Research paper

Impact of Neutral Loss and Conductor Corrosion on G3-PLC Performance in Large-Scale AMI Deployments

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Abstract: Advanced Metering Infrastructure (AMI) is being deployed by the Islamabad Electric Supply Company (IESCO) to modernize meter reading and improve operational efficiency through smart grid technologies. Under the IESCO AMI Project, G3-Power Line Communication (G3-PLC) is used to transmit meter data over existing low-voltage power distribution lines, eliminating the need for dedicated communication media. However, the reliability of PLC communication is highly dependent on the physical condition and material compatibility of the electrical network. In the deployed system, low-voltage distribution lines are primarily aluminum conductors, while the Data Concentrator Unit (DCU) connection cables selected are copper. These dissimilar metals are mechanically joined at transformer locations to facilitate data collection from smart meters. Field observations revealed that environmental factors, including moisture, humidity, and temperature variations, accelerate galvanic corrosion at these aluminum–copper joints. This paper presents a field-based investigation conducted under the IESCO AMI Project, focusing on DCUs exhibiting low meter data collection rates. Analysis of Head-End System (HES) data and DCU logs, combined with on-site inspections and field observations, suggests that galvanic corrosion and degraded neutral connections are associated with attenuation of PLC signals. Photographic evidence, detailed logs, and post-rectification performance analysis are presented to validate the findings. The study indicates a strong association between conductor material mismatch, environmental exposure, and PLC communication degradation and proposes practical technical measures to improve long-term AMI system reliability. Unlike simulation or laboratory-based studies, this work provides operational field observations from a large utility-scale AMI deployment in Pakistan, explicitly linking neutral degradation and aluminum–copper joint corrosion with measurable G3-PLC communication failures and recovery after rectification, resulting in improvement of meter data collection rates from below 20% to above 95%, based on HES data analysis.

Keywords: Advanced Metering Infrastructure; G3-PLC; Neutral Loss; Data Concentrator Unit; Smart Grid; Corrosion

1. Introduction

Advanced Metering Infrastructure (AMI) plays a critical role in modern power distribution systems by enabling automated meter reading, accurate billing, load profiling, outage detection, and real-time monitoring of consumer loads [1, 2]. By integrating smart meters with communication and data management systems, AMI supports improved operational efficiency, reduced losses, and enhanced decision-making for utilities.

In Pakistan, the Islamabad Electric Supply Company (IESCO) is implementing a large-scale AMI Project as part of its smart grid modernization initiative. The project utilizes G3-Power Line Communication (G3-PLC) technology to facilitate data exchange between smart meters and Data Concentrator Units (DCUs) over existing low-voltage power distribution lines [3-5]. While PLC offers the advantage of using existing infrastructure without additional communication cabling, its performance is inherently dependent on the electrical characteristics and physical condition of the power network.

Operational analysis of the Head-End System (HES) revealed that several deployed DCUs were consistently reporting low meter data collection rates and degraded G3-PLC communication performance [6, 7]. Detailed examination of DCU logs and network performance parameters showed recurring incidents of neutral loss and, in certain locations, partial or complete phase failure.

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These electrical anomalies adversely affect the signal-to-noise ratio and impedance characteristics of power lines, which are critical for reliable G3-PLC communication. As a result, PLC signal attenuation increases, communication availability decreases, and overall system performance is compromised. The persistence of these issues highlighted the need for a systematic field investigation to identify underlying electrical causes and implement corrective measures to restore reliable Meter Data Collection.

Persistent degradation in Data Concentrator Unit (DCU) data collection rates represents a significant operational and technical risk to large-scale AMI deployments [8, 9]. Reliable and continuous communication between smart meters and DCUs is essential for accurate billing, load analysis, loss reduction, and effective network planning. When communication becomes intermittent or fails completely, meter readings are missed or delayed, leading to estimated billing, revenue leakage, increased consumer complaints, and additional operational overhead for utilities.

Field observations and system-level diagnostics identified multiple electrical network issues contributing to this degradation. Neutral conductor loss, corrosion at conductor joints, and mechanically loose connections were repeatedly observed at transformer and DCU installation points. Environmental exposures such as moisture, humidity, and temperature fluctuations accelerate deterioration at these vulnerable points, causing progressive degradation rather than abrupt failure.

The cumulative impact of these factors necessitated a structured field investigation and targeted corrective interventions to identify root causes, restore communication performance, and develop sustainable technical solutions to enhance long-term AMI system reliability.

