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A Novel Edge Computing-Based System for Real-Time Neutral-to-Earth Voltage and Energy Monitoring in Distribution Networks

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WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Neutral-to-earth voltage (NTEV) is a well-known safety and power quality (PQ) issue in distribution systems, particularly in multi-grounded and unbalanced networks, where elevated levels may pose risks to humans, animals, and electrical equipment.*
- *Previous studies have proposed various NTEV monitoring, modeling, and detection techniques using circuit-based methods, signal processing, optimization, and phasor measurement unit-based (PMU) measurements; however, most of these approaches rely on centralized or offline analysis.*
- *Conventional cloud-centric or centralized monitoring architectures suffer from communication latency, bandwidth*

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ABSTRACT

Neutral-to-earth voltage (NTEV) is a critical indicator of grounding integrity, insulation degradation, and electrical safety in distribution networks; however, it is often monitored only through centralized cloud-based systems, resulting in high latency, limited visibility of time-dependent anomalies, and dependency on reliable communication infrastructure. This paper presents the design, implementation, and field validation of a Smart Energy Meter–Edge Gateway (SEM-EG) architecture that integrates continuous NTEV monitoring with edge-based analytics and cloud-supported supervision. The proposed system performs real-time measurement of NTEV together with voltage, current, and power-related parameters, enabling local anomaly detection and operational awareness at the field level while providing long-term data aggregation and visualization in the cloud. Long-term deployment in an operational distribution panel demonstrates that continuous edge-based monitoring detects time-dependent grounding-related faults that remain undetected by conventional measurements, and that corrective field interventions result in an approximately 80% reduction in night-time NTEV levels, quantitatively verifying maintenance effectiveness. In addition, a multi-parameter analysis framework combining NTEV, phase currents, phase voltages, and power metrics is used to assess indirect system impacts. The SEM-EG achieves a measurement precision of ±0.5% and reduces fault detection latency by 78% compared to cloud-only approaches. Results show that edge intelligence transforms NTEV from a passive diagnostic parameter into an active, real-time operational indicator, providing a scalable and practical solution for modern smart grids.

Index Terms—Distribution system, edge and cloud computing, neutral-to-earth voltage, real-time measurement, smart energy meter, warning system

I. INTRODUCTION

Neutral-to-earth voltage (NTEV), also known as stray voltage, has been recognized as a critical issue in power distribution systems since the 1940s. It primarily arises from multiple grounding points on primary and secondary neutral conductors, especially in unbalanced and non-symmetrical networks [1]. NTEV is defined as the voltage difference between the neutral conductor and earth, and excessive levels pose safety risks to humans and animals while also causing equipment damage [2–5]. Under normal operating conditions, NTEV values are typically below 5 V and rarely exceed 10 V [6], with Institute of Electrical and Electronics Engineers (IEEE) standards specifying an upper limit of 10 V [7]. During ground faults, the neutral conductor plays a vital role in maintaining service continuity and system reliability [8]. International standards such as International Electrotechnical Commission (IEC) 61936-1 and IEEE Std C62.92.1™ define grounding and fault behavior requirements to ensure that phase-to-ground voltages remain within acceptable limits [8, 9]. The increasing penetration of nonlinear loads and unbalanced topologies in modern distribution systems has further intensified the need for accurate evaluation of NTEV behavior [10–13].

To assess NTEV in Multi-grounded Neutral (MGN) systems, various passive monitoring techniques have been proposed. Methods based on voltage and current measurements estimate neutral impedance to detect open or broken neutral conditions without injecting external signals [14]. Optimization-based approaches incorporating phasor measurement unit (PMU) have

overhead, and limited capability to detect time-dependent or intermittent grounding faults in real time under field conditions.

WHAT THIS STUDY ADDS ON THIS TOPIC?

- *This study proposes a deployable edge–cloud architecture that performs continuous NTEV measurement and real-time edge-based analytics, enabling immediate detection of grounding-related anomalies without reliance on centralized processing.*
- *The proposed smart energy meter–edge gateway (SEM-EG) integrates local decision-making, automatic calibration, supervisory control and data acquisition (SCADA)/Internet of Things (IoT) communication, and multi-parameter energy monitoring within a single hardware platform validated under real field conditions.*
- *Long-term field deployment demonstrates that edge-based NTEV monitoring can reveal time-dependent grounding faults undetectable by conventional voltage, current, or power measurements, leading to up to 80% reduction in NTEV levels, while reducing fault detection latency and communication traffic.*

demonstrated improved estimation accuracy, particularly in unbalanced distribution networks [15]. In addition, signal processing techniques using Fourier and S-Transform analysis have been applied to detect and localize NTEV-related disturbances, while machine learning approaches such as Support Vector Machines (SVMs) have been employed to classify NTEV scenarios [16]. With the growing integration of distributed energy resources (DERs), the demand for time-synchronized measurements has increased. Phasor measurement units provide real-time visibility into voltage, current, frequency, and phase angle, enabling applications such as state estimation, fault detection, stability assessment, and enhanced system observability in both medium- and low-voltage networks [17–23]. However, PMU-based and cloud-centric architectures often suffer from communication latency and bandwidth overhead, limiting their effectiveness for time-critical fault detection.

Building on these capabilities, recent developments in smart meters, power quality (PQ) analyzers, residual-current monitoring devices, and intelligent field gateways have broadened the scope of distribution-system fault monitoring [24–26]. These devices can continuously acquire electrical and event data, generate configurable alarms, record disturbances, and communicate with SCADA or cloud platforms through industrial protocols [27]. Consequently, they provide the measurement and communication infrastructure required to identify voltage disturbances, current imbalance, leakage conditions, and ground-related abnormalities [28, 29]. More specialized methods have combined PMU-based Rate of Change of Frequency (ROCOF) measurements with Recurrent Neural Network (RNN) and Long Short-Term Memory (LSTM) models for real-time event detection and localization [30], while traveling-wave signals have been processed using wavelet transform, linear discriminant analysis, and naïve Bayes classification to identify faulted regions [31].

Recent monitoring architectures have also extended these functions beyond individual measurement devices. Cloud-based systems integrating smart sensors, 4G communication, and centralized processing have been proposed for line-condition monitoring and small-current grounding-fault location [32]. To reduce dependence on centralized processing, hierarchical cloud–edge structures using traveling-wave acquisition modules and edge gateways [33], as well as edge-assisted approaches based on fuzzy association rules and expert knowledge bases [34], have been developed. Nevertheless, most existing solutions primarily address general power-quality monitoring, event classification, or fault localization [35, 36].

Beyond fault monitoring and localization, accurate energy measurement is also essential for grid stability and efficient energy management. The increasing presence of harmonic distortion in modern power systems necessitates advanced energy meters capable of maintaining accuracy under non-ideal conditions [37]. Standards such as EN 50 470 define procedures for evaluating meter performance under harmonic interference [38]. Precise energy measurements support load forecasting, loss detection, and system optimization [39], with root mean square (RMS)-based techniques such as dual-slope analog-to-digital converters (ADCs) widely used for both linear and nonlinear loads [40]. Time-synchronized data further enhances monitoring, protection, and control functions in distribution networks [41]. Despite these advances, conventional centralized monitoring infrastructures face challenges related to latency, bandwidth consumption, and cybersecurity when transmitting large volumes of raw data to cloud platforms [42–45].

To address these limitations, distributed computing paradigms such as Cloud Computing (CC) and Edge Computing (EC) have gained prominence. While CC offers scalable storage and processing capabilities, it raises concerns regarding data integrity, confidentiality, and availability [42–44]. Edge computing mitigates these challenges by enabling data processing closer to the source, significantly reducing communication latency and network load [45–47]. By distributing computational tasks across devices, edge servers, and IoT endpoints, EC improves responsiveness and resource efficiency in smart grid applications [48, 49]. Edge computing architectures are typically organized into device, edge, and cloud layers, where field devices perform initial measurements and anomaly detection, edge nodes execute localized processing and decision-making, and the cloud layer supports long-term storage and advanced analytics. This hierarchical structure provides low-latency operation, scalability, and enhanced reliability for modern smart grid infrastructures.

Tables I and II provide a comprehensive comparison between existing approaches in the literature and the proposed system. The evaluated studies mainly rely on centralized, offline, or

TABLE I. COMPARISON OF RELATED WORK AND PROPOSED METHOD

Parameter/Ref No.	[50]	[15]	[51]	[52]	[53]
Smart grid use-case	NTEV modeling	Four-wire unbalanced feeders, NTEV estimation	Earth fault selectivity	Harmonics + Distributed Generators (DG) effect on fault	Protection in compensated networks
NTEV focus	Available	Available	NA	NA	NA
Architecture (edge/cloud [central]/hybrid)	Central	Central	Central	Central	Central
Real-time/latency	Offline	~0.8–1.0s	Millisecond transient	Offline	Not real-time
Accuracy/performance	Modeling	Voltage error < 1.2%, NTEV with loading	High accuracy (qualitative)	Qualitative	Zone detection
Inputs & sensors	Voltages, grounding	PMU + pseudo-measurements	Current transient sensors	Currents, harmonics	Currents, voltages
Analytics/method	Dynamic modeling	3-phase admittance + Weighted Least Squares (WLS)	Traveling waves	Harmonic modeling	Multi-frequency admittance
Edge intelligence/local processing	NA	NA	NA	NA	NA
Calibration/self-adjustment	NA	NA	NA	NA	NA
Deployment (simulation/lab/field)	Simulation	Simulation	Simulation + lab	Simulation	Lab-scale
SCADA/communication	NA	PMU only	NA	NA	NA
Main limitations	Only modeling	NA edge, and field validation	NA NTEV, only fault	NA real-time, and NTEV	Only protection, NA NTEV

*Note: NA = not applicable; NTEV = neutral-to-earth voltage; PMU = phasor measurement unit.

simulation-based architectures and exhibit limitations in real-time NTEV measurement, local processing, automatic calibration, and field integration. Although important functions such as fault selectivity, fault detection, and modeling are addressed in some studies, none combines sensor-level local processing with real-time alarm generation at the edge layer. In contrast, the proposed system employs a dual edge–cloud architecture deployed under field conditions, enabling local NTEV evaluation together with cloud-based long-term monitoring and analysis.

Tables III and IV provide an industrial comparison of the proposed smart energy meter–edge gateway (SEM-EG) with representative commercial power-quality and energy-monitoring devices, as well as fault-detection and fault-indication equipment. The comparison considers measurement scope, power-quality and harmonic capabilities, fault-related sensing, local processing and control functions, communication features, and response-related characteristics. Commercial analyzers mainly provide broad power quality, energy, harmonic, and disturbance analysis functions, whereas dedicated fault-detection devices primarily focus on identifying and indicating feeder, ground, overcurrent, and related fault conditions. Unlike these devices, the SEM-EG is not intended for fault location or conventional fault-indication functions; rather, it is designed for continuous NTEV supervision through local evaluation, alarm generation, corrective control, and cloud-supported monitoring. Therefore, it should be regarded as a complementary, application-specific solution rather than a replacement for advanced commercial analyzers or dedicated fault-detection devices.

