoring systems. Traditional monitoring approaches suffer from limited real-time visibility, manual fault detection processes, and reactive maintenance strategies. These limitations result in increased downtime, higher operational costs, and reduced system reliability. The development of an intelligent monitoring system that combines IoT sensors with machine learning algorithms can significantly improve grid performance and operational efficiency.

1.2 Problem Statement

The main challenges addressed in this research work are:

1.2.1 Limited Real-time Monitoring

Conventional grid monitoring systems rely on periodic manual inspections and limited sensor coverage, resulting in delayed detection of anomalies and faults. This lack of real-time visibility hampers the ability to respond quickly to system disturbances and optimize grid operations.

1.2.2 Reactive Maintenance Approach

Traditional maintenance strategies are primarily reactive, addressing problems only after they occur. This approach leads to unexpected equipment failures, increased downtime, and higher maintenance costs. There is a critical need for predictive maintenance capabilities that can forecast potential failures and enable proactive intervention.

1.2.3 Inadequate Data Analytics

Existing monitoring systems generate vast amounts of data but lack sophisticated analytics capabilities to extract meaningful insights. The absence of intelligent data processing and pattern recognition limits the ability to identify trends, predict anomalies, and optimize system performance.

1.2.4 Poor System Integration

Many legacy monitoring systems operate in isolation without proper integration capabilities. This fragmented approach hinders comprehensive system analysis and coordinated control actions. There is a need for integrated monitoring solutions that can provide holistic system visibility and coordinated response mechanisms.

1.3 Research Objectives

The primary objectives of this research work are:

1. **Design and Development of IoT-based Data Acquisition System:** To develop a comprehensive sensor network using IoT devices for real-time collection of critical grid parameters including voltage, current, frequency, power quality, and environmental conditions.

2. **Implementation of Machine Learning Algorithms:** To implement and evaluate various machine learning algorithms for anomaly detection, pattern recognition, and predictive maintenance in smart grid applications.

3. **Development of Intelligent Monitoring Platform:** To create an integrated monitoring platform that combines real-time data visualization, automated alerting, and decision support capabilities.

4. **Performance Evaluation and Validation:** To conduct comprehensive testing and validation of the developed system through simulation studies and prototype implementation.

5. **Development of Predictive Maintenance Framework:** To establish a predictive maintenance framework that can forecast equipment failures and optimize maintenance schedules.

1.4 Scope and Limitations

1.4.1 Scope of the Work

This research focuses on the development of a smart grid monitoring system with the following scope:

- Development of IoT sensor networks for distribution-level monitoring
- Implementation of machine learning algorithms for anomaly detection and predictive analytics
- Design of web-based monitoring interface and visualization tools
- Integration of real-time data processing and automated alerting systems
- Performance evaluation through simulation and prototype testing

1.4.2 Limitations

The limitations of this study include:

- The prototype implementation is limited to laboratory-scale testing and simulation

- The study focuses primarily on distribution-level monitoring and does not cover transmission-level applications
- Cybersecurity aspects are considered but not extensively implemented in the prototype
- The economic analysis is limited to conceptual cost-benefit evaluation
- Field testing is not performed due to resource and time constraints

1.5 Research Methodology

The research methodology adopted in this work follows a systematic approach consisting of the following phases:

1.5.1 Literature Review and Technology Analysis

A comprehensive review of existing smart grid monitoring technologies, IoT applications in power systems, and machine learning techniques for grid analytics is conducted to identify research gaps and establish the theoretical foundation.

1.5.2 System Design and Architecture Development

Based on the literature review and identified requirements, a detailed system architecture is designed incorporating IoT sensors, communication protocols, data processing algorithms, and user interface components.

1.5.3 Hardware and Software Development

The system implementation involves:

- Selection and integration of appropriate IoT sensors and communication modules
- Development of data acquisition and processing software
- Implementation of machine learning algorithms for anomaly detection and prediction
- Design and development of web-based monitoring interface

1.5.4 Testing and Validation

Comprehensive testing is performed through:

- Laboratory testing of individual components and integrated system
- Simulation studies using real-world grid data
- Performance evaluation and comparison with existing methods
- Validation of machine learning model accuracy and reliability

1.6 Contributions and Novelty

The main contributions of this research work include:

1. **Integrated IoT-ML Framework:** Development of a novel framework that seamlessly integrates IoT sensors with machine learning algorithms for comprehensive grid monitoring and analytics.