The primary objective of this study is to diagnose the root causes affecting the data collection performance of selected Data Concentrator Units (DCUs) operating under the IESCO AMI Project. The study aims to identify and rectify electrical network faults—particularly those related to neutral integrity, conductor joints, and connection quality—that adversely impact G3-Power Line Communication (G3-PLC) reliability.

In addition, the work evaluates the effectiveness of corrective measures by assessing improvements in DCU communication performance and meter data collection rates following field interventions. Finally, the study documents key findings and proposes practical, long-term technical solutions to mitigate the recurrence of similar issues and enhance the overall reliability and sustainability of AMI deployments. The key contributions of this study are as follows:

(i) Field-level identification of neutral loss and aluminum–copper joint corrosion as dominant causes of G3-PLC degradation;
(ii) Correlation of HES data, DCU logs, and physical inspections to quantify communication impact;
(iii) Validation of performance recovery through post-rectification analysis in a live AMI deployment.

Previous studies have highlighted the sensitivity of Power Line Communication (PLC) systems to electrical noise, impedance mismatches, and network topology variations. G3-PLC operates over low-voltage distribution networks that were not originally designed for high-frequency communication signals, making system performance highly dependent on conductor condition and network integrity. Several laboratory and simulation-based investigations have demonstrated that variations in line impedance and increased noise levels can significantly degrade PLC signal quality and data throughput.

Recent studies on narrowband Power Line Communication (PLC), including G3-PLC, have highlighted that communication performance in low-voltage distribution networks is strongly influenced by channel impedance variability, noise aggregation, and network topology-dependent signal attenuation [6, 10, 11]. Investigations have shown that LV distribution feeders exhibit highly time-varying impedance characteristics due to dynamic load switching, phase unbalance, and distributed nonlinear loads, which directly affect PLC signal propagation and coupling efficiency [6, 7, 11]. Furthermore, research on PLC channel modeling indicates that signal degradation is significantly intensified in the presence of poor neutral continuity, as neutral conductors play a critical role in providing a stable return path and maintaining channel symmetry for high-frequency communication signals [10, 11]. In addition, studies on electrical contact interfaces have demonstrated that corrosion-induced increases in contact resistance at conductor joints can introduce localized impedance discontinuities, resulting in additional signal reflections and attenuation in narrowband PLC systems [12]. However, most of these investigations are either simulation-based, laboratory-controlled, or limited to short-term experimental setups, and do not fully capture long-term operational behavior in utility-scale AMI deployments under real environmental and aging conditions.

Research has also emphasized the importance of neutral conductor continuity for reliable PLC communication. Neutral imbalance, floating neutrals, common neutrals with other transformers and poor grounding conditions have been shown to alter signal-to-noise ratios and introduce attenuation in PLC channels. However, much of the existing literature focuses on controlled environments or theoretical modeling, with limited validation under real field conditions.

Galvanic corrosion at dissimilar metal interfaces, particularly aluminum–copper joints, is a well-documented phenomenon in power distribution systems [12]. Electrochemical potential differences between conductors accelerate oxidation and increase contact resistance over time, especially in the presence of moisture and temperature variations. While the electrical consequences of such corrosion on power losses and overheating are known, its direct impact on PLC-based AMI communication remains underexplored.

Consequently, there exists a clear research gap in field-validated studies that directly correlate neutral integrity, conductor material mismatch, and galvanic corrosion with degraded G3-PLC communication performance in operational AMI deployments. In our earlier published work, we presented a comprehensive field-based feasibility analysis of PLC deployment under the IESCO AMI Project [5]. That study established baseline G3-PLC performance characteristics, network behavior, and data collection reliability across urban low-voltage distribution networks and validated the suitability of PLC for large-scale AMI implementation in Pakistan. Building upon those findings, the present study extends the investigation by focusing on operational degradation mechanisms observed during prolonged field deployment, specifically neutral loss and aluminum–copper conductor corrosion and evaluates their impact on G3-PLC communication performance using field data. This study presents a field case study based on operational AMI deployment data from a live utility network. This work is an extension of our previous study on G3-PLC feasibility in the IESCO AMI project, and focuses specifically on operational degradation mechanisms observed during long-term deployment.

2. Methodology

The investigation methodology adopted in this study was structured as a field-based diagnostic and validation framework to evaluate the impact of electrical network degradation on G3-PLC communication performance. The investigation consisted of five sequential stages: (i) backend Head-End System (HES) performance screening and identification of low-performing DCUs, (ii) DCU log analysis and alarm evaluation, (iii) targeted field inspections and physical assessment of neutral conductors and aluminum–copper joints, (iv) corrective rectification of identified electrical faults, and (v) post-rectification performance validation using HES operational data.