Its main application is continuous NTEV supervision in low-voltage and retrofit installations, while its current limitations include threshold-based detection and lower waveform and disturbance-analysis capability than high-end commercial analyzers. The novelty of the proposed SEM-EG architecture lies in the integration of calibrated NTEV measurement, multi-parameter energy monitoring, local edge-based threshold evaluation, automatic alarm generation, SCADA/cloud interoperability, and field-verified corrective-action assessment within a single deployable platform. In this architecture, the first-stage NTEV evaluation is performed at the field level, while the cloud layer is used mainly for visualization, historical analysis, and supervisory functions. Thus, the proposed dual-layer edge–cloud architecture enables real-time NTEV monitoring and long-term energy analytics within a deployable framework validated under real field conditions.

Based on this structure, the proposed system executes NTEV analytics directly at the endpoint device using locally measured voltage and current signals, allowing immediate detection of grounding-related anomalies and operational awareness at the field level. Long-term field deployment in an operational low-voltage distribution panel demonstrates that the system can detect time-dependent grounding faults that remain undetected by conventional voltage, current, and power measurements, and that corrective field interventions lead to an approximately 80% reduction in night-time NTEV levels. Under the evaluated

TABLE II. TABLE I CONTINUE

Parameter/Ref No.	[54]	[55]	[56]	[57]	Proposed Work
Smart grid use-case	Selectivity, protection	Intermittent fault detection	NTEV modeling	Faults in isolated Medium-Voltage (MV)	NTEV monitoring, safety alerts, PQ analysis
NTEV focus	NA	NA	NA	NA	Available
Architecture (edge/cloud [central]/ hybrid)	Central	Central	Model only	Central	Hybrid: edge + cloud
Real-time/latency	Offline, Bayesian	Offline	NA real-time	Offline, statistical	Milliseconds at edge, seconds to cloud
Accuracy/performance	High probability	NA	Modeling only	High discrimination	Voltage & current sensors, NTEV probe, local IoT gateway
Inputs & sensors	Currents, admittances	Time-domain signals	Voltages, grounding	Currents, transients	Currents, voltages
Analytics/method	Bayesian inference	Neural network	Circuit model	Spectral, statistical	Event-based analytics, thresholding, anomaly detection
Edge intelligence/local processing	NA	NA	NA	NA	Available—edge device performs local computation & decisions
Calibration/self-adjustment	NA	NA	NA	NA	Available—auto calibration & adaptive thresholding
Deployment (simulation/lab/field)	Simulation	Simulation	Simulation + lab	Simulation	Lab-scale
SCADA/communication	NA	NA	NA	NA	Available—SCADA/ Message Queuing Telemetry Transport (MQTT)/modbus integration
Main limitations	NA real-time, and field test	NA NTEV, and real-time measurement	NA deployment	NA NTEV, and edge	Limited to monitored feeders; requires gateway

*Note: NA = not applicable; NTEV = neutral-to-earth voltage; PQ = power quality.

test conditions, the architecture reduced the average alarm generation latency by up to approximately 78% compared with a cloud-only decision workflow, while current and voltage data acquisition and processing required approximately 500 ms on average. In addition, local filtering and event-triggered reporting reduced unnecessary communication traffic by transmitting processed measurement and alarm information instead of relying solely on continuous raw data forwarding.

II. System Overview

A. Hardware Architecture

The SEM-EG is a set of hardware and systems for industrial and commercial environments, combining energy monitoring methods with EC technology. In addition to traditional energy measurement, NTEV measurements are also integrated. The device analyzes measurement data locally using EC and transmits only processed event or action information to SCADA/cloud platforms, thereby reducing network traffic and computational load. Smart energy meter–edge gateway (SEM-EG) uses protocols such as IEC 60 870-5-104 and Modbus TCP/IP for integration with SCADA infrastructures. Communication with cloud-based platforms is achieved through communication protocols such as MQTT and Representational State Transfer Application Programming Interface (RESTful APIs). Data collection from external analyzers, measuring instruments, and sensors takes place via RS-485 connection. As a result, SEM-EG improves operational efficiency and supports faster decision-making processes. It acts as an adaptive platform that improves responsiveness in energy management applications. Fig. 1 shows the architecture of the device and possible deployment scenarios.

SEM-EG analyzes the signals measured between the neutral and earth conductors and continuously monitors NTEV values in real time. This functionality enables timely detection of NTEV anomalies associated with stray voltage conditions, early-stage grounding imbalances, leakage paths, or network inefficiencies. By evaluating NTEV values against predefined thresholds at the field level, the system supports electrical safety, assessment of earthing system effectiveness, predictive maintenance, and improved energy efficiency. When abnormal operating conditions are detected, the system can generate local alarms, initiate control actions through its digital outputs, and transmit processed event information to SCADA or cloud platforms for supervision, visualization, and user notification through channels such as SMS and email. This dual-layer edge–cloud structure reduces unnecessary data transmission while improving responsiveness, operational reliability, and centralized monitoring capability. Table V presents the SEM-EG as a low-power edge-processing and metering platform. The ESP32 microcontroller is used for local edge processing, communication, alarm management, and control functions. Precision voltage, current, and energy measurements are performed by a dedicated external energy-metering

TABLE III. FUNCTIONAL AND QUANTITATIVE COMPARISON OF THE SEM-EG WITH COMMERCIAL PQ, ENERGY-MONITORING, AND FAULT-DETECTION DEVICES

Parameter	Schneider PowerLogic ION9000 [58]	Janitza UMG 512-PRO [59]	Siemens SENTRON PAC4200 [60]	ABB M4M 30 [61]
Primary monitoring focus	Advanced energy and PQ monitoring	Class A PQ and residual-current monitoring	Electrical variables, energy, and PQ monitoring	Network, energy, and PQ monitoring
Dedicated NTEV measurement and decision function	Not identified in reviewed public documentation	Not identified in reviewed public documentation	Not identified in reviewed public documentation	Not identified in reviewed public documentation
Ground-related sensing	No dedicated ground-related sensor identified; standard voltage/current inputs	Two residual-current inputs; external residual-current transformer required	No dedicated ground-related sensor identified; standard voltage/current inputs	No dedicated ground-related sensor identified; standard voltage/current inputs
Active-energy accuracy class	Class 0.1S according to IEC 62053-22	Class 0.2S for 5 A current-transformer input	Class 0.2S according to IEC 62053-22	Class 0.5S according to IEC 62053-22
Harmonic analysis	Harmonic analysis up to the 63rd order	Harmonic and interharmonic analysis up to the 63rd order	Harmonic analysis from the second to the 64th order	True-root mean square (RMS) measurement up to the 40th harmonic
Published sampling or processing metric	Waveform capture up to 1024 samples/cycle	25.6 kHz continuous sampling; 512 measurement points/cycle; transient recording above 39 µs	No directly comparable metric used in this comparison	128 samples/cycle
Local alarm/event processing	Available	Available	Available	Available
Local control capability	Digital I/O available; configuration-dependent	Two digital outputs	Optional DI/DQ expansion	Programmable I/O; model-dependent
Main communication capabilities	Modbus Transmission Control Protocol (TCP)/Remote Terminal Unit (RTU), Distributed Network Protocol 3 (DNP3), IEC 61850, and ION protocols	Ethernet, Modbus TCP/RTU, Process Field Bus, and optional Building Automation and Control Networks (BACnet)	Modbus TCP, optional Modbus RTU, Process Field Bus, Process Field Network, Digital Input (DI) and Digital Output (DO)	Modbus TCP/RTU, BACnet, Process Field Bus, depending on model
Detectable events/abnormalities	PQ disturbances, transients, sags/swells, harmonics, and configurable events	PQ disturbances, residual-current conditions, transients, and configurable threshold events	Electrical limit violations, harmonics, and configurable events	Electrical limit violations, harmonics, and configurable alarm events
Processing approach/complexity	Manufacturer-specific embedded processing; computational complexity not publicly disclosed	Manufacturer-specific PQ and RCM processing; computational complexity not publicly disclosed	Embedded measurement and limit evaluation; computational complexity not publicly disclosed	Embedded measurement and alarm evaluation; computational complexity not publicly disclosed
Implementation considerations	High-end analyzer; configuration, optional I/O, and software integration depend on the deployment	External residual-current transformers are required for RCM functionality	Industrial meter with optional communication and I/O modules	Model- and communication-option-dependent
NTEV-specific field validation	Not reported in reviewed public documentation	Not reported in reviewed public documentation	Not reported in reviewed public documentation	Not reported in reviewed public documentation

Note: NTEV = neutral-to-earth voltage; PQ = power quality; SEM-EG = smart energy meter–edge gateway.

TABLE IV. TABLE III CONTINUE

Parameter	Siemens SICAM Fault Sensor Indicator (FSI) V2.0 [62]	Schneider Easergy Flair 23DM [63]	Proposed SEM-EG
Primary monitoring focus	Fault detection and localization in MV overhead lines	Fault passage indication and voltage detection in MV underground networks	NTEV and multi-parameter energy monitoring
Dedicated NTEV measurement and decision function	Not identified in reviewed public documentation	Not identified in reviewed public documentation	Available
Ground-related sensing	Continuous phase-current measurement with phase-fault and ground-fault detection	Earth-fault current detection using external current sensing	Direct NTEV sensing
Active-energy accuracy class	Not applicable	Not applicable	Class 0.5S-related performance of the calibrated external metering chain
Harmonic analysis	Not identified in reviewed public documentation	Not identified in reviewed public documentation	Harmonic analysis up to the 32nd order
Published sampling or processing metric	No directly comparable response-time metric identified	No directly comparable response-time metric identified	Approximately 500 ms local acquisition and processing
Local alarm/event processing	Available	Available	Available
Local control capability	Not identified; the device is primarily a fault indicator	Voltage-detection relay output available	2 relay outputs
Main communication capabilities	Local LED indication	Modbus	MQTT, Modbus TCP/IP, IEC 60 870-5-104, and REST
Detectable events / abnormalities	Phase faults, ground faults, temporary faults, and permanent faults	Overcurrent, earth-fault current, and voltage presence or absence	Elevated NTEV, time-dependent grounding anomalies, and configurable electrical threshold events
Processing approach / complexity	Embedded threshold and auto-threshold	Embedded threshold-based fault passage and voltage evaluation	Low-complexity threshold-based edge processing on a dual-core Microcontroller Unit (MCU)
Implementation considerations	Intended for MV overhead lines; typically installed one sensor per phase	Intended for MV underground networks	Compact application-specific platform; direct NTEV connection and site-specific threshold configuration required
NTEV-specific field validation	Not identified in reviewed public documentation	Not identified in reviewed public documentation	95% detection rate; 5% false-alarm ratio; approximately 80% reduction in night-time NTEV

Note: NTEV = neutral-to-earth voltage; SEM-EG = smart energy meter–edge gateway.

integrated circuit and ADC-based analog front end rather than by the internal ADCs of the ESP32. Therefore, the reported IEC 62 053-22 Class 0.5S-related performance refers to the calibrated external metering chain of the SEM-EG.

B. Software Architecture

The SEM-EG integrates EC functionality to locally process current, voltage, frequency, and NTEV data acquired through a dedicated external energy-metering integrated circuit and associated metering circuit. Electrical parameters are sampled from multiple points in the power grid, digitized by the metering stage, and analyzed within the EC framework for local threshold evaluation, anomaly detection, alarm generation, and control-oriented decision-making. This local processing capability enables low-latency fault detection compared to centralized cloud-based processing while reducing dependency on continuous cloud connectivity. The NTEV control flowchart, illustrated in Fig. 2, outlines this step-by-step local monitoring and analysis process.

