
A SECURITY-CONSTRAINED PEER-TO-PEER MARKET FRAMEWORK FOR RESILIENT DISTRIBUTION NETWORKS

**Olatunji Obalowu Mohammed^{1,*}, Shereefdeen O. Sanni², Nabila Ahmed Rufa'i³,
Olayinka Sikiru Zakariyya¹**

¹University of Ilorin

²Federal University Oye Ekiti, Nigeria

³University of Birmingham, UK

Email: mohammed.oo@unilorin.edu.ng*, shereefdeen.sanni@fuoye.edu.ng, n.a.rufai@bham.ac.uk,
zakariyya.os@unilorin.edu.ng

***Corresponding author:** Olatunji Obalowu Mohammed

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ABSTRACT

In the quest to decarbonize, decentralize, and digitalize the global energy systems, the conventional electricity consumers are becoming prosumers. This transition has challenged the traditional centralized utility model and demanded a direct, local energy exchange mechanism. Existing literature has neglected the influence of network security constraints on Peer-to-Peer (P2P) energy transactions. This paper therefore introduces a decentralized market framework designed to facilitate localized energy trading within physical grid constraints. An interior-point optimization algorithm balances economic welfare and network stability in the proposed framework. P2P outperforms a holistic benchmark against traditional centralized economic dispatch (CED) based on the IEEE 14-bus test system. The results show a net welfare gain of 375.54 m.u./h under the P2P framework; local generation of 57.83 MW compared to 57.97 MW under CED, achieves a lower operational cost (1125.10 m.u./h) and higher total consumer utility (2783.44 m.u./h) under the proposed P2P market, while nodal voltage profiles remained within the secure operating limit of 1.0206 p.u. Further rigorous testing across different Distributed Energy Resources penetration scenarios shows that the model is stress-resistant for grids. This will provide a scalable and robust solution for modern distribution network operators, where decentralized market clearing discovers previously unavailable network capacity without compromising the network's physical operating limits.

1. INTRODUCTION

Modern electrical distribution networks are rapidly evolving with the integration of small-scale renewables like rooftop solar and local energy storage. This shift has transformed traditional consumers into prosumers who consume and produce electricity, challenging the centralized utility model and creating new operational complexities, such as undervalued local generation and bidirectional power flows (Zheng et al., 2022). Peer-to-peer (P2P) energy trading offers a promising alternative, enabling prosumers and consumers to exchange energy locally without relying solely on utility intermediaries. This approach can enhance community self-sufficiency, reduce transmission losses, and optimize grid asset usage. P2P markets are typically structured across four layers (Aitzhan & Svetinovic, 2018; Dang et al., 2019; Lüth et al., 2018; Ping et al., 2026; Wu et al., 2023; Yan et al., 2023): business (market rules and financial flows), control (grid operations and transactive control), information and communication (secure data exchange and smart metering), and the physical network (infrastructure and reliability) (Ali et al., 2021; Nasiri, 2023; Soto et al., 2021; Zhang et al., 2018). All these layers must coordinate securely and interoperate seamlessly. To preserve overall grid integrity, any proposed energy transaction must be evaluated and either approved or denied based on strict network technical constraints (Nasiri, 2023).

The literature survey has shown that existing research in P2P spans these market layers, with each layer specifically focused on one of the layers within the energy trading framework. (Kang et al., 2017) proposed a secure, decentralized P2P electricity trading system among Plug-in Hybrid Electric Vehicles (PHEVs) using consortium blockchain technology to enhance security and privacy. The system aimed to maximize social welfare by optimizing electricity prices and the amount traded;

however, the system relies on local aggregators (LAGs) to act as energy brokers, run the consensus process, and maintain the blockchain. While this reduces the load on individual PHEVs, it introduces a semi-centralized element. If LAGs are compromised or malfunction, the system's security and reliability could be affected. The paper mentions mechanisms for accountability, but the risk remains.