The study was conducted as a focused operational case study on selected representative DCUs within the Seham subdivision of the IESCO AMI deployment. The objective was to investigate the association between neutral degradation, conductor-joint corrosion, and degraded G3-PLC communication performance under real field conditions. The study was designed as an operational field investigation based on utility deployment data and physical inspections. It was not intended to provide direct physical-layer characterization of PLC communication channels, but rather to evaluate field-observed relationships between network condition and communication performance. During the investigation and validation period, the network topology, connected meter population, DCU configuration, and firmware conditions remained unchanged, thereby supporting the assessment that the observed communication recovery was primarily associated with restoration of neutral integrity and rectification of degraded conductor joints.

2.1 Study Area and Selection Criteria

The study was conducted in the Seham Subdivision of the Rawalpindi City Circle, where several Data Concentrator Units (DCUs) were persistently reporting low meter data collection performance. Four distribution transformers connected to DCUs on the Chakra feeder were selected based on historical Head-End System (HES) records. These DCUs exhibited consistently low collection ratios over extended monitoring periods, indicating systemic communication issues.

Baseline performance data, including the total number of registered meters, meter visibility, and successful Meter Data Collection rates, was extracted from the HES prior to any field activity. Transformers showing repeated low collection behavior were shortlisted to ensure that the investigation focused on representative and recurring problem cases.

2.2 Backend System Analysis and Observations

Prior to field inspections, detailed analysis of HES reports and DCU communication logs was carried out [10, 11]. The analysis revealed frequent communication interruptions, intermittent meter availability, and prolonged periods of low or zero data reception from affected DCUs. In multiple cases, a substantial portion of connected meters failed to report data within scheduled reading cycles, resulting in consistently low collection percentages. Figures 1 and 2 present the daily meter data collection and energy load profile for the DCU installed on Transformer 4617, showing a significant drop in performance due to neutral loss and conductor corrosion before any field interventions were applied.

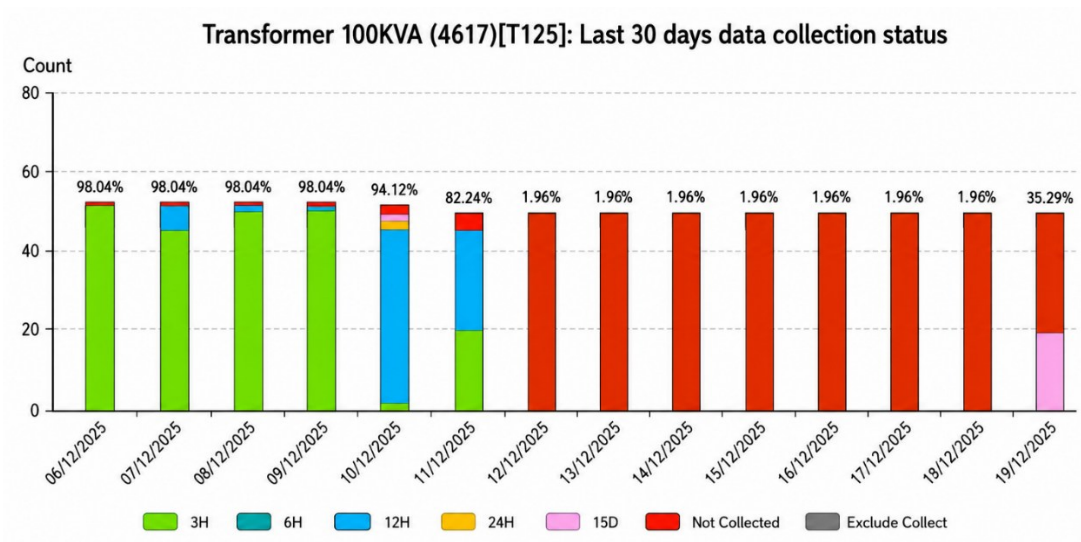


Figure 1. Daily meter data collection for DCU on Transformer 4617 shows significant drop.