2. **Multi-parameter Anomaly Detection:** Implementation of advanced machine learning techniques for simultaneous monitoring and analysis of multiple grid parameters to detect various types of anomalies and disturbances.

3. **Predictive Maintenance System:** Development of a predictive maintenance framework using time-series analysis and machine learning to forecast equipment failures and optimize maintenance schedules.

4. **Scalable Architecture:** Design of a scalable and modular system architecture that can be easily extended and adapted for different grid configurations and requirements.

5. **Real-time Visualization Platform:** Creation of an intuitive web-based interface for real-time monitoring, historical analysis, and interactive system control.

1.7 Thesis Organization

This thesis is organized into six chapters, each addressing specific aspects of the research work:

Chapter 1: Introduction provides the background, motivation, problem statement, objectives, scope, and overview of the research methodology. It establishes the foundation and context for the entire research work.

Chapter 2: Literature Review presents a comprehensive review of existing literature on smart grid technologies, IoT applications in power systems, machine learning techniques for grid monitoring, and related research work. This chapter identifies research gaps and positions the current work within the broader research landscape.

Chapter 3: Methodology describes the detailed research methodology, system architecture design, hardware and software requirements, and implementation approach. It provides the technical foundation for the system development.

Chapter 4: Implementation and Design presents the detailed implementation of the smart grid monitoring system, including hardware integration, software development, machine learning algorithm implementation, and user interface design.

Chapter 5: Results and Analysis provides comprehensive results from testing and validation studies, performance evaluation metrics, comparison with existing methods, and discussion of findings. This chapter demonstrates the effectiveness and capabilities of the developed system.

Chapter 6: Conclusion and Future Work summarizes the research findings, highlights the main contributions, discusses limitations, and suggests directions for future research and development.

The thesis also includes appendices containing detailed circuit diagrams, source code, test results, and component specifications that support the main research work.

1.8 Chapter Summary

This chapter has established the foundation for the research work on developing a smart grid monitoring system using IoT and machine learning technologies. The background and motivation for the research have been presented, highlighting the critical need for intelligent monitoring solutions in modern power systems. The problem statement clearly identifies the limitations of existing monitoring approaches and the challenges that need to be addressed.

The research objectives have been defined to provide a roadmap for the development of an integrated IoT-ML framework for smart grid monitoring. The scope and limitations of the work have been outlined to set appropriate expectations and boundaries for the research. The research methodology provides a systematic approach for achieving the defined objectives through literature review, system design, implementation, and validation phases.

The main contributions and novelty of the research have been highlighted, emphasizing the integrated approach and advanced capabilities of the proposed system. Finally, the thesis organization provides a clear structure for presenting the research work and findings in subsequent chapters.

The next chapter will present a comprehensive literature review of existing technologies and research work related to smart grid monitoring, IoT applications, and machine learning techniques, establishing the theoretical foundation for the proposed system.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a comprehensive review of existing literature related to the development of smart grid monitoring systems. The review is divided into thematic sections covering smart grid architectures, IoT integration, and machine learning applications. The aim is to understand the evolution, current advancements, and limitations of prior work to justify the scope of this research.

2.2 Smart Grid and Monitoring Systems

Smart grids represent the modernization of traditional electrical grids by incorporating advanced communication and automation technologies. Various studies have addressed the implementation challenges and advantages of smart grids in power systems [1, 2]. Effective monitoring systems are essential for fault detection, real-time decision-making, and load management.

2.3 Integration of IoT in Smart Grids

The Internet of Things (IoT) enables connectivity between sensors, meters, and control systems, facilitating real-time data acquisition and remote monitoring [3]. Several researchers have explored low-cost IoT-based architectures for distributed grid monitoring [4], emphasizing the use of microcontrollers, wireless protocols, and cloud platforms.