Measured data are continuously transmitted to the cloud layer via the MQTT protocol for long-term storage, anomaly detection, and alarm management. Neutral-to-earth voltage (NTEV) levels are evaluated against user-defined thresholds by triggering notifications upon threshold violations while SEM-EG maintains uninterrupted local monitoring. The integration of EC reduces communication overhead and dependency on cloud resources, improving responsiveness and system reliability. Additionally, SEM-EG supports flexible communication through MQTT and Modbus protocols, enabling structured data exchange for monitoring and control functions while ensuring secure and efficient operation.

B.1. SCADA Integration

The integration of SCADA systems is a key capability of the SEM-EG architecture, enabling real-time data acquisition, monitoring, and control. By incorporating EC, SEM-EG performs local processing of current, voltage, and NTEV measurements and transmits only

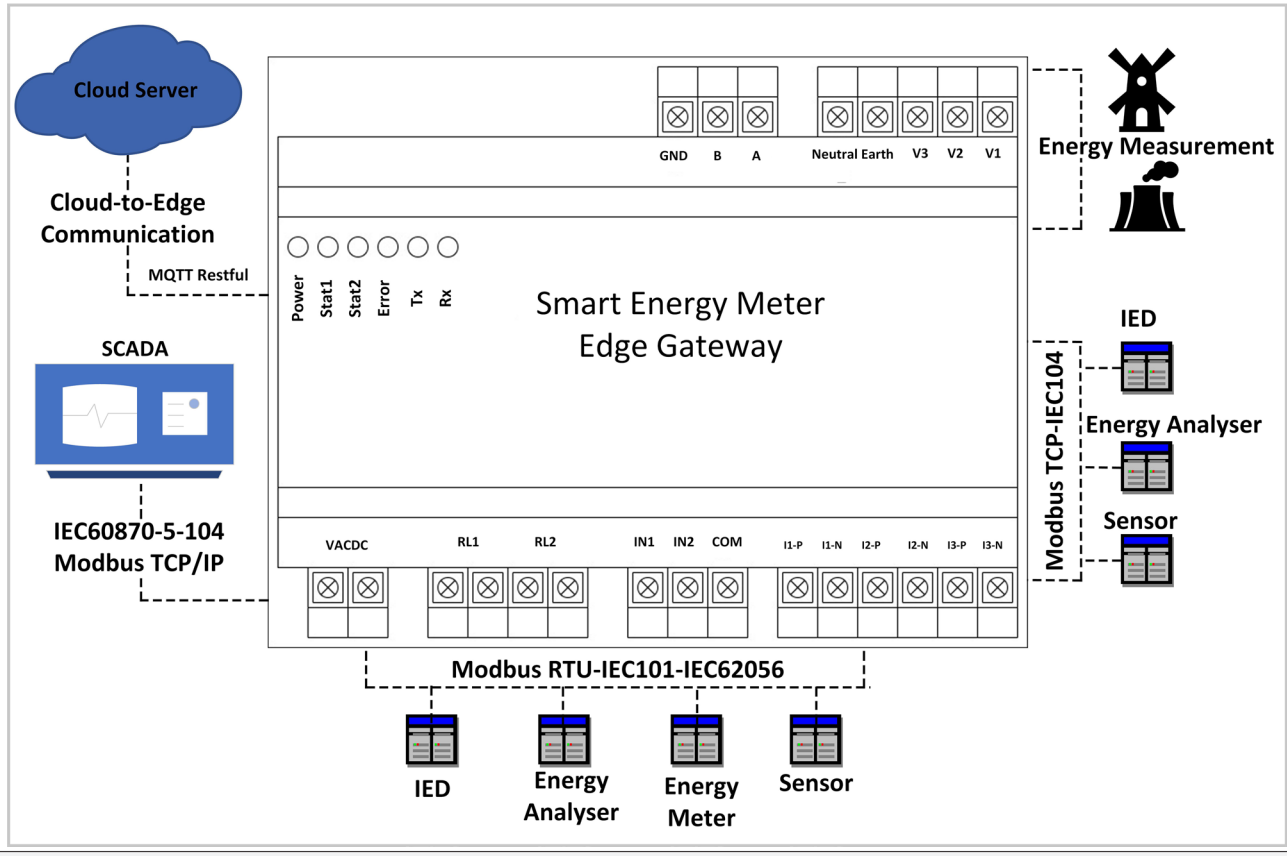


Fig. 1. Device connection diagram and applications of SEM-EG. Note: SEM-EG = smart energy meter–edge gateway.

processed results to SCADA platforms, significantly reducing communication latency, bandwidth usage, and improving system responsiveness. Meanwhile, the CC infrastructure serves as a centralized platform for long-term data storage and advanced analysis.

SCADA and cloud integration is achieved using MQTT, a lightweight publish–subscribe protocol widely adopted in IoT and industrial applications [64–66]. Smart energy meter–edge gateway (SEM-EG) periodically publishes essential electrical parameters, including energy consumption, voltage, current, and phase angle, to an MQTT broker, allowing subscribed SCADA and cloud systems to access real-time measurements. Local data filtering and analysis within the EC layer ensure that only relevant and actionable information is transmitted, thereby optimizing network efficiency and overall system performance. From a reliability and scalability perspective, local threshold evaluation allows the SEM-EG to maintain NTEV alarm generation during temporary communication interruptions, while event-based reporting reduces the amount of data transmitted to the cloud as the number of deployed devices increases. Additionally, SEM-EG supports remote digital I/O control via MQTT-based messages, enabling functions such as relay activation during high NTEV conditions or load shedding in critical events. MQTT messages are formatted in JavaScript Object Notation (JSON), facilitating seamless integration with SCADA and cloud-based energy management platforms. Multiple Quality of Service (QoS) levels and optional Transport Layer Security (TLS)/Secure Sockets Layer (SSL)-based security mechanisms further enhance communication reliability and data integrity. In the evaluated configuration, the system operates with QoS level 0 to meet real-time, low-latency monitoring requirements.

For secure smart grid deployment, the communication layer is supported by TLS/SSL-based MQTT communication, device-level authentication, and restricted network access mechanisms. Each SEM-EG device can be configured with unique credentials or certificate-based identities to prevent unauthorized access and false data injection. In addition, firewall rules, Virtual Private Network (VPN) tunnels, or private APN-based cellular communication provide network isolation from public networks, while role-based access control protects configuration parameters, alarm thresholds, and remote-control functions.

B.2. Neutral-to-Earth Voltage Measurement

In one of the circuit models used to describe disturbances in the NTEV profile, the equipment body is represented in (1) as Z_e, an impedance between the neutral conductor and the earthing system. This equivalent impedance model is used to explain the physical relationship between the grounding path, leakage components, neutral current, and the resulting NTEV behavior. This impedance consists of a resistor and a capacitor connected in parallel. Therefore, Fig. 3 illustrates the impedance Z_e which acts as a bridge connection between the neutral conductor and the earthing system, Fig. 4 shows the current flow directions. The general grounding impedance in the earthing system used to define the NTEV profile is Z_g, expressed in (2), and the combination of these two impedances is expressed as follows.

TABLE V. TECHNICAL AND FUNCTIONAL SPECIFICATIONS OF THE PROPOSED SEM-EG DEVICE

Subsystem	Parameter	Specification	Compliance
Power supply	Input voltage range	85–265 Volts Alternating Current (VAC)	Wide-range operation for diverse grid conditions
NTEV focus	Nominal supply voltage	220 VAC	Single-phase
Architecture (edge/cloud [central]/ hybrid)	Average power consumption	3 W	Suitable for energy-constrained installations
Real-time/latency	Average current consumption	0.3 A	Nominal operating conditions
Processing unit	Main processor	ESP-32 dual core MCU	Edge processing, communication and control
	Flash memory	16 MB	Local data buffering and firmware storage
	RAM	8 MB	Real-time data processing
	Watchdog timer	System reset (5 s)	Fault recovery and autonomous operation
	Real-time clock (RTC)	Available	Time-stamped measurements
Communication	Wireless connectivity	Wi-Fi (IEEE 802.11 b/g/n)	Local and cloud connectivity
	Cellular connectivity	4G GSM (900/1800 MHz)	Remote and backup communication
	Communication protocols	MQTT, Modbus TCP/IP	SCADA and IoT interoperability
	Wi-Fi operating modes	Station/softAP/hybrid	Flexible network deployment
	Maximum connections	Up to 6 clients	Multi-node monitoring capability
Interfaces	Serial communication	RS-485 (1×)	Industrial fieldbus interface
Security & networking	Wireless security	WPA/WPA2	Encrypted communication
	Network stack	IPv4, TCP/UDP, HTTP, FTP	Standard IP-based communication
	MQTT security	TLS/SSL support	Secure SCADA/cloud data exchange
	Network access control	VPN/private APN/firewall support	Restricted smart grid deployment
Certification	RF compliance	FCC, CE (RED), IC, NCC, KCC, TELEC	Global regulatory conformity
	Wi-Fi certification	Wi-Fi alliance	Interoperability assurance
Digital I/O	Digital inputs	2 (0–24 VDC, 1.5 mA/input)	Optically isolated
	Digital outputs	2 (relay, dry contact)	Magnetically isolated
Measurement	Measurement configuration	Single-phase/three-phase (3P, 3P + N)	Flexible deployment
	Voltage measurement range	0–665 VAC	Phase-neutral
	Frequency measurement range	45–65 Hz	Grid-frequency monitoring
	Harmonic analysis	Up to 32nd order	PQ assessment
	Voltage/current accuracy	±0.5%	Achieved through calibrated external metering chain
	Energy accuracy	IEC 6205 322 Class 0.5S	Refers to calibrated external metering chain
	Sensitivity class	IEC 61 000-4-30 Class S	PQ measurements
	Advanced measurements	Outage, max demand values	Event-based analysis
Alarms & control	Programmable alarms	Voltage and current thresholds	Event-driven response

Note: NTEV = neutral-to-earth voltage; PQ = power quality; RTC = real time clock; SEM-EG = smart energy meter–edge gateway.

$$Z_e = \frac{R^* \frac{1}{jwC}}{R + \frac{1}{jwC}} = \frac{R}{1+(wRC)^2} - jw^* \frac{R^2 C}{1+(wRC)^2}, \quad (1)$$

$$Z_g = jwL + \frac{R^* \frac{1}{jwC}}{R + \frac{1}{jwC}}, \quad (2)$$

The vector equivalent of the magnitudes of the grounding system resistance for Z_e and Z_g are given in (1) and (3).

$$Z_g = \frac{R}{1+(wRC)^2} + jw^* \frac{L - R^2 C + (wRC)^2 L}{1+(wRC)^2}, \quad (3)$$

$$Z_{Gn} = Z_e + Z_g = \frac{2R}{1+(wRC)^2} + jw^* \left(L - \frac{2R^2 C}{1+(wRC)^2} \right), \quad (4)$$

