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A Software-Driven Framework for Decentralized Peer-to-Peer Energy Exchange in Smart Distribution Networks

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Abstract

This paper introduces a software-driven framework for enabling decentralized peer-to-peer (P2P) energy exchange within smart distribution networks. The architecture is built around intelligent metering nodes deployed at consumer endpoints, which relay real-time generation and consumption telemetry to a feeder-level aggregation controller designated as the primary node. This controller oversees transformer operational health, consolidates nodal data streams, and executes energy reconciliation processes. The framework employs a cooperative pooling mechanism for energy redistribution, wherein distributed energy resources (DERs) such as rooftop photovoltaic installations prioritize self-consumption before contributing excess generation to a shared local pool. A real-time backend allocation engine dynamically manages energy distribution across connected users. Furthermore, the system incorporates a loss identification module that cross-references transformer-level measurements against cumulative smart meter readings. Evaluation through simulation scenarios confirms that the proposed framework enhances local energy utilization efficiency and provides a scalable foundation for advanced features including high renewable penetration and cross-feeder energy transactions.

Keywords: Peer-to-Peer Energy Exchange, Smart Distribution Network, Intelligent Metering, Distributed Energy Resources, Cooperative Pooling, IoT-Based Energy Management.

1. Introduction

The global energy landscape is undergoing a fundamental transformation driven by the proliferation of distributed renewable generation assets and the growing imperative for localized energy management. Conventional centralized power distribution architectures are increasingly constrained by inherent inefficiencies such as significant transmission losses, limited adaptability to dynamic load conditions, and challenges in accommodating bidirectional energy flows from prosumer installations. These limitations have catalyzed interest in peer-to-peer energy trading paradigms that empower end-users to participate actively in energy markets as both consumers and producers.

Contemporary distribution networks equipped with advanced metering infrastructure offer unprecedented visibility into energy flows at granular levels. This capability creates opportunities for developing feeder-level energy exchange platforms that operate within the physical boundaries of individual distribution transformers. In the proposed framework, each distribution transformer is augmented with a primary aggregation node that registers, authenticates, and manages all metering endpoints within its service territory.

The primary node maintains continuous surveillance of critical transformer parameters including voltage stability, thermal loading, and power quality metrics while simultaneously ingesting energy telemetry from all connected nodes. This consolidated data repository serves as the foundation for automated energy accounting, real-time allocation decisions, and anomaly detection within the local distribution segment.

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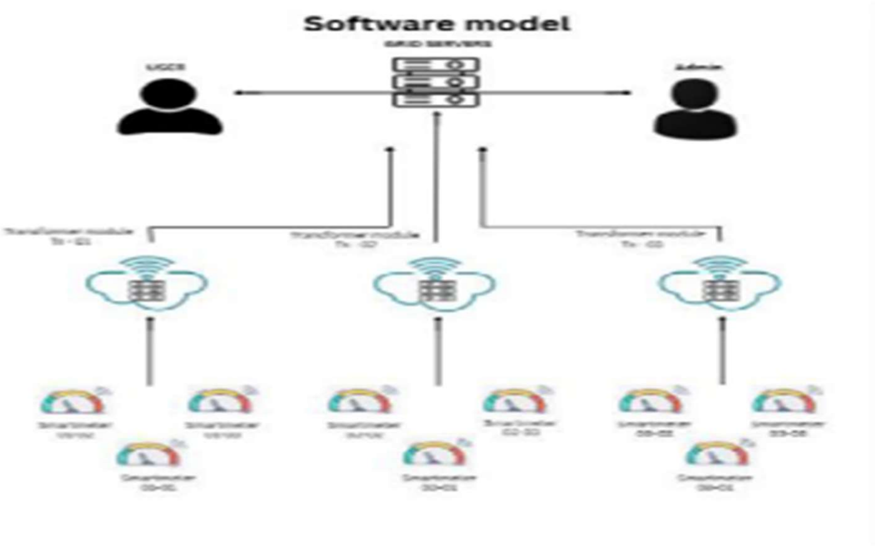

Fig. 1: Hierarchical software model of the proposed P2P energy exchange framework

Fig. 1 illustrates the hierarchical software architecture. The framework extends existing smart metering and microgrid management concepts with a specific emphasis on feeder-constrained energy trading within distribution transformer boundaries.