A framework for prosumer participation in peer-to-peer (P2P) energy trading and flexibility markets was presented in (Khorasany et al., 2022), aiming to enhance grid stability and reduce costs. The flexibility market is cleared through an iterative auction, in which the distribution system operator adjusts the flexibility price to minimize costs, while prosumers independently decide how much flexibility to offer. A graph-based framework for allocating losses in unbalanced radial distribution networks within transactive energy markets was developed in (Nikolaidis et al., 2018), considering physical topology and financial transactions. The sensitivity analysis in the paper reveals that as DG penetration increases, neutral losses also increase. While DG can reduce total phase losses, the increased use of the neutral conductor can counteract these benefits. This introduces a trade-off that is not always straightforward to manage, especially as the impact of DG on neutral losses may not be fully captured in simpler allocation methods.

In (Hoque et al., 2024), a framework for prosumer-centric peer-to-peer energy trading was proposed. A double auction-based P2P trading mechanism was employed, allowing prosumers to submit offers within their dynamic operating envelope limits. In (Morstyn et al., 2018), a Federated Power Plant (FPP) was proposed as a new model that combines the benefits of virtual power plants and P2P energy trading platforms. The FPP is a VPP formed through P2P transactions between self-organizing prosumers. The paper aims to solve the problem of incentivizing coordination among large numbers of DERs owned by different prosumers, each with unique characteristics and preferences. The paper acknowledges that while the FPP concept is promising, several technical and operational challenges remain. For example, it is unclear to what extent a P2P energy trading market can achieve optimal economic benefits for a DER portfolio, or how to ensure that bilateral energy transactions do not breach the physical constraints of local distribution networks.

The application of blockchain technology for managing energy transactions and technical operations in microgrids was proposed in (Di Silvestre et al., 2018). The authors emphasize real-time attribution of power losses to specific transactions and address the complexity introduced by reactive power flows. The blockchain approach was integrated with power flow analysis to improve technical management of microgrids. In (Tong et al., 2026), a non-convex peer-to-peer (P2P) energy trading model for prosumer-based distribution networks was proposed, explicitly accounting for the binary (on/off) operating states of distributed energy resources (DERs), such as gas turbines and energy storage systems. A prosumer-centric internal uncertainty-balancing mechanism using stochastic programming was introduced, allowing each prosumer to absorb uncertainty in renewable generation locally and deliver deterministic net power injections to the network. While the two-stage distributed framework improves convergence and scalability compared to traditional methods, the approach still involves significant computational tasks, especially in large-scale systems with many prosumers and DERs.

Existing literature has focused on business and market layers, with extensive research on market design and loss allocation mechanisms. However, these economic frameworks frequently overlook the physical operational limits of the power network, leading to dispatch strategies that may prove operationally infeasible in practice. This paper introduces a security-constrained P2P market framework that integrates AC power flow into the market clearing process. By integrating physical network constraints directly into the optimization, the proposed approach ensures that all local energy trades are both economically efficient and physically viable. Comparative analysis with traditional centralized dispatch demonstrates that this framework can unlock new network capacity, improve welfare, and maintain grid stability under diverse operating scenarios.

2. METHODOLOGY

This section outlines the integrated framework that bridges the business layer (market clearing) and the physical layer (grid security). The proposed SC-P2P framework models the distribution network as a balanced, single-phase equivalent AC system. The methodology is structured to maximize community social welfare by matching localized generation and demand (Dong et al., 2025). Unlike traditional economic models that focus on economic dispatch without considering consumer benefit,

this framework explicitly couples the economic objective function to nonlinear AC power-flow equations, nodal voltage boundaries, and line thermal limits (Tarashandeh & Karimi, 2024) to maximize participants' welfare. The resulting non-linear, non-convex optimization problem is solved using an Interior Point Method (IPM), ensuring that all cleared Peer-to-Peer (P2P) trades are physically viable and do not compromise the operational stability of the distribution network.

2.1. Participant characteristics

Let $N = \{1, 2, \dots, N\}$ represent the set of all participants (nodes) connected to the local distribution network. At any dispatch interval t , a peer $i \in N$ is characterized by its net power profile, determined by its local load and generation (Hoque et al., 2024; Zhang et al., 2018):

$$P_i^{net}(t) = P_i^{load}(t) - P_i^{gen}(t) \quad (1)$$

Based on this profile, the participant's role is defined as follows:

Buyer: if $P_i^{net}(t) > 0$, peer i has a power deficit and demands $P_i^d(t) = P_i^{net}(t)$.

Seller (prosumer): $P_i^{net}(t) < 0$, peer i has surplus generation to sell, denoted by $P_i^s(t) = P_i^{net}(t)$.