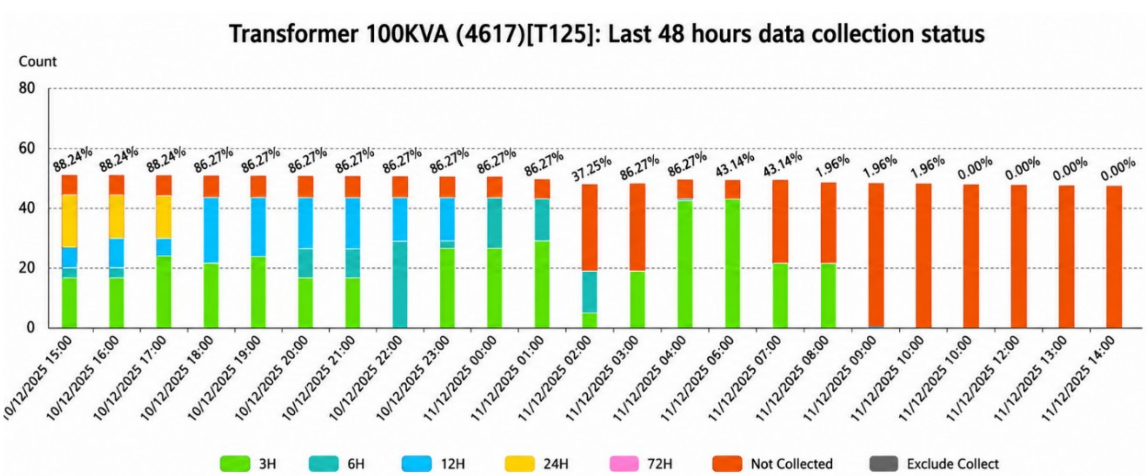
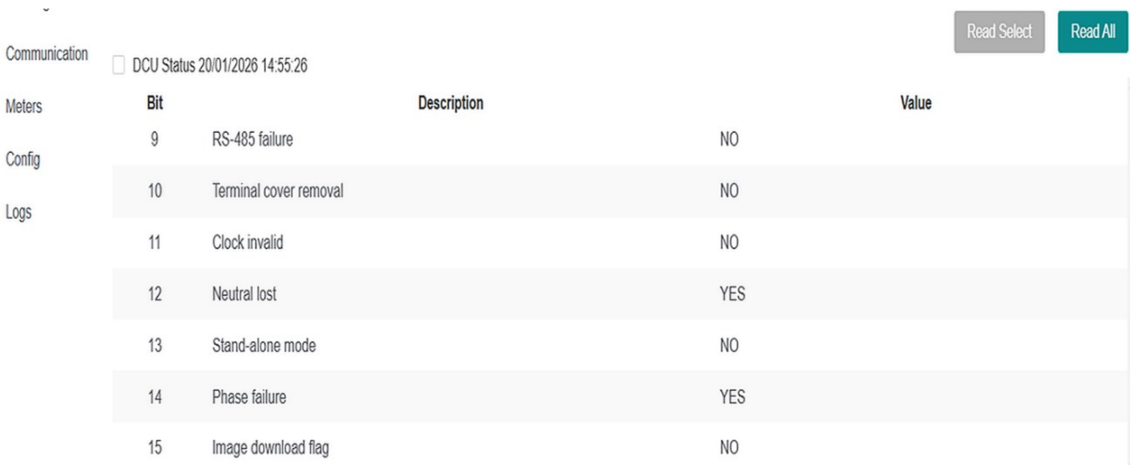


Figure 2. Energy Load Profile for DCU on Transformer 4617 before rectification.

Analysis of the DCU logs for Transformer 4617 is presented in Figure 3, which highlights the events recorded by the device. Most alarm bits, including 4G/2G module failure, PLC module failure, and phase failure, remained inactive. However, the Neutral

Lost event (Bit 12) was flagged as YES, indicating a loss of neutral connection. This log evidence supports the observed drop in meter data collection and degraded G3-PLC performance seen in Figures 1 and 2, confirming that compromised neutral integrity was a major contributor to communication issues prior to field interventions.



Bit	Description	Value
9	RS-485 failure	NO
10	Terminal cover removal	NO
11	Clock invalid	NO
12	Neutral lost	YES
13	Stand-alone mode	NO
14	Phase failure	YES
15	Image download flag	NO

Figure 3. DCU log for Transformer 4617 showing Neutral Lost event.

2.3 Field Observations and Material Condition Assessment

Following the backend analysis, on-site inspections were conducted at the selected transformer locations to visually assess the physical condition of the electrical network and its impact on PLC communication. Particular attention was given to DCU connection points, neutral conductors, and joints where aluminum low-voltage distribution lines were interfaced with copper DCU cables. These inspections aimed to identify visible signs of corrosion, loose connections, and any other factors that could explain the degraded data collection and signal quality observed in the HES and DCU logs. Field observations revealed visible corrosion, discoloration, and carbon-like deposits at several aluminum–copper joints [12]. The condition of these joints was consistent with galvanic corrosion, likely accelerated by environmental exposure such as moisture, humidity, and temperature fluctuations. In addition, localized degradation and carbon-like surface deposits were observed at neutral connection points, indicating long-term electrochemical and thermal stress at the conductor interface. These physical deteriorations were observed concurrently with degraded communication performance and may contribute to intermittent meter communication issues documented in Figures 4 and 5.