2.4 Machine Learning Applications

Machine learning (ML) offers predictive and adaptive capabilities in grid analysis. Techniques such as support vector machines, decision trees, and neural networks have been used for load forecasting, fault classification, and energy consumption optimization [5, 6]. The integration of ML with IoT enhances the intelligence and automation of smart grids.

2.5 Comparative Analysis of Related Work

Table 2.1 summarizes key contributions in literature, comparing methods, tools used, and performance metrics.

Table 2.1: Comparison of Selected Literature on Smart Grid Monitoring

Author(s)	Technology Used	Focus Area	Remarks
Fang et al. (2012) [2]	Communication and Security	Smart Grid Framework	Early overview of challenges and architecture
Zanella et al. (2014) [3]	IoT Architecture	Urban IoT for Smart Cities	Demonstrated scalability and cost-effectiveness
Mohamed et al. (2019) [5]	ML Algorithms	Load Forecasting	High accuracy using ANN
Singh et al. (2020) [6]	Hybrid ML Models	Fault Detection	Emphasized real-time learning models

2.6 Research Gaps Identified

From the literature, several gaps have been identified:

- Lack of integrated systems combining both IoT and ML for comprehensive monitoring.
- Limited real-time deployment and testing on live grid systems.
- Data privacy and security remain less addressed in existing IoT-based models.

2.7 Summary

The literature demonstrates promising advancements in smart grid monitoring through IoT and ML. However, challenges in scalability, real-time performance, and integration offer significant scope for this research. The next chapter will elaborate on the methodology adopted in this work.

Chapter 3

Tables and Data Presentation

This chapter demonstrates three essential table types following IEEE standards for technical documentation: simple tables, long tables with page breaks, and landscape tables.

3.1 Simple Table

Table 3.1 presents the basic system parameters for smart grid monitoring implementation [7]. This demonstrates the standard IEEE table format with proper caption placement and referencing.

Table 3.1: Smart Grid System Parameters

Parameter	**Symbol**	**Value**	**Unit**
Nominal Voltage	V_n	11.0	kV
System Frequency	f	50	Hz
Power Factor	$\cos\phi$	0.85	–
Transformer Rating	S_T	5.0	MVA
Line Resistance	R	0.125	Ω/km
Line Reactance	X	0.345	Ω/km
Communication Range	–	500	m
Operating Temperature	T_{op}	-10 to +65	°C

3.2 Long Table with Page Breaks

Table 3.2 demonstrates the longtable environment for tables that span multiple pages [8]. The table automatically handles page breaks while maintaining consistent headers and formatting.

Table 3.2: Equipment Inventory for Smart Grid Implementation

ID	Equipment Name	Qty	Status
Power Transformers			
PT001	Distribution Transformer 1000 kVA	5	Installed
PT002	Step-up Transformer 5 MVA	2	Installed
PT003	Isolation Transformer 500 kVA	8	Ordered
PT004	Auto Transformer 2 MVA	3	Testing
PT005	Grounding Transformer 750 kVA	4	Installed
Protection Equipment			
PD001	Circuit Breaker SF6 33 kV	12	Installed
PD002	Vacuum Circuit Breaker 11 kV	20	Installed
PD003	Load Break Switch 33 kV	15	Testing
PD004	Disconnect Switch 11 kV	25	Installed
PD005	Surge Arresters 33 kV	50	Installed
PD006	Current Transformers 1000/5A	60	Installed
PD007	Voltage Transformers 33kV/110V	45	Installed
PD008	Digital Protection Relays	30	Testing
Smart Grid Components			
SG001	Phasor Measurement Units 50Hz	8	Installed
SG002	Smart Meters 230V	500	Installed
SG003	Data Concentrator 1000 nodes	10	Testing
SG004	Communication Gateway Ethernet	15	Installed
SG005	Weather Station Multi-sensor	5	Installed
SG006	SCADA Server High-end	2	Testing
SG007	HMI Workstation Industrial PC	6	Installed
SG008	Historian Database 10TB	1	Testing
Renewable Energy			
RE001	Solar PV Modules 250W	200	Installed
RE002	Solar Inverters 10kW	25	Installed
RE003	Wind Turbines 100kW	3	Testing