2. Literature Survey

Considerable research efforts have been directed toward decentralized energy market mechanisms and intelligent grid management systems. Prior investigations have explored direct prosumer-to-prosumer electricity exchange models, frequently leveraging distributed ledger technologies or autonomous control architectures for transaction management and settlement.

Advanced metering infrastructure has matured to provide high-fidelity real-time data acquisition capabilities across modern power networks, establishing the technical prerequisites for sophisticated P2P trading implementations. Several research groups have proposed allocation strategies that enforce priority consumption of locally generated renewable energy before grid interaction.

Nevertheless, the majority of existing frameworks do not incorporate transformer-level health monitoring and systematic loss quantification within an integrated feeder-bounded P2P trading architecture. The present work addresses this research gap by unifying energy trading, equipment monitoring, and comprehensive energy accounting within a cohesive system design.

3. Problem Formulation

The central research objective is to engineer a system capable of efficiently equilibrating local energy generation and consumption within a distribution feeder while ensuring precise energy accounting and preserving grid operational stability. The key technical challenges addressed include:

- **Local Optimization:** Ensuring DER output is preferentially consumed within the feeder before any surplus is exported.

- **Loss Identification:** Detecting discrepancies between transformer supply measurements and aggregated meter readings to quantify technical and non-technical losses.
- **Scalability:** Architecting a communication framework that supports growing numbers of metering endpoints without bandwidth degradation.
- **Grid Stability:** Integrating transformer health telemetry to prevent overloading and manage reverse power flow scenarios.

For each sampling interval, the system determines: total DER generation across the feeder (G), aggregate load demand (L), and transformer supply (T). The allocation engine assigns min(G, L) kWh to local consumption with priority given to DER owners, marks surplus (G - L) for external availability, and computes loss as (T - G - L) representing unaccounted energy.

4. System Architecture and Design

The proposed software architecture is structured as a three-tier hierarchical system encompassing the metering layer, the aggregation layer, and the analytics layer.

4.1 Metering Layer: Each consumer endpoint is instrumented with an intelligent metering device capable of high-resolution measurement of electrical parameters including active power, reactive power, voltage, and current. These devices constitute a local mesh communication network and transmit timestamped readings to the aggregation controller at configurable intervals, typically every 60 seconds.

4.2 Aggregation Layer: The primary node functions as the computational hub of the feeder-level system. It consolidates incoming data streams from all connected meters, monitors transformer operational parameters including thermal state and voltage regulation, and performs preliminary data validation and processing. Processed data is forwarded to the analytics server through a secure internet connection, establishing a hierarchical data flow architecture that ensures both scalability and efficient bandwidth utilization.

4.3 Analytics Layer: The central analytics server hosts the backend intelligence responsible for executing energy trading algorithms, performing comprehensive energy accounting, and generating operational dashboards. It processes real-time telemetry from multiple feeder controllers simultaneously, enabling system-wide optimization of energy allocation decisions.

5. Mathematical Framework

The energy accounting and allocation engine operates on the following mathematical constructs at each sampling interval:

Total DER Generation:

$$G\_total = \Sigma\, G\_i \quad (\text{for } i = 1 \text{ to } n)$$

Total Load Consumption:

$$C\_total = \Sigma\, C\_j \quad (\text{for } j = 1 \text{ to } m)$$

Loss Quantification:

$$L = T\_supply - (G\_total + C\_total)$$

Local Allocation:

$$E\_local = \min(G\_total, C\_total)$$

Surplus/Deficit Determination:

$$E\_surplus = G\_total - C\_total \quad (\text{when } G > C)$$
$$E\_deficit = C\_total - G\_total \quad (\text{when } C > G)$$

Individual DER Owner Allocation:

$$E\_i = \min(G\_i, C\_i)$$

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Residual generation after self-consumption is aggregated into the shared pool and redistributed proportionally among remaining consumers based on their instantaneous demand.