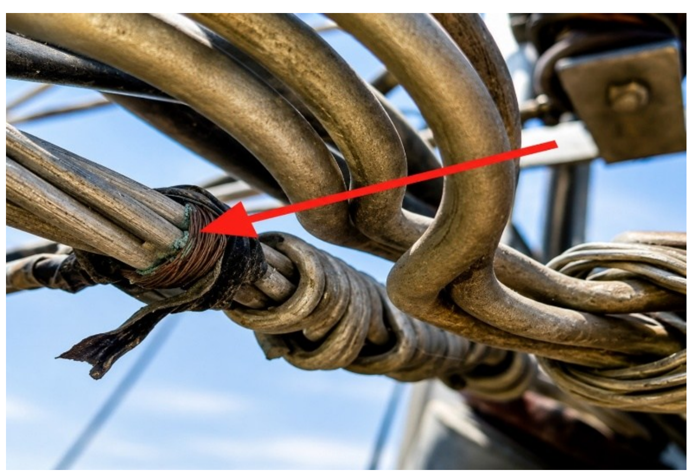


Figure 4. Corrosion and discoloration at aluminum–copper DCU 1 joints observed on-site.

Figure 5. Corrosion and discoloration at aluminum–copper DCU 2 joints were observed on-site.

3. Results and Discussion

Analysis of Head-End System records indicated that, prior to rectification, the affected DCUs exhibited meter data collection rates ranging from approximately 5% to 20%. Following restoration of neutral integrity and correction of degraded conductor joints, data collection performance improved significantly, reaching levels between 90% and 97%, thereby indicating a strong association between electrical network conditions and G3-PLC Communication Performance. This improvement is quantitatively illustrated in Figure 6, which compares meter data collection percentages for the same DCUs before and after rectification, based on Head-End System (HES) records.

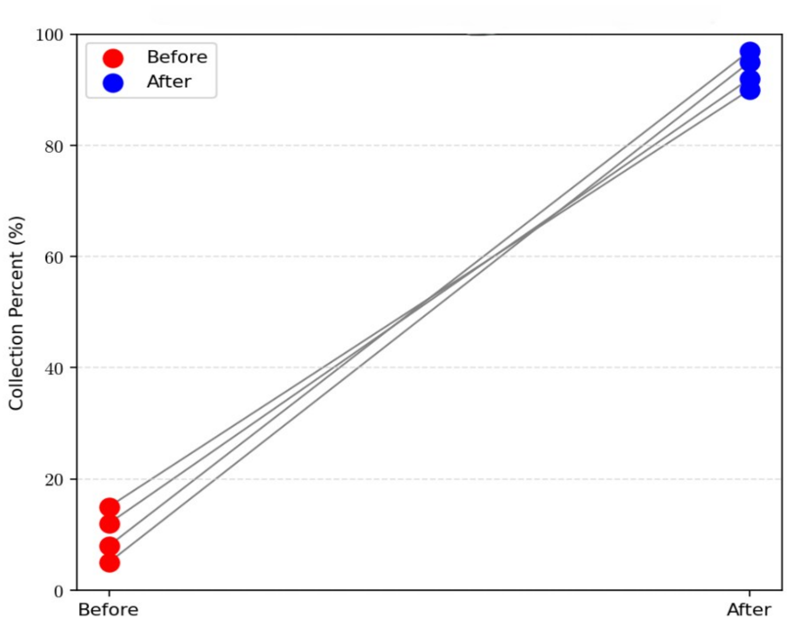


Figure 6. Pre- and post-rectification comparison of DCU meter data collection performance.

Restoration of neutral continuity reduced impedance imbalance and stabilized return current paths, thereby improving PLC signal coupling and reducing attenuation across the low-voltage network. To analyze the impact of neutral loss and conductor corrosion on G3-PLC communication, a field survey was conducted on the selected transformers in the Seham Subdivision.

The key findings from this survey, including diagnosed issues, corrective actions taken, and monitoring observations for the selected DCUs during the period from 05/11/2025 to 26/03/2026, are summarized in Table 1.