2.2. Market Objective Formulation

The fundamental objective of the local P2P market coordinator is to maximize the total social welfare (W). Welfare is defined as the net difference between the total utility gained by consumers and the total operational cost incurred by producers during the interval t (Kang et al., 2017; Khorasany et al., 2022):

$$\max_{P_{i,j}^{trade}} W = \sum_{i \in N_{buyer}} U_i(P_i^d) - \sum_{j \in N_{seller}} C_j(P_j^s) \quad (2)$$

where

$U_i()$ is the economic benefit function of the consumer i , $C_j()$ is the cost function of generation for the prosumer j and $P_{i,j}^{trade}$ denotes the matched energy quantity cleared between peers i and j .

The economic benefit derived by a consumer i consuming power P_i^d (in MW) is modeled using a concave quadratic utility function:

$$U_i(P_i^d) = \alpha_i P_i^d - \beta_i (P_i^d)^2 \quad (3)$$

where $\alpha_i > 0$ denotes the consumer's baseline willingness-to-pay and $\beta_i > 0$ represents the marginal utility decline parameter.

The operational cost incurred by a prosumer j producing active power P_j^s (in MW) is modeled using a standard convex quadratic function:

$$C_j(P_j^s) = a_j (P_j^s)^2 + b_j P_j^s + c_j \quad (4)$$

where $a_j > 0$, $b_j \geq 0$, and $c_j \geq 0$ represent the cost coefficients reflecting fuel, degradation, and operational expenses of localized DERs.

Before market clearing, participant net injections are calculated as $P_i^{net} = P_i^{load} - P_i^{gen}$. Participants with $P_i^{net} > 0$ bid into the market as buyers demanding $P_i^d = P_i^{net}$, while those with $P_i^{net} < 0$ offer surplus capacity as sellers with $P_j^s = |P_i^{net}|$.

Table 1: Economic Utility and Generation Cost Parameters

Participant	Role	Utility / Cost Function Coefficients	Parameter Values
Bus 2	Seller	$C_2(P_2^s) = a_2(P_2^s)^2 + b_2P_2^s + c_2$	$a_2 = 0.035 \text{ m.u./MW}^2\text{h},$ $b_2 = 20.0 \text{ m.u./MWh}, c_2 = 0.0$
Bus 5	Seller	$C_5(P_5^s) = a_5(P_5^s)^2 + b_5P_5^s + c_5$	$a_5 = 0.025 \text{ m.u./MW}^2\text{h},$ $b_5 = 18.0 \text{ m.u./MWh}, c_5 = 0.0$
Bus 6	Seller	$C_6(P_6^s) = a_6(P_6^s)^2 + b_6P_6^s + c_6$	$a_6 = 0.015 \text{ m.u./MW}^2\text{h},$ $b_6 = 15.0 \text{ m.u./MWh}, c_6 = 0.0$
Bus 8	Seller	$C_8(P_8^s) = a_8(P_8^s)^2 + b_8P_8^s + c_8$	$a_8 = 0.040 \text{ m.u./MW}^2\text{h},$ $b_8 = 25.0 \text{ m.u./MWh}, c_8 = 0.0$
Bus 3	Buyer	$U_3(P_3^d) = \alpha_3P_3^d - \beta_3(P_3^d)^2$	$\alpha_3 = 60.0 \text{ m.u./MWh},$ $\beta_3 = 0.50 \text{ m.u./MW}^2\text{h}$
Bus 9	Buyer	$U_9(P_9^d) = \alpha_9P_9^d - \beta_9(P_9^d)^2$	$\alpha_9 = 55.0 \text{ m.u./MWh},$ $\beta_9 = 0.45 \text{ m.u./MW}^2\text{h}$
Bus 10	Buyer	$U_{10}(P_{10}^d) = \alpha_{10}P_{10}^d - \beta_{10}(P_{10}^d)^2$	$\alpha_{10} = 58.0 \text{ m.u./MWh},$ $\beta_{10} = 0.55 \text{ m.u./MW}^2\text{h}$
Bus 11	Buyer	$U_{11}(P_{11}^d) = \alpha_{11}P_{11}^d - \beta_{11}(P_{11}^d)^2$	$\alpha_{11} = 62.0 \text{ m.u./MWh},$ $\beta_{11} = 0.60 \text{ m.u./MW}^2\text{h}$
Bus 14	Buyer	$U_{14}(P_{14}^d) = \alpha_{14}P_{14}^d - \beta_{14}(P_{14}^d)^2$	$\alpha_{14} = 50.0 \text{ m.u./MWh},$ $\beta_{14} = 0.40 \text{ m.u./MW}^2\text{h}$

2.3. Network Constraints

To guarantee that the market-cleared transactions are secure and physically executable, the optimization is heavily constrained by the physical layer (Dong et al., 2025; Nasiri, 2023; Zimmerman et al., 2010).