The current load, I_L, symbolised as the earth current, I_G, and the neutral current, I_N, are transmitted as shown in (6). Under unbalanced operating conditions, the neutral current is formed by the phasor combination of the load current components. The impedance in the earthing system, Z_g and Z_e, must be combined to produce Z_{Gn} as specified in (4) to define the NTEV profile [67]. This impedance-based representation clarifies the relationship between grounding impedance, leakage paths, neutral current components, and the resulting NTEV behavior.

$$I_{NL} = I_{A_n} \angle \vartheta_{A_n} + I_{B_n} \angle \vartheta_{B_n} + I_{C_n} \angle \vartheta_{C_n} + \ldots, \quad (5)$$

$$I_{NL} = I_{G_n} \angle \vartheta_{G_n} + I_{N_n} \angle \vartheta_{N_n}, \quad (6)$$

where, $n = 1,2,\ldots,N$, (7)

The neutral current is affected by the vector sum of load currents under unbalanced operating conditions. Therefore, the total load current can be expressed as the phasor sum of the phase or branch

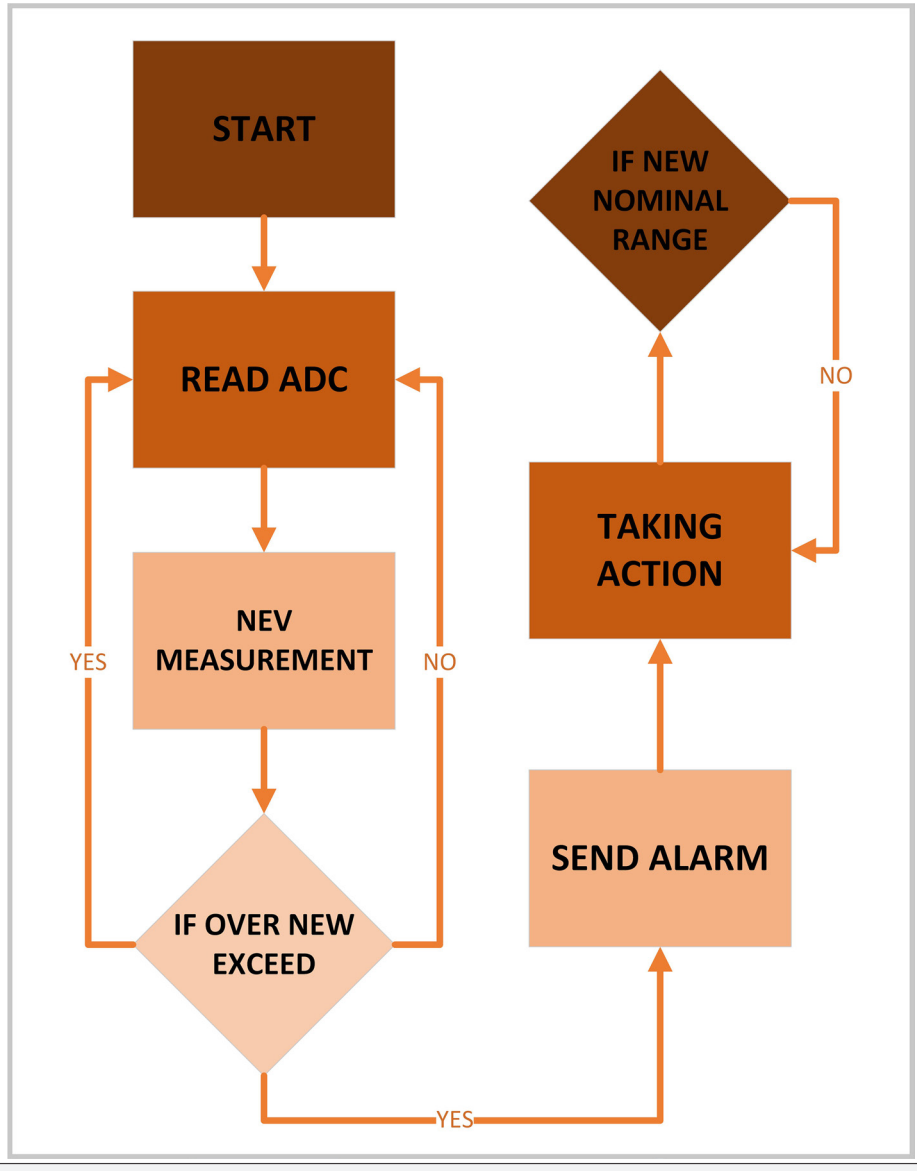


Fig. 2. NTEV control flowchart. Note: NTEV = neutral-to-earth voltage.

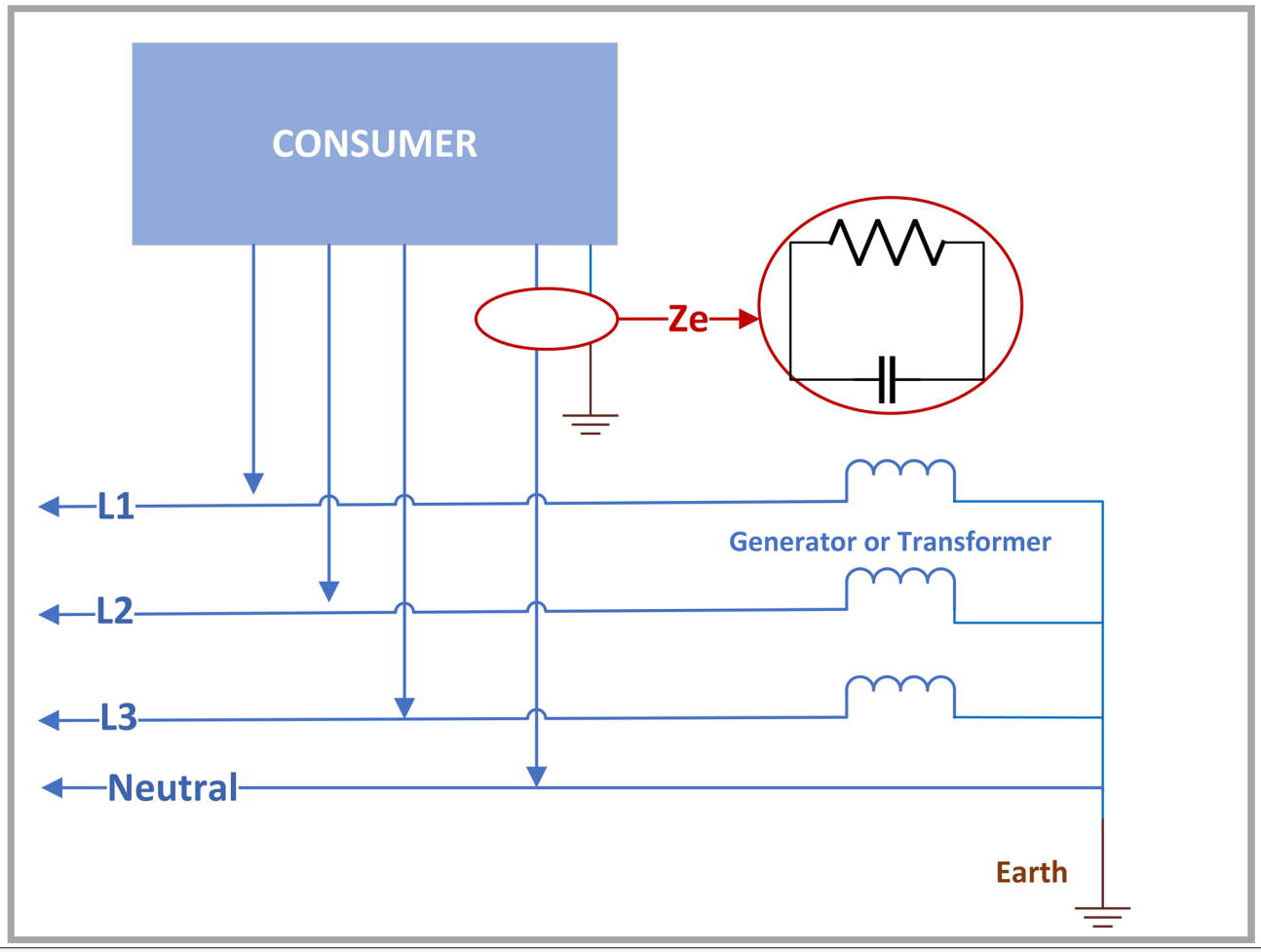


Fig. 3. Earthing system in commercial building [67].

current components. The neutral-to-earth current component is then represented by the contribution of the earth current and the neutral current components, as given in (5)–(7).

The NTEV profile in normal operation can be written as in (8) and (9) [50]:

$$Z_{Gn} = \frac{NTEV_n}{I_{Gn}} = \frac{NTEV_n}{I_{N_n} - I_{NL}}, \tag{8}$$

$$NTEV_n = I_{Gn} * Z_{GS_n}, \tag{9}$$

$$NTEV_n = I_{G_n}\left(\frac{2R_n}{1+(wR_nC_n)^2} + jw*\left(L - \frac{2R_n{}^2C_n}{1+(wR_nC_n)^2}\right)\right), \tag{10}$$

The SEM-EG provides high-precision NTEV measurements, which are locally analyzed using EC to enable rapid detection of potential

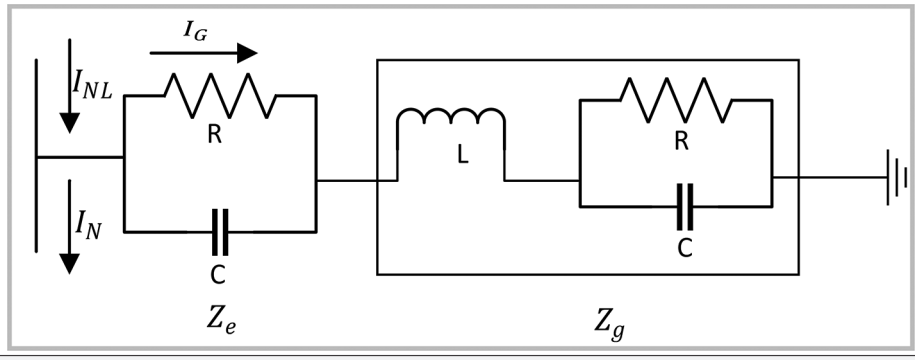


Fig. 4. Neutral current flows [50].