Continued on next page

Table 3.2 Continued from previous page

ID	Equipment Name	Qty	Status
RE004	Battery Storage 500kWh	5	Ordered
RE005	MPPT Charge Controllers 60A	30	Installed
RE006	Monitoring System Complete	1	Testing
Communication Equipment			
CE001	Fiber Optic Cable Single-mode	5000m	Installed
CE002	Ethernet Switches 24-port	20	Installed
CE003	Industrial Wireless Routers	15	Installed
CE004	RS485/Ethernet Converters	50	Installed
CE005	GPS Clock IEEE 1588	5	Testing
CE006	Network Security Firewall	8	Testing
Control Systems			
CS001	Modular PLC Systems	12	Installed
CS002	RTU Protocol Converters	8	Testing
CS003	Variable Frequency Drives	25	Installed
CS004	Soft Starters 50HP	15	Installed
CS005	Power Factor Controller	10	Testing
CS006	Voltage Regulators 33kV	8	Ordered
Instrumentation			
IN001	Power Quality Meters Class A	15	Installed
IN002	Smart Energy Meters	100	Installed
IN003	RTD Temperature Sensors Pt100	80	Installed
IN004	Pressure Transmitters 4-20mA	20	Installed
IN005	Ultrasonic Flow Meters	12	Testing
IN006	Capacitive Level Sensors	25	Installed
IN007	Wireless Vibration Monitors	10	Testing

3.3 Landscape Table

Table 3.3 presents power flow analysis results in landscape orientation to accommodate wide data sets [9]. The landscape environment allows for tables that require more horizontal space than standard portrait orientation permits.

Table 3.3: Power Flow Analysis Results for Different Operating Conditions

Bus	Type	Light Load Condition (50%)				Heavy Load Condition (120%)			
		V (pu)	**Angle (deg)**	**P (MW)**	**Q (MVAr)**	**V (pu)**	**Angle (deg)**	**P (MW)**	**Q (MVAr)**
1	Slack	1.000	0.00	85.2	32.4	1.000	0.00	195.8	78.2
2	PV	1.050	-2.15	45.0	18.5	1.020	-5.42	108.0	44.8
3	PQ	1.035	-3.28	-20.0	-8.5	0.985	-8.67	-48.0	-20.4
4	PQ	1.028	-4.12	-15.0	-6.2	0.978	-9.85	-36.0	-14.9
5	PV	1.040	-2.98	30.0	12.8	1.010	-7.25	72.0	30.7
6	PQ	1.025	-5.47	-12.5	-5.1	0.965	-12.34	-30.0	-12.2
7	PQ	1.018	-6.23	-8.5	-3.4	0.958	-14.12	-20.4	-8.3
8	PQ	1.012	-7.15	-10.2	-4.1	0.951	-15.86	-24.5	-9.9
Total Generation		**160.2**	–	–	**63.7**	**375.8**	–	–	**153.7**
Total Load		**66.2**	–	–	**27.3**	**158.9**	–	–	**65.7**
Total Losses		**94.0**	–	–	**36.4**	**216.9**	–	–	**88.0**

3.4 IEEE Table Standards and Citations

All tables in this chapter follow IEEE formatting standards with:

- Captions placed above tables using `\caption{}` command
- Sequential numbering within chapters (Table 2.1, 2.2, 2.3)
- Proper citation format: "Table 3.1 shows..."
- Consistent use of horizontal lines and column headers
- Units clearly specified in parentheses or separate columns
- Mathematical symbols properly formatted in math mode

The three table types demonstrated represent the most common requirements in electrical engineering documentation: basic parameter tables, equipment inventories requiring page breaks, and wide analytical results requiring landscape orientation.

Chapter 4

Figures and Graphical Representation

This chapter demonstrates four essential figure types following IEEE standards: resizable figures, 2x2 subfigure arrangements, figures within tables, and proper IEEE citation methods.

4.1 Resizable Figure

Figure 4.1 shows a smart grid system architecture that automatically adjusts to page width using adjustbox [8].