2.3.1. AC Power Flow Constraints

The active and reactive power injections at each bus i must satisfy the non-linear AC power balance equations:

$$P_i^{inj} = V_i \sum_{k \in N} V_k (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) \quad (5)$$

$$Q_i^{inj} = V_i \sum_{k \in N} V_k (G_{ik} \sin \theta_{ik} - B_{ik} \cos \theta_{ik}) \quad (6)$$

where V_i and V_k are the voltage magnitudes at buses i and k , θ_{ik} is the voltage angle difference, and G_{ik} and B_{ik} represent the conductance and susceptance elements of the bus admittance matrix (Y_{bus}).

2.3.2. Inequality constraints

To prevent voltage collapse and equipment damage, strict operational boundaries are enforced:

$$V_{min} \leq V_i(t) \leq V_{max} \quad \forall i \in N \quad (7)$$

$$|S_{ik}(t)| \leq S_{ik}^{max} \quad \forall (i, k) \in L \quad (8)$$

where V_{min} and V_{max} are the nodal voltage limits (0.95 p.u. to 1.05 p.u.), $S_{ik}(t)$ is the apparent power flowing through the line connecting the buses i and k , and S_{ik}^{max} is the maximum thermal capacity of branch L .

2.3.3. The Interior Point Method

AC power-flow constraints are highly nonlinear and nonconvex; standard linear-matching algorithms are inadequate. To solve this complex constrained optimization problem, we employ the Interior Point Method (IPM). The IPM is particularly powerful for large-scale Non-Linear Programming (NLP) because it avoids the combinatorial complexity of active-set methods. It handles inequality constraints by converting them into equality constraints with slack variables, then penalizing the slack variables in the objective function via a logarithmic barrier. As the algorithm iterates, a barrier parameter (μ) is gradually reduced toward zero, forcing the solution to converge to the optimal feasible point strictly from within the feasible region (Tarashandeh & Karimi, 2024; Zimmerman et al., 2010).

To apply the IPM, the original welfare maximization problem is rewritten in the standard NLP minimization form:

$$\min_x f(x) = -W \quad (9)$$

Subject to the equality constraints $g(x) = 0$ (the AC power balance equations) and inequality constraints $h(x) \leq 0$ (the voltage and thermal limits), where x represents the vector of state variables (voltages, angles, and power injections).

The IPM transforms the inequality constraints into equality constraints by introducing a vector of strictly positive slack variables s :

$$h(x) + s = 0, \quad s > 0 \quad (10)$$

The objective function is then augmented with a logarithmic barrier term to prevent the slack variables from reaching zero prematurely:

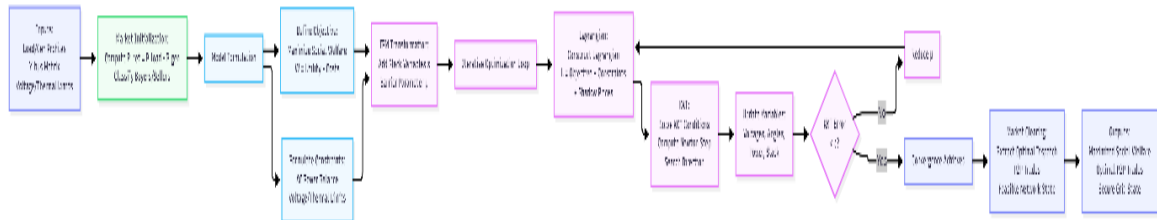
$$\min_{x,s} \left(f(x) - \mu \sum_{m=1}^M \ln(s_m) \right) \quad (11)$$

where: $\mu > 0$ is the barrier parameter, M is the total number of inequality constraints, s_m represents the m -th slack variable.