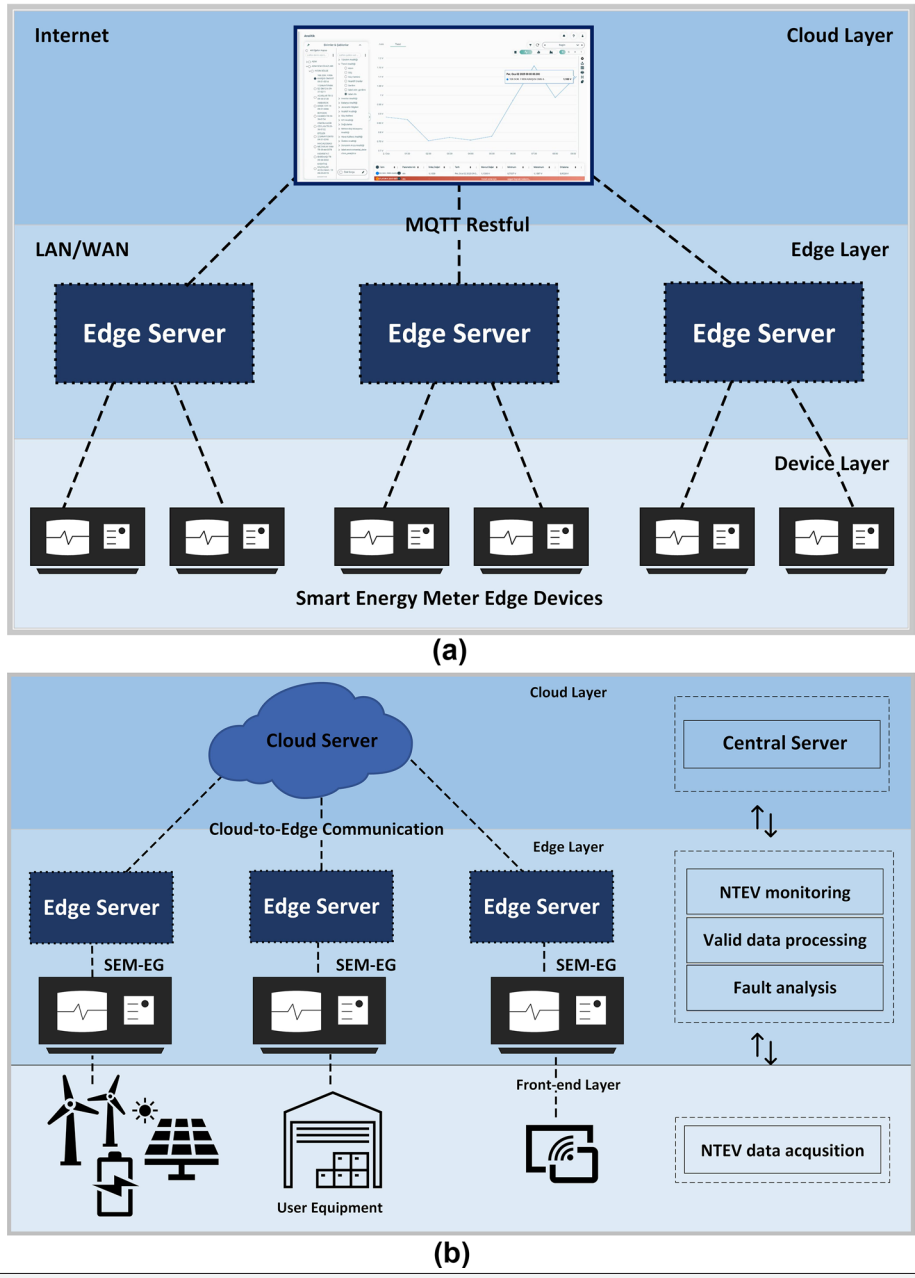


Fig. 5. (a) System topology and edge-cloud communication architecture; (b) Functional architecture showing local NTEV measurement and data processing. Note: NTEV = neutral-to-earth voltage.

safety issues and timely corrective actions. Processed measurement data are selectively transmitted to the cloud for long-term storage and historical analysis, forming a dual-layer edge–cloud architecture that enhances latency performance, cybersecurity, and data management efficiency. Fig. 5(a) presents the overall edge–cloud system topology, while Fig. 5(b) illustrates the corresponding functional architecture.

Smart energy meter–edge gateway integrates real-time measurement, local analytics, and autonomous control within an EC architecture, enabling low-latency anomaly detection and rapid response without reliance on centralized processing. Operating in a three-layer device–edge–cloud architecture, the system performs on-device evaluation of critical electrical parameters and transmits filtered data to the cloud via MQTT for scalable monitoring and long-term analysis. Smart energy meter–edge gateway provides instantaneous, autonomous response based on user-defined thresholds, particularly for NTEV, enabling local control actions such as alarm activation or load isolation without external commands. Time-based trend analysis and a structured event mechanism enhance anomaly detection and traceability, while the threshold-based event evaluation reduced false alarms from 12% in the rule-based approach to 5% and achieved a 95% event-level detection rate. The latency performance was evaluated under the tested operating conditions, where the SEM-EG performed current and voltage data acquisition and local processing in approximately 500 ms on average, supporting

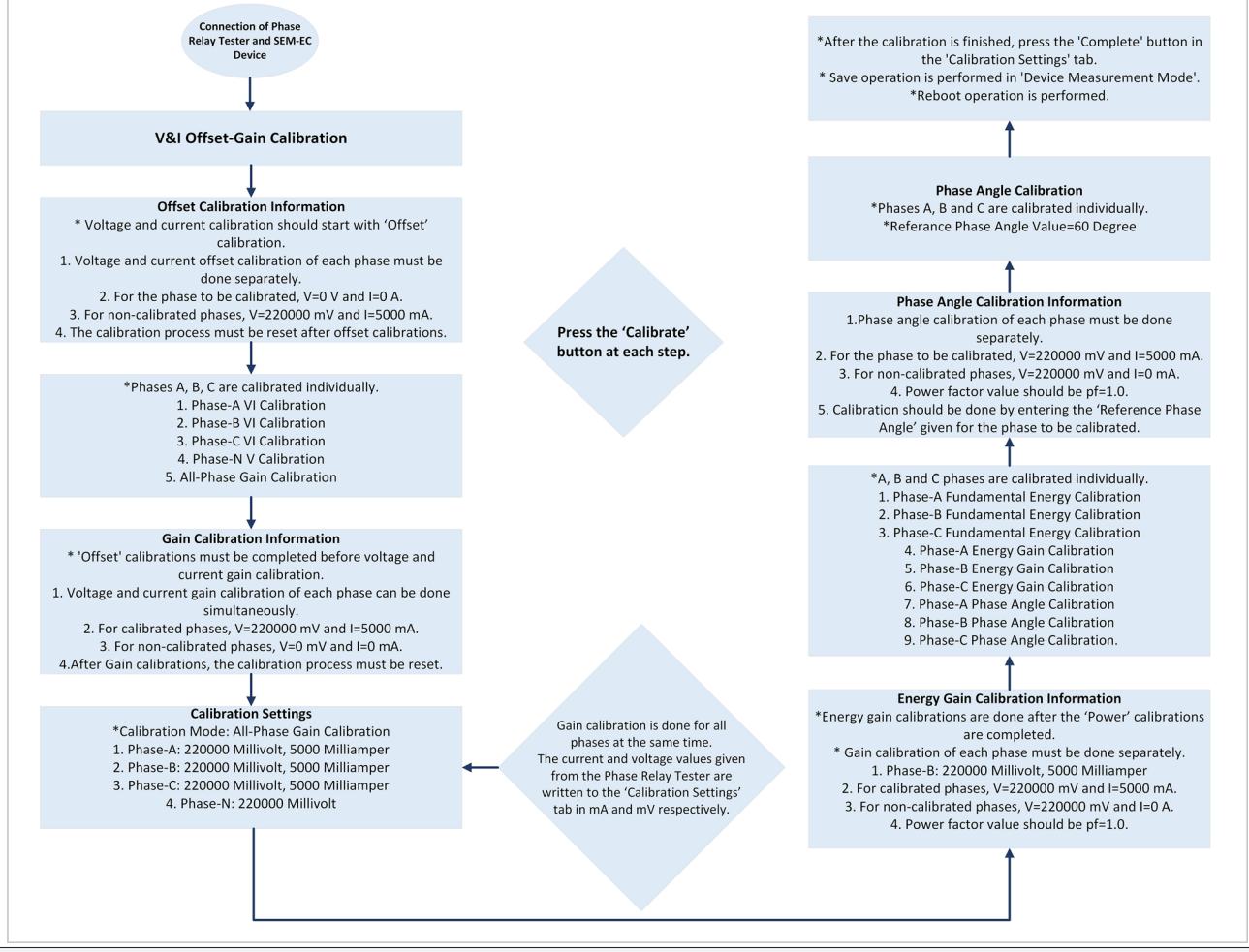


Fig. 6. SEM-EG calibration process. Note: SEM-EG = smart energy meter–edge gateway.

faster edge-side decision-making without relying solely on cloud-side evaluation. Supporting vertical and horizontal communication, SEM-EG enables distributed decision-making and reliable operation in multi-device smart grid environments.

B.3. Calibration Process

Accurate calibration is essential for ensuring high-precision electrical measurements, regulatory compliance, and reliable edge-based decision-making in smart grid applications. The SEM-EG employs a multi-stage, phase-specific calibration process executed locally within the Edge Computing framework, comprising the following steps:

- Voltage and Current Offset Calibration (V&I Offset),
- Voltage and Current Gain Calibration (V&I Gain—All Phase Gain),
- Energy Gain Calibrations,
- Phase Angle Calibration.

The SEM-EG utilizes a multi-stage calibration process to ensure precise and repeatable measurements of voltage, power, and phase angle across all electrical phases, in compliance with IEC standards. The calibration workflow, illustrated in Fig. 6, resulted in a reduction of the average active power measurement error from 1.8% to 0.5%. Voltage measurement error decreased from ±1.2% to ±0.4%, while current measurement error decreased from ±1.5% to ±0.5%.

Overall, the applied calibration steps achieved an approximate 70% improvement in measurement accuracy, as summarized in Table VI.

TABLE VI. MEASUREMENT ERROR COMPARISON BEFORE AND AFTER CALIBRATION

Parameter (%)	Uncalibrated Error	After Calibration
Voltage	1.2	0.4
Current	1.5	0.5
Active power	1.8	0.5
Reactive power	2.0	0.6
Energy	1.6	0.5

III. APPLICATION RESULTS

The proposed SEM-EG system was evaluated through field deployments to assess its operational performance under real-world conditions. The application results focus on two complementary aspects of the proposed architecture. First, the capability of the system to perform autonomous