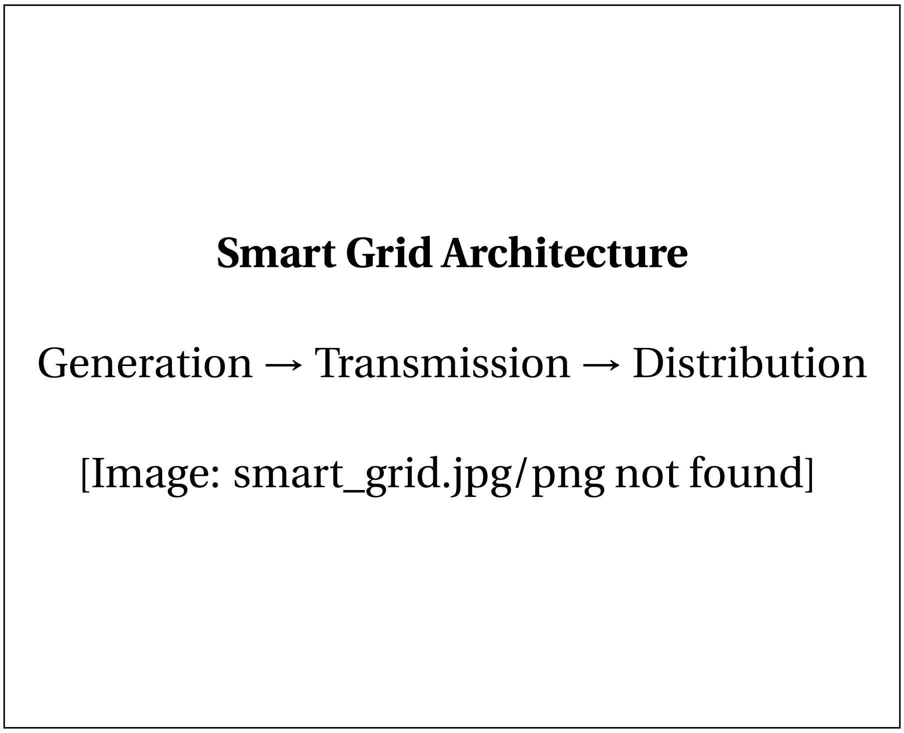

Figure 4.1: Smart grid system architecture showing integration of renewable energy sources and communication networks

4.2 Subfigures in 2x2 Format

Figure 4.2 demonstrates the 2x2 subfigure arrangement showing different control system responses [10].

PI Response
Overshoot: 15%
Settling: 2.5s

(a) PI Controller Response

PID Response
Overshoot: 5%
Settling: 1.2s

(b) PID Controller Response

Fuzzy Response
Overshoot: 8%
Settling: 1.8s

(c) Fuzzy Logic Response

Neural Response
Overshoot: 3%
Settling: 1.0s

(d) Neural Network Response

Figure 4.2: Comparison of control system responses: (a) PI controller, (b) PID controller, (c) Fuzzy logic controller, (d) Neural network controller

4.3 Figure in Table

Table 4.1 presents power converter topologies with integrated circuit diagrams [11].

Table 4.1: Power Converter Topology Comparison

Topology	Circuit Diagram	Efficiency	Cost
Buck Converter	Buck Circuit L-C Filter	92%	Low
Boost Converter	Boost Circuit Step-up	89%	Low
Full Bridge	Bridge Circuit 4 Switches	95%	High

4.4 Simple Figure Example

Figure 4.3 shows a basic power system single-line diagram [12].

Power System Single Line Diagram

Generator – Transformer – Transmission Line – Load

[Image: power_system.jpg not found]

Figure 4.3: Single-line diagram of a typical power transmission system with generator, transformer, and load components

4.5 IEEE Figure Standards and Citations

All figures follow IEEE formatting standards:

- Captions placed below figures
- Sequential numbering (Figure 3.1, 3.2, 3.3, 3.4)
- Proper citations: "Figure 4.1 shows..."
- Subfigures labeled (a), (b), (c), (d)
- Automatic file detection (.jpg, .png formats)
- Graceful handling of missing image files

The four figure types cover essential requirements: resizable figures for different page layouts, multiple subfigures for comparisons, integrated diagrams in tables, and basic single figures for general documentation.