The Lagrangian of this barrier problem is formulated as:

$$\mathcal{L}_\mu(x, s, \lambda, \gamma) = f(x) - \mu \sum_{m=1}^M \ln(s_m) + \lambda^T g(x) + \gamma^T (h(x) + s) \quad (12)$$

where x represents the decision variables of the grid ($P_{gen}, Q_{gen}, V, \theta$), $f(x)$ is the objective function, representing the negative of the social welfare function ($-W$), s is the slack variable, representing the distance a specific bus or line is from the limit, λ and γ are the Lagrange multipliers associated with equality and transformed inequality constraints, respectively. Figure 1 summarises the methodology framework.



3. RESULTS AND DISCUSSION

Table 2: System Parameters

The optimization is modelled in MATLAB using the MATPOWER environment modified for non-convex P2P market formulations. The interior-point optimization solver (MIPS) handles the nonlinear AC power-flow balance equations and inequality constraints. Convergence is set to $\epsilon = 10^{-6}$ for KKT optimality conditions. Per-unit (p.u.) state variables are explicitly scaled by a base MVA of 100 during optimization and converted back to real-power units (MW) for welfare and dispatch evaluation. To evaluate performance, the proposed P2P framework is benchmarked directly against a standard Centralized Economic Dispatch (CED) model. CED optimizes generation to meet aggregate system demand through a single utility entity. In contrast, the P2P mechanism clears bilateral localized trades while respecting non-linear AC power flows and thermal branch limits.

3.1. Baseline Market Clearing and Network Security

matching total buyer demand (57.00 MW). The slack bus (Bus 1) injected an additional 0.83 MW into the network, serving exclusively as loss-compensation power to cover active transmission line losses (P_{loss}) across the feeder branches without forcing prosumers to bear unallocated physical grid losses.

Table 3: Base case P2P Market Dispatch

Bus Index	Participant Role	Max Capacity (MW)	Cleared Power (MW)	Market Status
Bus 2	Seller	15.00	15.00	Fully Cleared
Bus 3	Buyer	12.00	12.00	100% Demand Met
Bus 5	Seller	20.00	16.84	Partially Cleared
Bus 6	Seller	25.00	25.00	Fully Cleared
Bus 8	Seller	15.00	0.16	Marginal Reserve
Bus 9	Buyer	15.00	15.00	100% Demand Met
Bus 10	Buyer	10.00	10.00	100% Demand Met
Bus 11	Buyer	8.00	8.00	100% Demand Met
Bus 14	Buyer	12.00	12.00	100% Demand Met

Total Slack Grid Power Exchange: 0.83 MW

From Table 3, all buyer demands (Buses 3, 9, 10, 11, and 14) were fully satisfied, totaling 57.00 MW of cleared consumption. Sellers at Buses 2 and 6 operated at full capacity (15.00 MW and 25.00 MW respectively), while Bus 5 cleared 16.84 MW and Bus 8 served as the marginal unit clearing 0.16 MW. Figure 2 illustrates the nodal voltage profile under baseline P2P market clearing. The voltage remains strictly within statutory bounds (0.95 – 1.05 p.u.), peaking at Bus 9 with $V_9 = 1.0361$ p.u.