Table 1. Summary of Survey Findings

Sub division	Feeder	Concentrator	Total Meters	Daily Collection Before Diagnosis (%)	Daily Collection After Diagnosed (%)	Diagnosed Issue	Status/ Rectified
Seham	Chakra	DCU 1	80	10.2	98	Corrosion	Joint Refreshed
Seham	Chakra	DCU 2	293	5.6	89	Corrosion	
Seham	Chakra	DCU 3	70	15	96	Corrosion	
Seham	Chakra	DCU 4	190	12	90	Corrosion	
Seham	Chakra	DCU 5	55	1.96	96	Corrosion	
Seham	Lakhu	DCU 6	155	1.0	99.8	DCU PLC Module failure	Module Changed
Seham	Lakhu	DCU 7	233	11.3	88	Corrosion	Joint Refreshed
Seham	Lakhu	DCU 8	78	18	94	Corrosion	
Seham	Lakhu	DCU 9	198	20.22	98	Corrosion	
Seham	Lakhu	DCU 10	25	0	92	Transformer Damaged	Transformer Changed
Seham	I-16	DCU 11	109	15.9	79	Corrosion	Joint Refreshed
Seham	I-16	DCU 12	210	0.5	94	Corrosion	
Seham	I-16	DCU 13	170	15	88	loose connections	Connections Tightened
Seham	I-16	DCU 14	60	18.9	78	Corrosion	Joint Refreshed
Seham	I-16	DCU 15	98	20	98	conductor-joint degradation	

Post-rectification analysis showed a noticeable improvement in DCU data collection performance, supporting a strong association between neutral integrity and G3-PLC communication performance under the investigated field conditions. Figures 7 and 8 present the daily data collection profile and the energy load profile for the DCU installed on Transformer 4617 after rectification. The daily profile shows that meter readings are consistently collected across successive days, while the energy load profile over the observed period indicates continuous availability of load data at regular time intervals. Together, these profiles demonstrate stable and sustained data reporting from the connected meters during the post-rectification period.

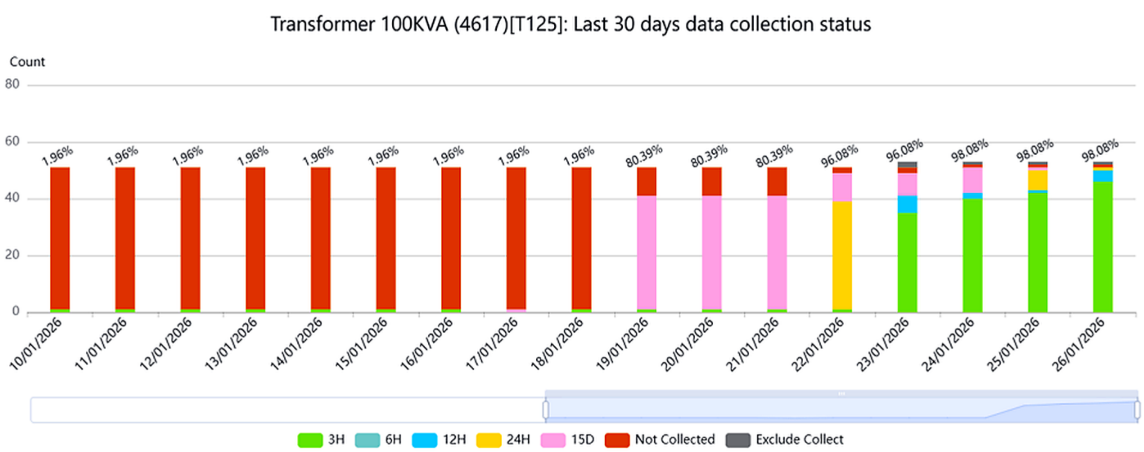


Figure 7. Daily meter data collection profile for DCU on Transformer 4617 after rectification.