6. Software Implementation

The framework is realized using Python and C++ on an embedded Linux platform, specifically a Raspberry Pi single-board computer functioning as the feeder-level aggregation controller. Each intelligent meter operates on a microcontroller-based embedded system performing voltage and current sampling at regular intervals.

6.1 Data Acquisition Pipeline: Metering devices attach precise timestamps to each measurement sample and transmit data securely to the aggregation controller using the MQTT messaging protocol. Transport Layer Security (TLS) encryption is applied to all communication channels to ensure data integrity and confidentiality.

6.2 Allocation Engine: At each sampling interval, the controller executes a multi-stage allocation process: (i) ingestion of generation and consumption data, (ii) computation of aggregate totals, (iii) self-consumption allocation for each DER owner, (iv) pooling of residual generation, (v) proportional distribution among demand nodes, (vi) surplus/deficit classification, and (vii) ledger update for billing and audit purposes.

6.3 Loss Detection Module: The system performs continuous loss detection by cross-referencing transformer supply measurements against the summation of metered generation and consumption. Persistent deviations exceeding a configurable threshold trigger alerts for maintenance investigation.

6.4 Communication Architecture: The communication stack utilizes MQTT for local meter-to-controller data transport and HTTPS for controller-to-server communication. Data persistence is managed through a PostgreSQL database at the server tier, with the software stack incorporating paho-MQTT for messaging and NumPy for computational operations.

7. Evaluation and Results

The proposed framework was evaluated using both simulation models and real-time data from a representative residential feeder designated TX-ALPHA-09, comprising 10 household nodes. The monitoring interface provides multiple analytical views including system overview, individual node status, and energy trading transaction details.

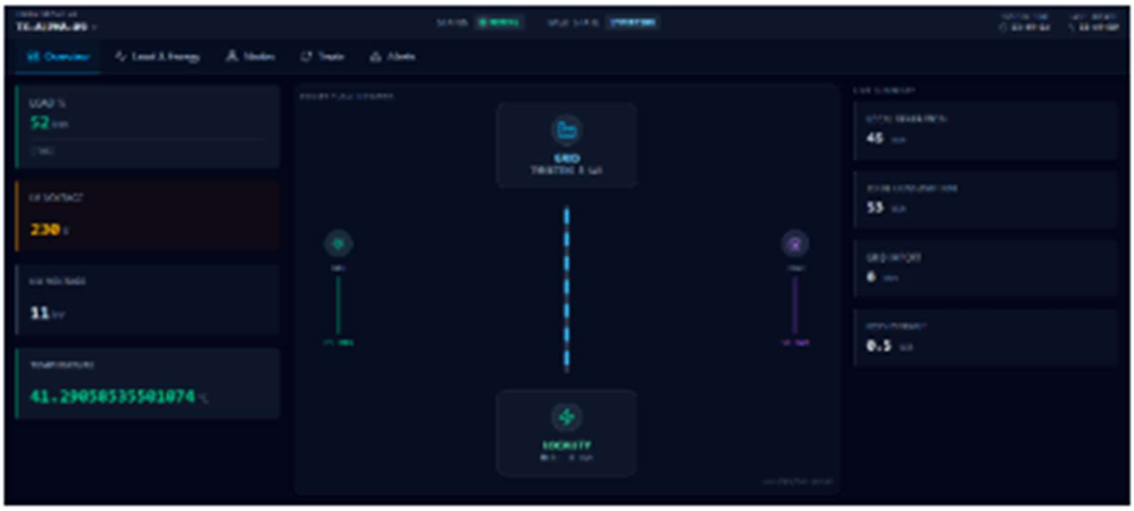

Fig. 2: System monitoring dashboard displaying transformer parameters and energy flow overview

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In the overview analysis, the transformer operates at approximately 70% of rated capacity, maintaining a low-voltage output of 230 V and a high-voltage input of 11 kV. The system records aggregate local generation of 45 kWh against total consumption of 53 kWh, yielding a deficit of 8 kWh supplemented by grid supply. The loss detection module identifies approximately 0.5 kWh of unaccounted energy, confirming proper system operation under realistic load imbalance conditions.