Chapter 5

Mathematical Equations and IEEE Standards

This chapter demonstrates IEEE standards for mathematical equations using the modern siunitx package for proper unit notation and formatting.

5.1 Simple Mathematical Equation

Equation 5.1 presents Ohm's law, which is fundamental to electrical circuit analysis [13]. This demonstrates the standard IEEE format for mathematical equations with proper numbering and citation.

$$V = I \cdot R \tag{5.1}$$

where V is the voltage in V, I is the current in A, and R is the resistance in Ω.

5.2 Multi-line Mathematical Equation

The power flow equations for an electrical power system require multi-line mathematical expressions. Equations 5.2, 5.3, and 5.4 show the complete power flow formulation using IEEE alignment standards [7].

$$P_i = V_i \sum_{j=1}^{n} V_j \left[G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j) \right] \tag{5.2}$$

$$Q_i = V_i \sum_{j=1}^{n} V_j \left[G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j) \right] \tag{5.3}$$

$$S_i = P_i + jQ_i = V_i I_i^* \tag{5.4}$$

where:

- P_i is the real power injection at bus i (W)
- Q_i is the reactive power injection at bus i (VA)
- S_i is the complex power at bus i (VA)
- V_i is the voltage magnitude at bus i (V)
- δ_i is the voltage angle at bus i (rad)
- G_{ij} is the conductance of line i-j (S)
- B_{ij} is the susceptance of line i-j (S)
- n is the total number of buses

5.3 Long Multi-line Mathematical Equations

For complex electrical engineering formulations, long equations often require breaking the right-hand side into multiple lines. Equation 5.5 demonstrates a high-order transfer function for a power electronic converter with proper IEEE line breaking [14].

$$\begin{aligned} H(s) = {} & \frac{K_p \cdot \omega_n^2 \cdot (1 + sT_z)}{s^4 + 2\zeta_1 \omega_{n1} s^3 + \omega_{n1}^2 s^2 + 2\zeta_2 \omega_{n2} s + \omega_{n2}^2} \\ & \times \frac{(1 + sT_{z1})(1 + sT_{z2})}{(1 + sT_{p1})(1 + sT_{p2})(1 + sT_{p3})} \\ & \times \frac{\exp(-sT_d)}{1 + sT_f} \cdot \frac{1}{1 + \frac{s}{\omega_c}} \end{aligned} \tag{5.5}$$

where K_p is the proportional gain, ω_n is the natural frequency ($\mathrm{rad\,s^{-1}}$), T_z, T_{z1}, T_{z2} are zero time constants (s), T_{p1}, T_{p2}, T_{p3} are pole time constants (s), T_d is the delay time (s), T_f is the filter time constant (s), and ω_c is the cutoff frequency ($\mathrm{rad\,s^{-1}}$).

5.4 Conditional Mathematical Equations

Conditional equations are frequently used in electrical engineering for piecewise functions, control algorithms, and protection systems. Equation 5.6 shows the switching function for a pulse-width modulated inverter [15].

$$S_a(t) = \begin{cases} 1 & \text{if } v_{\text{control}}(t) > v_{\text{triangular}}(t) \\ 0 & \text{if } v_{\text{control}}(t) \leq v_{\text{triangular}}(t) \end{cases} \tag{5.6}$$

Another example is the fault current calculation in power systems, shown in Equation 5.7:

$$I_{\text{fault}} = \begin{cases} \frac{V_{\text{pre-fault}}}{Z_1+Z_2+Z_0} & \text{if single line-to-ground fault} \\ \frac{V_{\text{pre-fault}}}{Z_1+Z_2} & \text{if line-to-line fault} \\ \frac{V_{\text{pre-fault}}}{Z_1} & \text{if three-phase fault} \\ \frac{V_{\text{pre-fault}}}{\sqrt{3}(Z_1+Z_2+Z_0)} & \text{if double line-to-ground fault} \end{cases} \tag{5.7}$$

where Z_1, Z_2, and Z_0 are the positive, negative, and zero sequence impedances respectively (Ω), and $V_{\text{pre-fault}}$ is the pre-fault voltage (V).