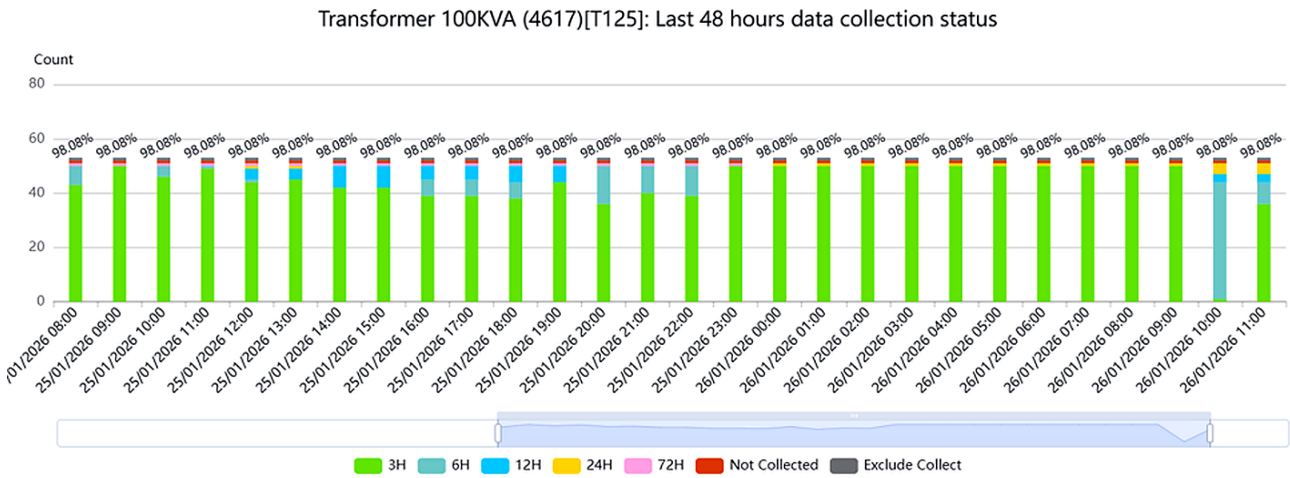
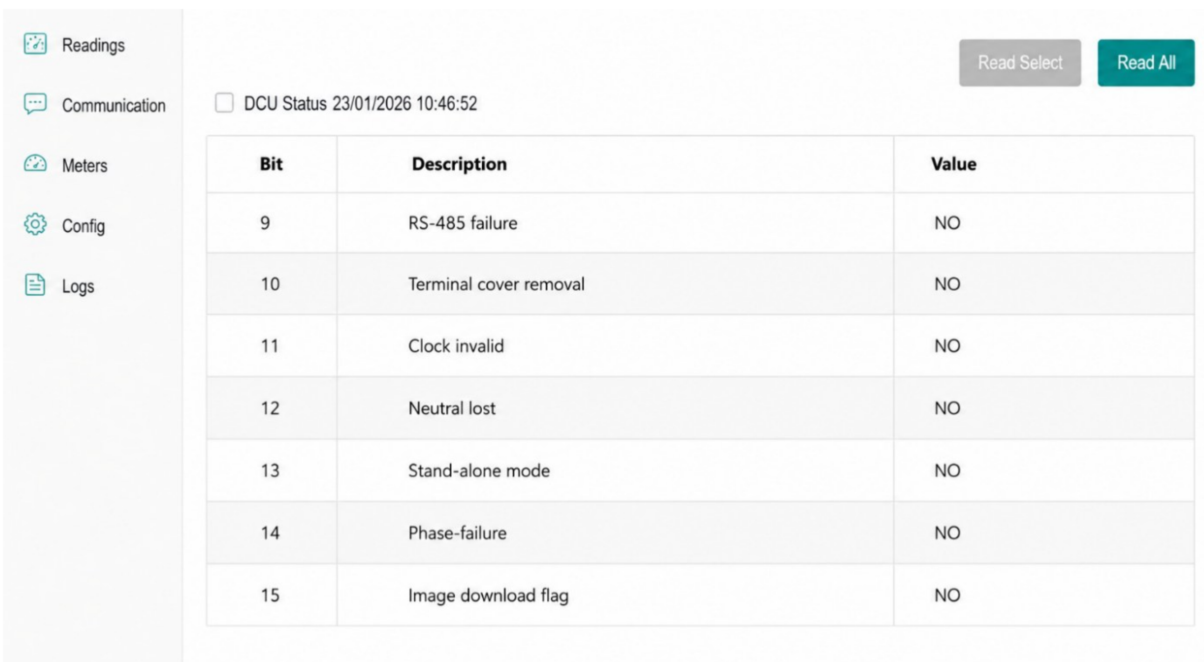


Figure 8. Energy load profile for DCU on Transformer 4617 after rectification.

Figure 9 presents the DCU status information obtained from the Head-End System after rectification. The Neutral Lost event (Bit 12), which was previously flagged during degraded operation, is now reported as NO. All other monitored status indicators, including phase failure and communication-related alarms, also remain inactive, indicating normal operational status of the DCU during the observed period.



Bit	Description	Value
9	RS-485 failure	NO
10	Terminal cover removal	NO
11	Clock invalid	NO
12	Neutral lost	NO
13	Stand-alone mode	NO
14	Phase-failure	NO
15	Image download flag	NO

Figure 9. DCU status showing all alarms cleared and neutral restored for TR 4617.

4. Limitations of the Study

This study is limited to a specific subdivision and feeder within the IESCO network, and the findings may vary under different network configurations, load conditions, or environmental exposures. Seasonal variations and laboratory-based PLC signal measurements were not included. Nevertheless, the field-based evidence presented provides valuable insight applicable to similar AMI deployments in comparable distribution networks.