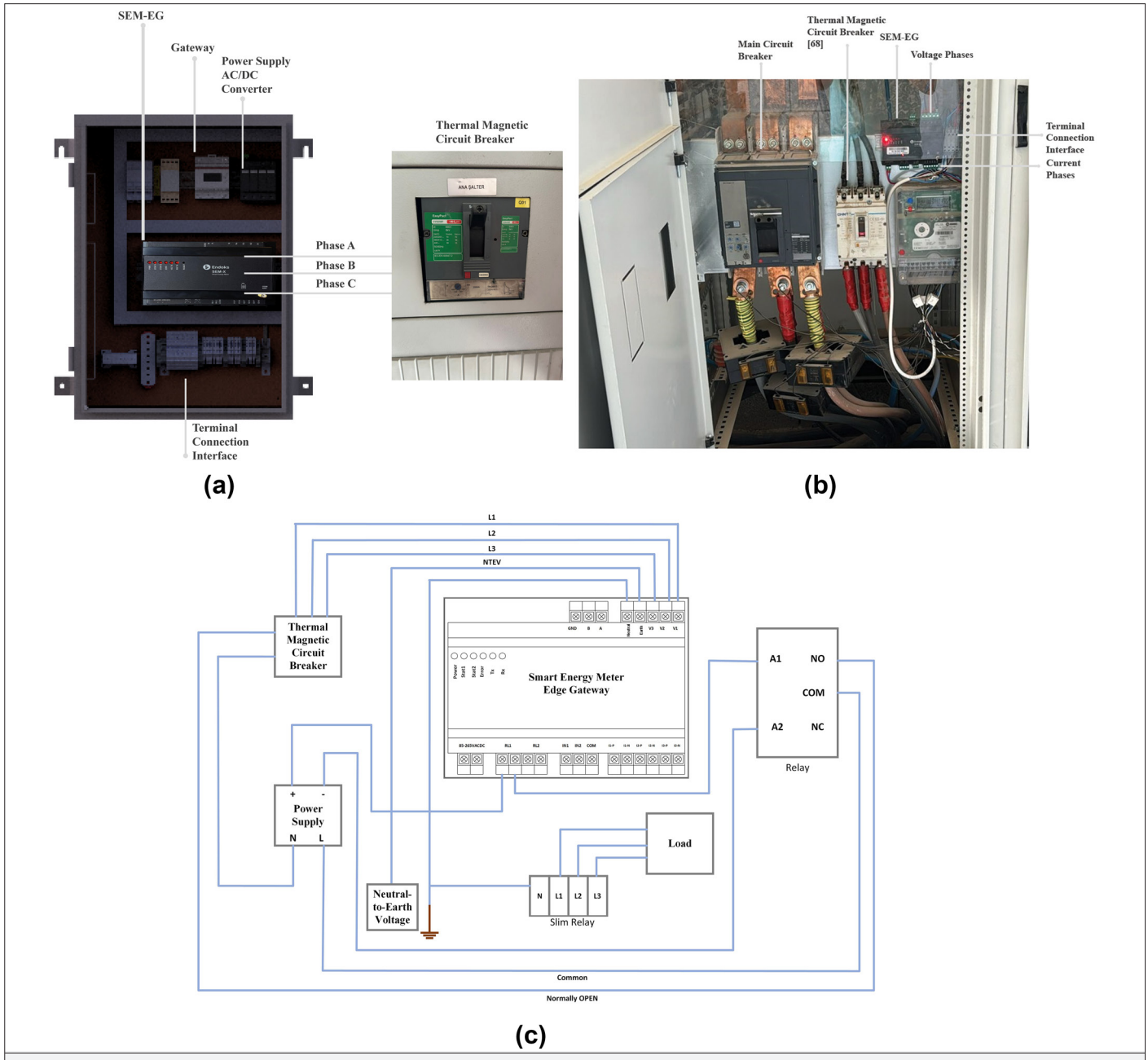


Fig. 7. (a) SEM-EG-based EC architecture for NTEV measurement and thermal magnetic circuit breaker (TMCB) control; (b) Field implementation of the SEM-EG system inside a distribution panel; (c) Connection diagram showing NTEV sensing and relay-controlled TMCB operation. Note: NTEV = neutral-to-earth voltage; SEM-EG = smart energy meter–edge gateway; TMCB = thermal magnetic circuit breaker.

local switching operations using EC is examined. Second, the effectiveness of continuous NTEV monitoring in improving operational safety and fault awareness is evaluated. The system was installed in operational low-voltage distribution and tested under actual load profiles, environmental conditions, and network constraints. This section presents the implementation details, operational behavior, and observed field outcomes of the proposed edge-enabled monitoring and control approach.

A. Edge-Based Local Switching and Operational Validation

Thermal magnetic circuit breakers (TMCBs) [68] are critical protection devices in low-voltage distribution systems, typically operated through centralized control or manual intervention, which may introduce delays in safety-critical conditions. In the proposed architecture, TMCB switching operations are autonomously managed at the field level by the SEM-EG using an EC approach.

The NTEV signal is locally processed within the embedded EC unit and evaluated against predefined safety thresholds stored on the device. Based on this local evaluation, the operational state of the TMCB is determined directly at the edge layer without reliance on cloud-based processing or external supervisory commands.

When the measured NTEV exceeds the configured threshold, the SEM-EG activates an external relay through its digital output

interface, enabling autonomous opening or closing of the TMCB to isolate faulty loads or restore normal operation once safe conditions are re-established. The complete control sequence, measurement, decision-making, and actuation is executed locally, ensuring deterministic response and minimal latency. The overall system configuration and electrical connections are illustrated in Fig. 7(a) and Fig. 7(b), while Fig. 7(c) presents the field implementation within an operational distribution panel. Field tests confirm that the SEM-EG reliably performs NTEV-based autonomous switching without dependence on centralized systems, improving response time and operational resilience under communication-limited conditions.

B. Field Validation and Long-Term Neutral-to-Earth Voltage-Based Fault Detection

The field performance of the SEM-EG device was evaluated through a long-term deployment in an operational low-voltage distribution environment. The system was installed on-site and operated continuously for approximately 45 days to assess its ability to perform real-time monitoring, anomaly detection, and operational



Fig. 8. SEM-EG mounted on distribution panel. Note: SEM-EG = smart energy meter–edge gateway.

TABLE VII. FIELD MEASUREMENT DATASET FOR NTEV, CURRENT, VOLTAGE, AND POWER ANALYSIS

General				
Neutral-to-earth voltage			2178 Milivolt	
Frequency			50.01 Hertz	
Temperature			22 Celcius	
Power				
	All phase	Phase-1	Phase-2	Phase-3
Power factor	1	0.993	1	1
Active power (Watt)	83 312	24 842	26 814	31 655
Reactive power (VAR)	−1985	−2611	514	110
Apparent power (VA)	83 453	24 978	26 819	31 655
V & I				
		Phase-1	Phase-2	Phase-3
Current (Miliamper)		103 357	111 251	132 117
Phase-neutral voltage (Milivolt)		227 078	226 542	226 540
Phase-phase voltage (Milivolt)		399 729	387 679	390 802
Angle				
		Phase-1	Phase-2	Phase-3
V & I phase angle (degree)		−6	1.1	0.2
Phase-phase angle (degree)		119.8	120.6	119.6
Metering				
Forward metering values				
	All Phase	Phase-1	Phase-2	Phase-3
Active energy (Watt/hour)	58 646 796	18 186 226	18 794 088	21 665 918
Reactive energy (VAR/hour)	4 767 622	1 699 547	2 528 926	829 836
Active harmonic energy (Watt/hour)	0	19 407	10 588	0
Active fundamental energy (Watt/hour)	58 931 860	18 166 774	18 783 856	21 979 928
Reverse metering values				
	All phase	Phase-1	Phase-2	Phase-3
Active energy (Watt/hour)	0	1286	0	0
Reactive energy (VAR/hour)	255 506	169 460	59 733	314 110
Active harmonic energy (Watt/hour)	284 433	0	423	314 277
Active fundamental energy (Watt/hour)	0	1286	0	0
Apparent metering values				
	All phase	Phase-1	Phase-2	Phase-3
Apparent energy (VA/hour)	59 054 480	18 347 148	18 976 556	21 727 984

decision support under actual load and environmental conditions. Throughout the deployment period, the SEM-EG demonstrated stable operation in terms of data acquisition, local edge processing, and secure data transmission, confirming its suitability for field-level monitoring and decision-making.

During normal daytime operation, the measured NTEV values remained within expected limits, indicating stable grounding conditions. In contrast, consistently elevated NTEV values were observed during nighttime periods, revealing a clear and repeatable day–night pattern. This behavior indicated the presence of a time-dependent abnormal condition rather than sporadic disturbances or measurement noise. The SEM-EG detected these abnormal NTEV levels in real time using its embedded threshold-based evaluation logic and recorded them as exceedance events, enabling early identification of a potential grounding-related safety issue. The overall field deployment configuration and the corresponding measurement dataset are summarized in Fig. 8 and Table VII, respectively, which form the basis for the subsequent NTEV, voltage, current, and power analyses.

Following the repeated detection of night-time NTEV anomalies, a detailed on-site inspection was conducted to identify the root cause of the observed behavior. The investigation revealed a fault condition associated with the lighting circuit, where the lighting cable intermittently contacted the pole structure, creating an unintended conductive path to earth when the lighting system was energized. This condition resulted in elevated NTEV levels during night-time operation, with measured values exceeding predefined safety thresholds and reaching approximately 2178 mV. These exceedances were detected and reported by the SEM-EG in real time through edge-based processing, allowing early awareness of a hidden grounding fault before any visible failure or conventional protection mechanism was triggered.

After confirming the fault condition through field inspection, the detection performance of the SEM-EG was evaluated at the event level using the identified abnormal NTEV intervals. Since the implemented detection mechanism is based on local threshold evaluation rather than a trained classification model, the performance assessment was carried out by comparing the alarm records generated by the SEM-EG with abnormal NTEV intervals identified through long-term trend analysis and confirmed by on-site inspection. A true positive was defined as an alarm generated during an abnormal NTEV interval, whereas a false negative was defined as an abnormal interval without a corresponding alarm. A false positive was defined as an alarm generated outside the identified abnormal intervals. The resulting event-level detection statistics are summarized in Table VIII.

The corresponding voltage and current records showed that their magnitudes largely remained within nominal ranges; however, temporal fluctuations and phase deviations were observed prior to corrective actions. These observations indicate that grounding abnormalities can influence system stability and PQ without necessarily activating traditional protection devices. The analysis of voltage–current phase angles and phase-to-phase relationships further supported accurate power factor assessment and synchronization evaluation, contributing to a comprehensive understanding of system behavior during the fault condition.

Following the identification of the grounding-related fault, corrective field interventions were implemented to eliminate the unintended conductive path, resulting in a substantial and sustained reduction in NTEV levels during both daytime and night-time operation.

TABLE VIII. EVENT-LEVEL DETECTION PERFORMANCE OF THE SEM-EG DURING FIELD DEPLOYMENT

Metric	Description	Value
Field monitoring duration	Continuous field operation used for NTEV monitoring	45 days
Measurement interval	SEM-EG acquisition interval during testing	1 s
Detection method	Local edge-based NTEV threshold evaluation	Threshold-based
Ground-truth verification	Verification of abnormal NTEV behavior	Long-term trend analysis and on-site inspection
Verified abnormal condition	Identified root cause	Lighting circuit contact with pole structure
Maximum observed NTEV	Peak NTEV during abnormal night-time operation	2178 mV
Verified anomaly events/windows	Field-verified abnormal NTEV intervals	20
Correctly detected events/windows, True Positive (TP)	Alarm generated during verified abnormal interval	19
Missed events/windows, False Negative (FN)	Verified abnormal interval without alarm	1
False alarm events, False Positive (FP)	Alarm outside verified abnormal interval	1
Event detection rate	19 correctly detected abnormal events out of 20 verified abnormal events (TP/[TP + FN] × 100)	95%
False alarm ratio	1 false alarm out of 20 alarm events (FP/[TP + FP] × 100)	5%
Post-correction improvement	Reduction in average night-time NTEV after field intervention	≈80%

Note: NTEV = neutral-to-earth voltage; SEM-EG = smart energy meter–edge gateway.

A quantitative comparison of measurements before and after the intervention shows that average night-time NTEV levels were reduced by approximately 80%, confirming a significant improvement in grounding conditions. This improvement is illustrated in Fig. 9(a) and Fig. 9(b), which show persistently elevated night-time NTEV values prior to the intervention, and in Fig. 9(c), which demonstrates convergence toward normal operating levels following corrective actions. The long-term evolution of NTEV behavior is further presented in Fig. 9(d), where high-resolution data visualized on the central server clearly indicate a sustained change in NTEV behavior after 24 October.