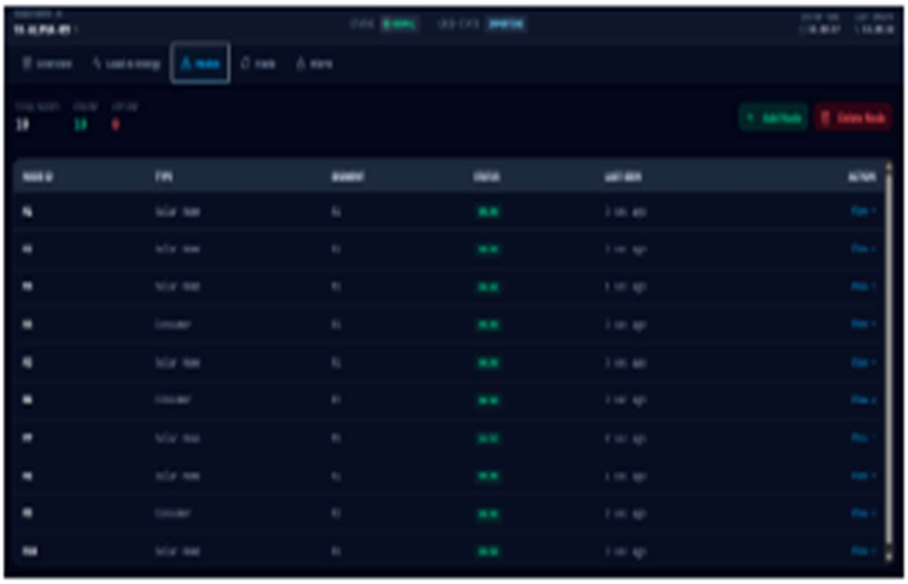

Fig. 3: Node monitoring interface showing real-time status of all connected smart meters

The node monitoring view confirms that all 10 intelligent meters maintain active connectivity with minimal communication latency, with each node reporting updated readings within seconds. This validates the reliability and responsiveness of the communication infrastructure under operational conditions.

Table 1: Summary of Evaluation Results for Feeder TX-ALPHA-09

Parameter	Value
Active Metering Nodes	10
Total Local Generation	45 kWh
Total Local Consumption	53 kWh
Energy Deficit (Grid Supplied)	8 kWh
Detected System Loss	0.5 kWh
Transformer Load Factor	~70%
LV Output / HV Input	230 V / 11 kV
Communication Latency	< 5 seconds

8. Advantages of the Proposed Framework

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The proposed software framework delivers several significant advantages. It maximizes utilization of locally generated renewable energy by enforcing self-consumption priority and cooperative pooling of surplus generation. The real-time monitoring capability provides continuous visibility into energy flows and transformer health, enabling proactive maintenance and operational optimization. The integrated loss detection mechanism enhances grid transparency by systematically identifying technical and non-technical losses. Furthermore, the modular hierarchical architecture ensures natural scalability, allowing seamless expansion to accommodate additional feeders and metering endpoints without fundamental architectural modifications.

9. Conclusion and Future Directions

This paper presented a comprehensive software-driven framework for decentralized peer-to-peer energy exchange within smart distribution networks. The architecture integrates intelligent metering infrastructure, a feeder-level aggregation controller, and a backend analytics engine to facilitate efficient energy allocation, real-time monitoring, and systematic loss detection. The cooperative pooling strategy ensures optimal utilization of locally generated renewable energy while maintaining supply-demand equilibrium across the feeder.

Simulation and evaluation results confirm the framework's effectiveness in managing energy flows within a representative residential feeder, achieving accurate energy accounting with minimal latency. Future research directions include integration of distributed ledger technologies for tamper-proof transaction recording, application of machine learning algorithms for predictive load forecasting and anomaly detection, and development of inter-feeder energy trading protocols to enable broader community-level energy optimization.

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