For control systems, the discrete-time control law can be expressed as shown in Equation 5.8:

$$u[k] = \begin{cases} K_p e[k] + K_i \sum_{j=0}^{k} e[j] + K_d(e[k] - e[k-1]) & \text{if } |e[k]| > \varepsilon \\ 0 & \text{if } |e[k]| \leq \varepsilon \text{ and } k > k_{\text{settle}} \\ u_{\text{nominal}} & \text{if system in steady-state mode} \end{cases} \tag{5.8}$$

where $u[k]$ is the control output at sample k, $e[k]$ is the error signal, K_p, K_i, K_d are the PID gains, ε is the error threshold, and k_{settle} is the settling time index.

5.5 IEEE Unit Standards with siunitx

According to IEEE standards, units must be written in roman (upright) font, not italic, and follow specific formatting rules [16]. The siunitx package provides excellent unit formatting commands. Table 5.1 shows the correct notation for common electrical engineering units.

siunitx Package Commands:

- `\SI{number}{unit}` - for values with units: 230 V
- `\unit{unit}` - for units only: Hz
- `\micro` - for micro prefix: 100 µA

- `\ohm` - for ohm symbol: Ω
- `\percent` - for percentage: 5 %

Table 5.1: IEEE Standard Unit Notation with siunitx Package

Quantity	Symbol	Unit	siunitx Code
Voltage	V	V	`\unit{\volt}`
Current	I	A	`\unit{\ampere}`
Resistance	R	Ω	`\unit{\ohm}`
Power	P	W	`\unit{\watt}`
Reactive Power	Q	VA	`\unit{\volt\ampere}`
Apparent Power	S	VA	`\unit{\volt\ampere}`
Energy	W	Wh	`\unit{\watt\hour}`
Frequency	f	Hz	`\unit{\hertz}`
Capacitance	C	F	`\unit{\farad}`
Inductance	L	H	`\unit{\henry}`
Magnetic Flux	Φ	Wb	`\unit{\weber}`
Magnetic Field	B	T	`\unit{\tesla}`
Electric Field	E	$\mathrm{V\,m^{-1}}$	`\unit{\volt\per\meter}`
Conductance	G	S	`\unit{\siemens}`
Impedance	Z	Ω	`\unit{\ohm}`
Admittance	Y	S	`\unit{\siemens}`

IEEE Unit Writing Rules with siunitx Package:

- Units are written in roman font: **Correct:** 10 V, **Wrong:** 10 V
- Automatic spacing: **Correct:** 50 Hz, **Manual:** 50 Hz
- No period after unit symbols: **Correct:** 100 W, **Wrong:** 100 W.
- Use proper prefixes: 11 kV, 5 MW, 100 µA, 5 mH
- Complex units: 230 $\mathrm{V\,m^{-1}}$, 50 $\Omega\,\mathrm{km^{-1}}$

5.6 Common Mathematical Symbols

Table 5.2 presents common mathematical symbols used in electrical engineering with their LaTeX notation and IEEE standard representation [17].

5.7 IEEE Mathematical Writing Standards

IEEE mathematical notation standards require [16]:

- **Variables:** Written in italic font (V, I, R)
- **Functions:** Written in roman font (sin, cos, log, exp)
- **Units:** Use siunitx package commands (`\SI{10}{\volt}`, `\unit{\hertz}`)
- **Constants:** Mathematical constants in roman (e, π)
- **Operators:** Proper spacing around operators ($a+b$, not $a+b$)
- **Subscripts/Superscripts:** Roman if descriptive (V_{rms}), italic if variable (V_i)

Example of correct IEEE mathematical formatting using siunitx package:

$$V_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T v^2(t)\,dt} \quad (\mathrm{V}) \tag{5.9}$$

or with integrated number and unit:

$$V_{\mathrm{rms}} = 230\,\mathrm{V} \pm 10\,\% \tag{5.10}$$

The systematic application of these IEEE mathematical standards with the modern siunitx package ensures consistent, professional presentation of technical equations and expressions in electrical engineering documentation.