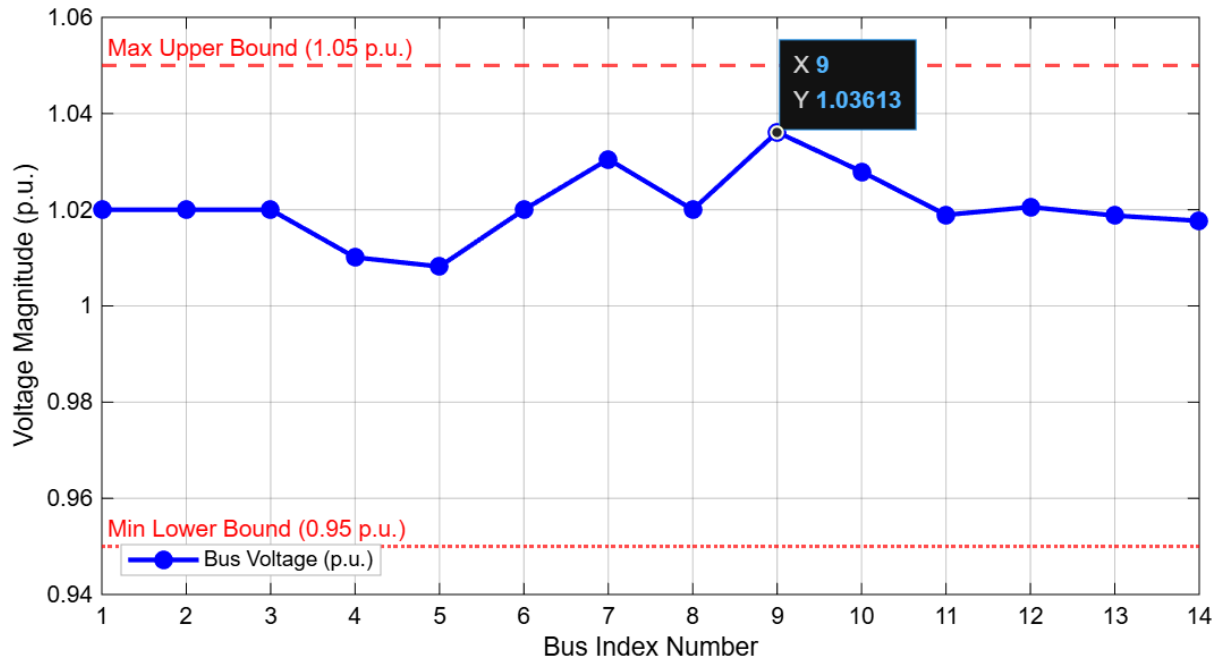


Figure 2: Voltage profile under optimal P2P dispatches for base case scenario

3.2. Comparative Economic and Operational Benchmarking: P2P vs. CED

To quantify performance gains, the proposed framework was benchmarked against traditional centralized economic dispatch.

Table 4: Economic and Operational Benchmarking Metrics

Performance Metric	Centralized Economic Dispatch (CED)	Security-Constrained P2P Market	Operational Differential
Total Operating Cost (C) (m.u./h)	1282.80	1125.10	-157.70 (Lower Cost)
Total Consumer Utility (U) (m.u./h)	2565.60	2783.44	217.84 (Higher Utility)
Net Social Welfare ($W = U - C$) (m.u./h)	1282.80	1658.34	375.54 (Welfare Improvement)
Total Power Generation (ϕ)	57.97	57.83	-0.14 (Loss Reduction)
Average Nodal Voltage (p.u.)	1.0430	1.0206	-0.0224 p.u.

From Table 4, the P2P market structure achieves a lower operational cost and higher total consumer utility (U) achieved under the proposed P2P market (2783.44 m.u./h) compared to CED (2565.60 m.u./h). The P2P market framework achieved a net social welfare of 1658.34 m.u./h, while CED achieved 1282.80 m.u./h, resulting in a net economic welfare improvement of 375.54 m.u./h in addition to loss reduction. Under Centralized Economic Dispatch (CED), consumer demand is inelastic, giving a base-case total utility $U = 2565.60$ m.u./h. The resulting minimum operating cost $C = 1282.80$ m.u./h yields $W = U - C = 1282.80$ m.u./h. The numerical identity $W = C$ shows that C is equal to $0.5 \times U$ at the fixed CED dispatch point. The P2P market reduces system losses by matching buyers with nearby prosumer generation, requiring 0.14 MW less slack grid compensation than centralized dispatch. Total required generation dropped from 57.97 MW under CED to 57.83 MW under P2P, reducing 0.14 MW loss compensation from the slack Bus. The voltage regulation is improved, as CED tends to push generator node voltages higher to force power across long feeder lines, leading to an elevated average nodal voltage of 1.0430 p.u. P2P decentralized clearing maintains a flatter, less stressed voltage profile averaging 1.0206 p.u. preserving distribution equipment health. This demonstrates superior demand-side value realization. While traditional CED exclusively minimizes generator production costs ($\min C$) under passive load constraints, the P2P market-clearing algorithm maximizes net social welfare ($\max W = U - C$). Higher consumer utility (U) in the P2P market indicates that consumers derive greater economic value, satisfaction, and demand fulfillment from their energy consumption compared to traditional Centralized Economic Dispatch (CED).