To complement the NTEV-based fault analysis, phase current measurements recorded by the SEM-EG were evaluated before and after the corrective field actions to assess their impact on load behavior. As shown in Fig. 10(a), phase currents measured between 2 September and 22 October exhibit short-term fluctuations and phase-to-phase deviations, while remaining within nominal operating ranges. When interpreted alongside elevated night-time NTEV levels, these variations indicate that the grounding-related anomaly influenced system behavior without triggering conventional overcurrent protection. Following corrective actions, Fig. 10(b) shows reduced short-term current fluctuations during the period from 24 October to 13 November, with average current magnitudes remaining comparable to pre-correction values. This suggests that the intervention primarily mitigated transient current irregularities rather than steady-state current levels. The long-term suppression of current fluctuations after 24 October is further confirmed by cloud-based analysis presented in Fig. 10(c), demonstrating a secondary but measurable improvement in load behavior after eliminating the unintended grounding path.

To assess the indirect impact of the grounding-related fault on PQ, phase voltage measurements recorded by the SEM-EG were analyzed before and after corrective field actions. As shown in Fig. 11(a), phase voltages measured between 2 September and 22 October remain within nominal limits but exhibit temporal fluctuations and intermittent phase-to-phase deviations, consistent with unstable operating conditions observed alongside elevated night-time NTEV levels. Following corrective actions, Fig. 11(b) demonstrates a clear reduction in short-term voltage fluctuations during the period from 24 October to 13 November, with improved uniformity across all phases. The sustained stabilization of voltage profiles after 24 October is further confirmed by cloud-based analysis presented in Fig. 11(c), validating the consistency between edge-level measurements and long-term centralized visualization.

Beyond voltage and current profiles, power-related parameters were analyzed to assess load behavior and overall system performance. As shown in Fig. 12(a), active power exhibits moderate fluctuations consistent with normal load dynamics and remains within expected operational ranges, indicating no sustained disturbance associated with the grounding-related fault. The apparent power profile in Fig. 12(b) shows a gradual and consistent increase over time, reflecting cumulative load demand rather than abnormal operating conditions. Power factor measurements presented in Fig. 12(c) remain close to unity throughout the monitoring period, with only minor short-term deviations, indicating efficient energy utilization and balanced load conditions. These results confirm that the detected anomaly primarily affected NTEV behavior and grounding integrity, without causing significant degradation in active power consumption, apparent power demand, or power factor performance.

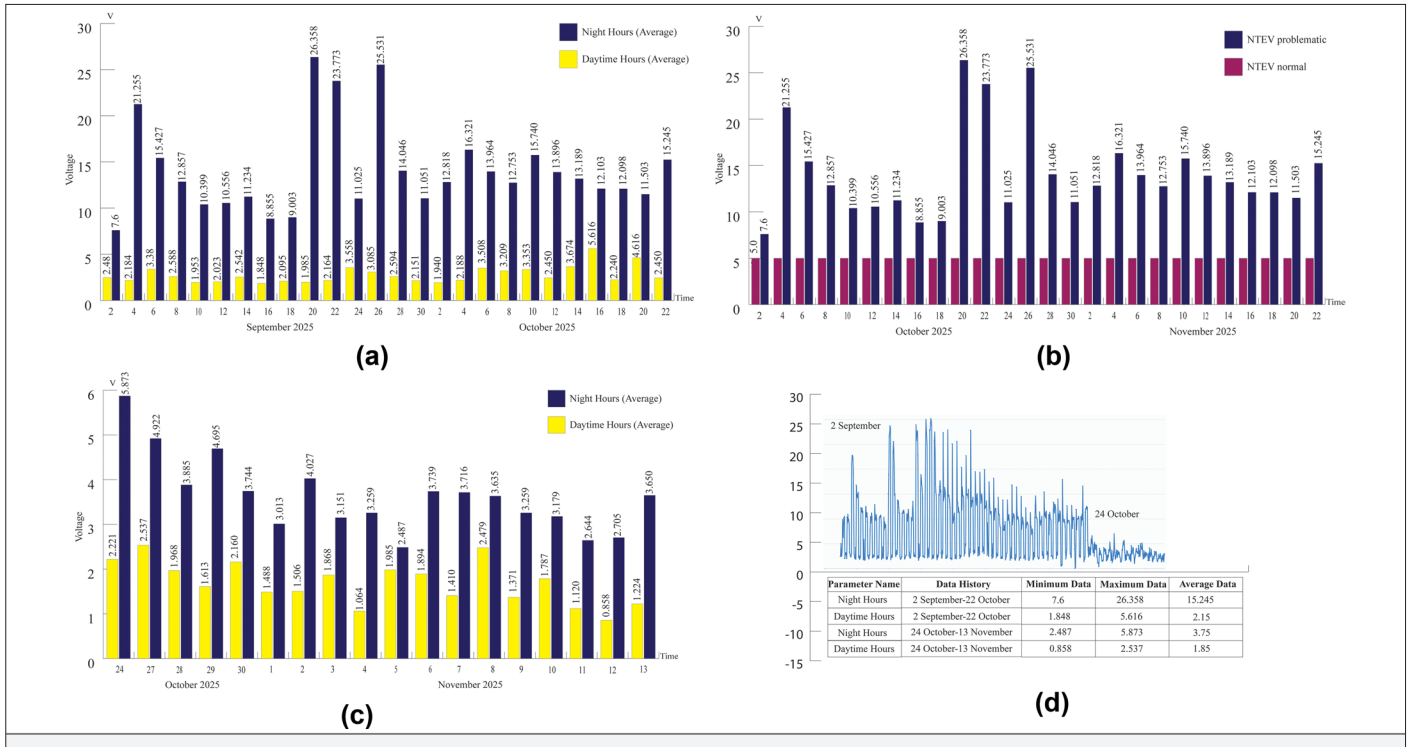
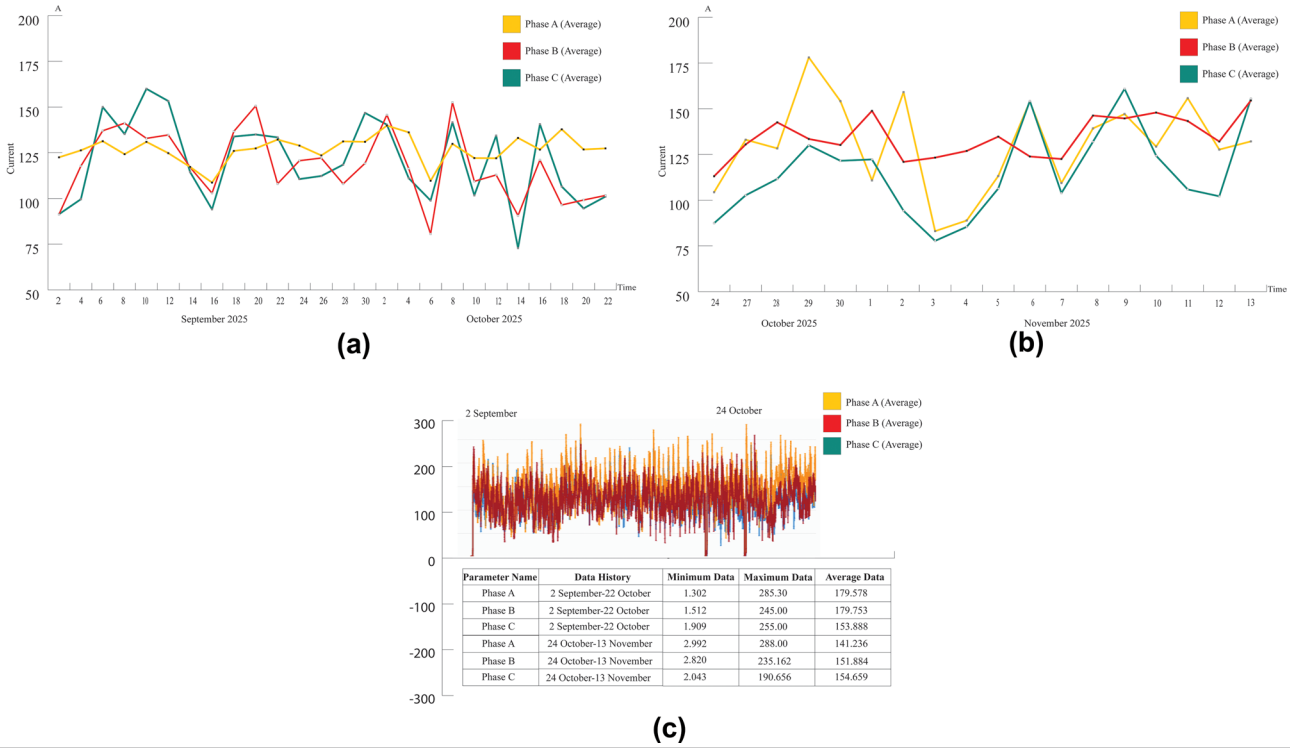
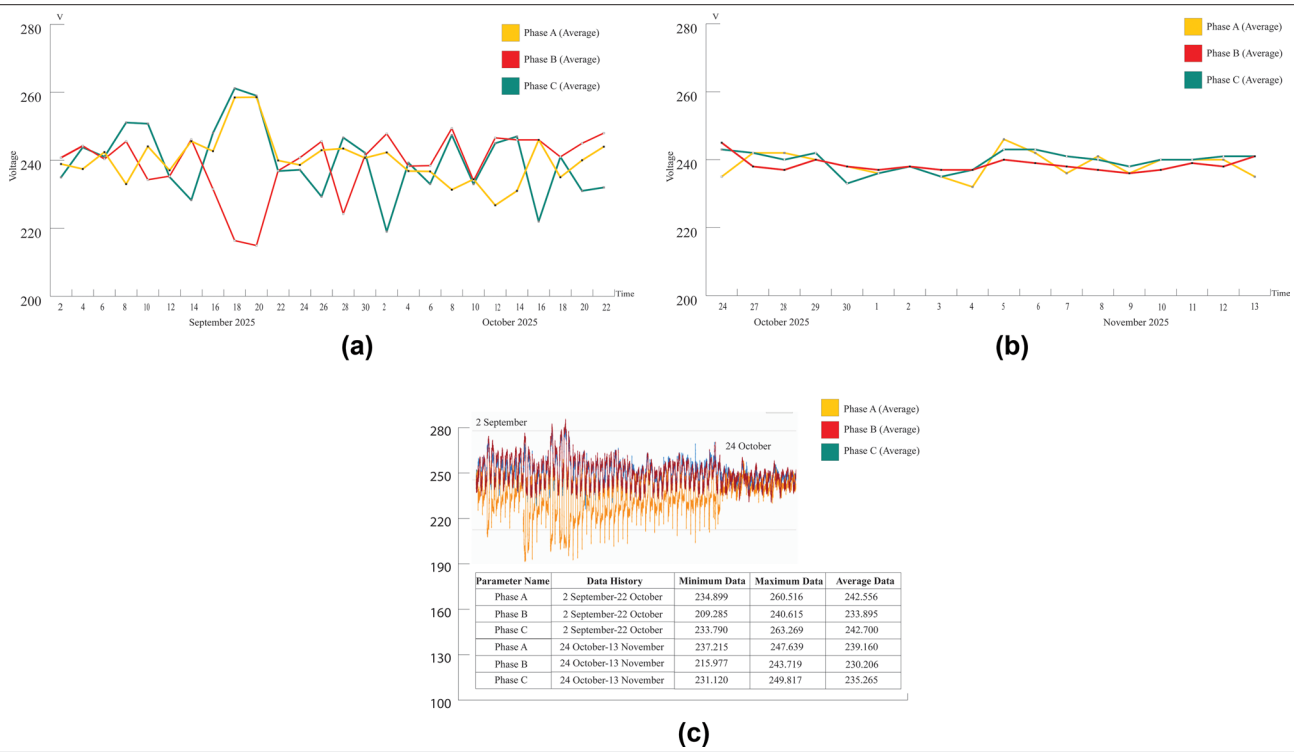


Fig. 9. (a) Average day-time and night-time NTEV values before corrective actions (2 Sept–22 Oct); (b) comparison of measured and expected operating range; (c) average NTEV values after corrective field intervention (24 Oct–13 Nov); (d) comparison of minimum and maximum values before and after intervention. Note: NTEV = neutral-to-earth voltage.