Furthermore, this study did not include direct communication-layer measurements such as signal-to-noise ratio (SNR), received signal strength indication (RSSI), packet loss statistics, retry counts, impedance characterization, or PLC signal attenuation measurements. Therefore, the findings should be interpreted as field-observed associations between electrical network condition and G3-PLC communication performance rather than definitive physical-layer causal validation. Future studies incorporating communication-layer diagnostics would provide additional insight into the underlying mechanisms influencing PLC performance.

5. Corrosion Mechanism

Sustained neutral current leads to localized heating at joints and terminals. In the presence of moisture, this accelerates oxidation. While high-temperature conditions can produce black copper sulfide, the green corrosion observed during this survey indicates copper oxide formation. The increase in joint resistance and impedance mismatch associated with corrosion may reduce the coupling efficiency of high-frequency PLC signals. This results in increased signal attenuation, reduced signal-to-noise ratio, and degraded communication performance between smart meters and DCUs. Additionally, where copper conductors were terminated on dissimilar metal connectors, galvanic corrosion was evident. Electrochemical potential differences between copper and metals such as aluminum or steel accelerate degradation, increasing resistance and the likelihood of communication failure. This degradation process is progressive in nature, leading to gradual communication deterioration rather than abrupt failure, which explains prolonged periods of intermittent data loss observed in the HES.

6. Conclusions

This study indicates that the reliability of G3-PLC communication in large-scale AMI deployments is closely associated with the physical and electrical integrity of low-voltage distribution networks. Field investigations under the IESCO AMI Project revealed that neutral loss, galvanic corrosion at aluminum–copper joints, and poor termination practices were consistently associated with degraded G3-PLC communication performance, low meter data collection rates, and reduced system efficiency. Prior observations from our earlier study [5] established baseline performance characteristics and highlighted the sensitivity of G3-PLC to network conditions. Building on this foundation, the present work suggests that operational degradation is not solely a function of communication protocols but is also associated with electrical network health and environmental exposure.

- Post-rectification analysis demonstrated measurable improvements across multiple KPIs:
- Meter data collection rates improved from below 20% to above 95%, indicating substantial recovery in DCU performance.
- System reliability and efficiency were enhanced, with restored neutral continuity reducing impedance imbalance and stabilizing return current paths for PLC signal propagation.
- Operational continuity was achieved, minimizing missed readings and estimated billing, thereby supporting accurate revenue tracking and improved utility management.

These results underscore the importance of integrating electrical network maintenance into AMI performance management. Specifically, corrosion mitigation, proper conductor termination, and periodic inspection of neutrals and DCU connections are critical to sustaining communication reliability in smart grids. The study also validates that field-based, empirical diagnostics provide actionable insights that complement laboratory and simulation-based evaluations, bridging the gap between theoretical performance expectations and real-world operational realities.

Furthermore, this investigation highlights the practical implications for AMI deployments operating in similar low-voltage distribution environments. The findings suggest that periodic inspection of neutral conductors, proper conductor termination practices, and mitigation of conductor-joint degradation can support improved G3-PLC communication performance and meter data collection. The corrective interventions applied during this study were associated with substantial recovery of DCU performance and provided a practical framework for addressing similar operational issues in large-scale AMI deployments.

To ensure long-term reliability of AMI systems, the following measures are recommended. Recommendations 3 and 4 were validated through field implementation during the study, while Recommendations 1 and 2 are based on observed failures and established engineering practice.

1. Use of bimetallic connectors or transition lugs at all joints involving dissimilar metals to prevent galvanic corrosion.
2. Preference for aluminum conductors instead of copper for DCU connections, where compatible, reducing electrochemical mismatch.
3. Standardized joint preparation, including proper conductor twisting, insulation taping, and mechanical tightening.
4. Periodic inspection and preventive maintenance of neutral conductors and DCU terminations.

Conflict of Interest

The authors declare no conflict of interest related to the publication of this research.

Data Availability Statement

The data supporting the findings of this study are included within the article. Additional field data, HES records, DCU logs, and related inspection records may be made available from the corresponding author upon reasonable request, subject to permission from the relevant utility/company and any applicable confidentiality or operational restrictions.

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Author Contributions

Conceptualization, Sabir Hussain and Saddam Hussain; methodology, Sabir Hussain; investigation, Sabir Hussain; data curation, Sabir Hussain; formal analysis, Sabir Hussain and Saddam Hussain; writing—original draft preparation, Sabir Hussain; writing—review and editing, Sabir Hussain and Saddam Hussain; supervision, Saddam Hussain. All authors have read and agreed to the published version of the manuscript.

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