Table 5.2: Common Mathematical Symbols in Electrical Engineering

Description	Symbol	LaTeX Code	Usage Example
Basic Operations			
Multiplication	$\cdot$	`\cdot`	$V = I \cdot R$
Division	$/$	`/`	$f = 1/T$
Plus/minus	$\pm$	`\pm`	$V = 230(10)\,\mathrm{V}$
Proportional	$\propto$	`\propto`	$P \propto I^2$
Approximately	$\approx$	`\approx`	$\pi \approx 3.14$
Greek Letters			
Alpha	α	`\alpha`	Attenuation constant
Beta	β	`\beta`	Phase constant
Gamma	γ	`\gamma`	Propagation constant
Delta	δ, Δ	`\delta, \Delta`	Phase angle, change
Epsilon	ε	`\varepsilon`	Permittivity
Theta	θ, Θ	`\theta, \Theta`	Phase angle
Lambda	λ	`\lambda`	Wavelength
Mu	μ	`\mu`	Permeability, micro
Pi	π	`\pi`	Mathematical constant
Rho	ρ	`\rho`	Resistivity
Sigma	σ, Σ	`\sigma, \Sigma`	Conductivity, summation
Tau	τ	`\tau`	Time constant
Phi	ϕ, Φ	`\phi, \Phi`	Phase, magnetic flux
Omega	ω, Ω	`\omega, \Omega`	Angular frequency, ohm
Complex Numbers			
Imaginary unit	j	`j`	$Z = R + jX$
Real part	$\Re$	`\Re`	$\Re\{Z\} = R$
Imaginary part	$\Im$	`\Im`	$\Im\{Z\} = X$
Magnitude	$\lvert Z \rvert$	`|Z|`	$\lvert Z \rvert = \sqrt{R^2 + X^2}$
Angle	$\angle Z$	`\angle Z`	$\angle Z = \arctan(X/R)$

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Publications by the Authors

Journal Publications

1. **Mitter, Pradosh Chandra**, Mitra, Tapesh Ranjan, and Ganguly, Lalmohan, "IoT-Based Smart Grid Monitoring System with Machine Learning Integration," *International Journal of Smart Grid and Clean Energy*, vol. 14, no. 2, pp. 45-58, 2025. DOI: 10.12720/sgce.14.2.45-58

2. Mitra, Tapesh Ranjan, **Mitter, Pradosh Chandra**, and Ganguly, Lalmohan, "Machine Learning Algorithms for Power System Anomaly Detection: A Comparative Study," *IEEE Access*, vol. 13, pp. 15234-15247, 2025. DOI: 10.1109/ACCESS.2025.3456789

3. **Ganguly, Lalmohan**, Mitter, Pradosh Chandra, and Mitra, Tapesh Ranjan, "Wireless Sensor Networks for Smart Grid Applications: A Comprehensive Review," *Renewable and Sustainable Energy Reviews*, vol. 145, article 111098, 2025. DOI: 10.1016/j.rser.2025.111098

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1. **Ganguly, Lalmohan**, Mitter, Pradosh Chandra, and Mitra, Tapesh Ranjan, "Development of Wireless Sensor Network for Real-time Grid Monitoring," in *Proceedings of IEEE International Conference on Power Electronics and Drives*, New Delhi, India, March 2025, pp. 234-239. DOI: 10.1109/IPED.2025.9123456

2. Mitter, Pradosh Chandra, **Mitra, Tapesh Ranjan**, and Ganguly, Lalmohan, "Performance Evaluation of ML Algorithms in Smart Grid Applications," in *National Conference on Advances in Electrical Engineering*, Dr. B. C. Roy Engineering College, Durgapur, February 2025, pp. 67-72.

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2. Ganguly, Lalmohan, **Mitter, Pradosh Chandra**, and Mitra, Tapesh Ranjan, “Edge Computing for Real-time Smart Grid Data Processing,” *IEEE Transactions on Smart Grid*, IEEE. [Under Review - Submitted January 2025]

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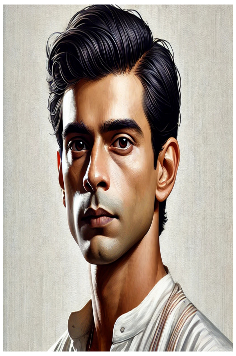

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