Parameter Name	Data History	Minimum Data	Maximum Data	Average Data
Phase A	2 September-22 October	1.302	285.30	179.578
Phase B	2 September-22 October	1.512	245.00	179.753
Phase C	2 September-22 October	1.909	255.00	153.888
Phase A	24 October-13 November	2.992	288.00	141.236
Phase B	24 October-13 November	2.820	235.162	151.884
Phase C	24 October-13 November	2.043	190.656	154.659

Fig. 10. (a) Average phase current profiles before corrective actions (2 Sept–22 Oct); (b) average phase current profiles after corrective actions (24 Oct–13 Nov); (c) long-term phase current trends visualized on the central server.



Parameter Name	Data History	Minimum Data	Maximum Data	Average Data
Phase A	2 September-22 October	234.899	260.516	242.556
Phase B	2 September-22 October	209.285	240.615	233.895
Phase C	2 September-22 October	233.790	263.269	242.700
Phase A	24 October-13 November	237.215	247.639	239.160
Phase B	24 October-13 November	215.977	243.719	230.206
Phase C	24 October-13 November	231.120	249.817	235.265

Fig. 11. (a) Average phase voltage profiles before corrective actions (2 Sept–22 Oct); (b) average phase voltage profiles after corrective actions (24 Oct–13 Nov); (c) long-term phase voltage trends visualized on the central server.

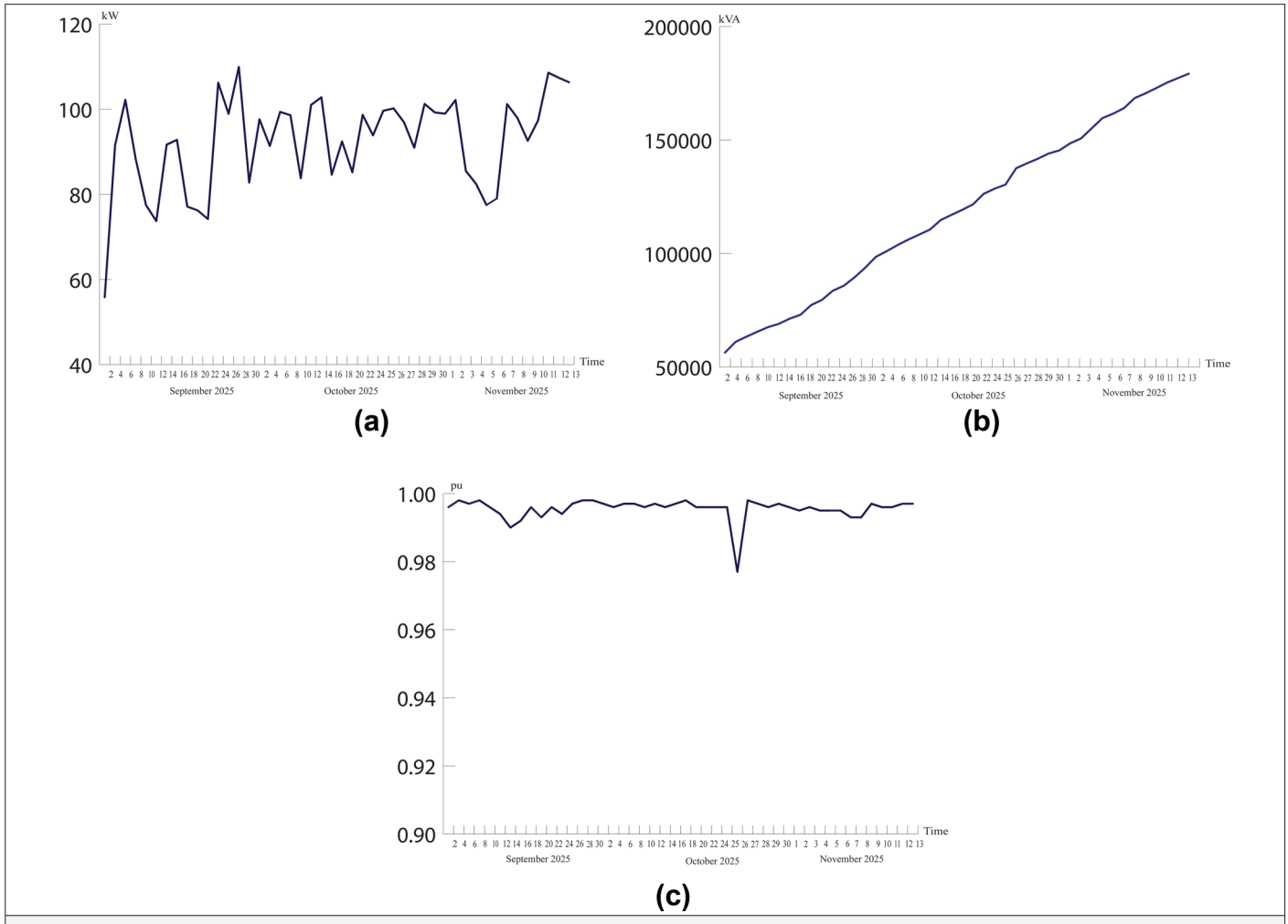


Fig. 12. (a) Active power variation before and after corrective field intervention; (b) apparent power variation reflecting cumulative load behavior; (c) long-term power factor variation under normal operating conditions.

During testing, the SEM-EG maintained stable one-second data acquisition and demonstrated reliable interoperability with SCADA platforms, cloud-based dashboards, and IoT systems using Modbus TCP and MQTT. In addition, edge-based data filtering and analytics reduced network congestion and bandwidth usage while enhancing data privacy. Combined with robust hardware, modular software architecture, and calibration-enhanced measurement accuracy, the SEM-EG provides a scalable, efficient, and resilient edge–cloud solution for real-time monitoring and centralized supervision in modern smart grid infrastructures.

Overall, the long-term field deployment confirms that the SEM-EG extends beyond conventional monitoring by integrating real-time measurement, edge-based analytics, and autonomous decision-making within a unified platform. Continuous high-resolution NTEV monitoring enabled early detection of time-dependent grounding-related faults that remained undetectable through conventional voltage, current, or power measurements, while post-correction analysis quantitatively verified the effectiveness of maintenance actions. The combined evaluation of NTEV, phase currents, voltages, and power-related parameters demonstrates that grounding abnormalities can indirectly affect system behavior without triggering traditional protection mechanisms. By processing NTEV as an active operational parameter at the edge and complementing it with cloud-based visualization and historical analysis, the SEM-EG enhances operational safety, system resilience, and long-term reliability in smart grid infrastructures.

IV. Future Work and Perspectives

To further enhance the scalability, intelligence, and operational robustness of the proposed SEM-EG architecture, the following research directions are identified:

- Large-scale and multi-site deployment: Deploy SEM-EG devices across multiple low-voltage feeders and geographically distributed sites to systematically evaluate scalability, interoperability, and long-term reliability under heterogeneous grid conditions, including different grounding schemes, network topologies, and load compositions.
- Adaptive and context-aware NTEV thresholding: Develop and implement dynamic NTEV thresholding mechanisms that adapt to seasonal variations, load dynamics, and historical operating patterns, enabling improved fault detection sensitivity while minimizing false alarms in environments with variable load behavior.

- Advanced analytics and edge intelligence: Integrate machine learning–based anomaly detection and fault classification algorithms within the EC layer to capture complex temporal and contextual patterns in NTEV, voltage, and current data, enabling early identification of emerging grounding or insulation-related issues with low-latency edge-level responses.
- Integration with future smart grid platforms: Integrate SEM-EG data streams with digital twin platforms, asset health management systems, and evolving smart grid standards to support predictive maintenance workflows, asset-level condition monitoring, and enhanced operational resilience in low-voltage distribution networks.

V. CONCLUSION

This study presented the design, implementation, and field validation of the SEM-EG, an EC-enabled solution for NTEV and energy monitoring in low-voltage distribution networks. By performing continuous measurement and local analytics directly at the edge layer, the proposed system eliminates dependency on centralized processing for safety-critical decisions. The long-term field deployment demonstrated that edge-based NTEV evaluation enables early detection of time-dependent grounding-related faults that may remain hidden when relying solely on conventional voltage, current, or power measurements. The observed nighttime NTEV anomalies, subsequent field investigation, and post-correction improvements confirm the effectiveness of EC in supporting rapid fault awareness, targeted maintenance actions, and verification of corrective interventions.

Beyond NTEV-driven fault detection, the SEM-EG leverages EC to simultaneously analyze phase currents, phase voltages, and power-related parameters, enabling a holistic assessment of system behavior and PQ. The results show that grounding abnormalities can indirectly affect voltage stability and current distribution without necessarily triggering traditional protection mechanisms, underscoring the value of multi-parameter, edge-level analysis. Through calibration-enhanced measurement accuracy, low-latency local decision-making, and seamless integration with SCADA and cloud platforms, the SEM-EG improves operational safety, energy efficiency, and system resilience while reducing communication overhead. These capabilities position the proposed edge-enabled architecture as a scalable and future-proof solution for modern smart grid infrastructures, with strong potential for further expansion through large-scale deployments and advanced data-driven analytics.

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Artificial Intelligence Usage Statement: The authors declared that no artificial intelligence tool was used in the preparation of the manuscript.

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Author Contributions: Concept – F.Y., Y.Y., K.Ç.B., E.T.; Design – F.Y., Y.Y.; Supervision – Y.Y., K.Ç.B., E.T; Resources – F.Y.; Materials – F.Y., Y.Y.; Data Collection and/or Processing – F.Y., Y.Y., K.Ç.B., E.T.; Analysis and/or Interpretation – F.Y., Y.Y., K.Ç.B., E.T.; Literature Search – F.Y., Y.Y.; Writing – F.Y., Y.Y., K.Ç.B., E.T.; Critical Review – F.Y., Y.Y., K.Ç.B., E.T.

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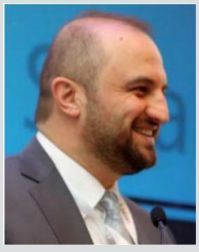
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