3.3. Dynamic Operational Stress Scenarios

To verify framework robustness, three severe grid stress scenarios were evaluated: Bus 6 Generation Outage Contingency, High Solar DER Penetration Scenario, and Peak (150%) vs. Off-Peak (50%) Demand Variations.

Table 5: Contingency (Gen outage at Bus 6) P2P Market Dispatch

BUS	ROLE	MAX Capacity (MW)	Cleared (MW)
2	Seller	15.00	15.00
3	Buyer	12.00	12.00
5	Seller	20.00	20.00
6	Seller	0.00	0.00
8	Seller	15.00	15.00
9	Buyer	15.00	15.00
10	Buyer	10.00	10.00
11	Buyer	8.00	1.00
14	Buyer	12.00	12.00

An unexpected loss of the primary supplier at Bus 6 (25.00 MW $\rightarrow$ 0.00 MW) was simulated. Table 5 shows that the algorithm automatically re-cleared the market by ramping up Seller 5 from 16.84 MW (base case) to its maximum capacity of 20.00 MW and ramping up Seller 8 from 0.16 MW to 15.00 MW. Due to localized line thermal capacity bottlenecks following the outage, Buyer 11 demand was partially curtailed from 8.0 MW to 1.0 MW to prevent line overloading. Figure 3 shows the voltage profile under N-1 contingency, where Bus 9 voltage reached a maximum of 1.04167 p.u., proving that the framework successfully maintains voltage stability under major supply contingencies without exceeding the 1.05 p.u. limit.

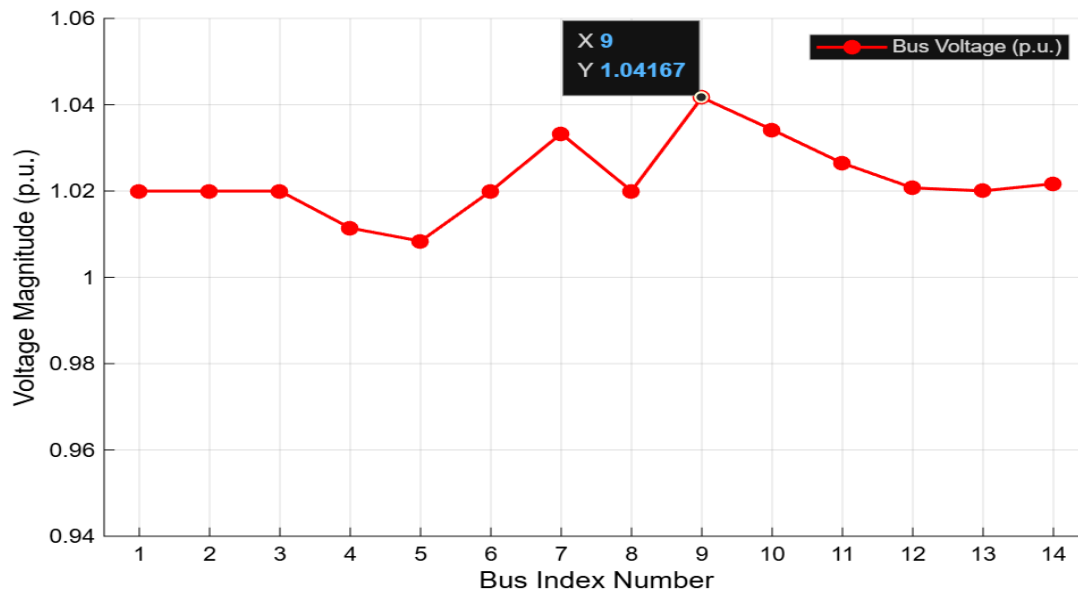


Figure 3: Voltage profile under N-1 contingency scenario

Under high solar DER availability, generation capacity shifts across the network. From Table 6, Seller 8 cleared its maximum capacity of 15.00 MW, allowing Seller 6 to back off generation to 7.00 MW while Seller 5 cleared 20.00 MW. All buyers' demand across all nodes was cleared while maintaining a stable voltage profile peaking at 1.04027 p.u. at Bus 9 as shown in Figure 4.

Table 6: P2P Market Dispatch under High Solar DER penetration

Bus Index	Participant Role	Max Capacity (MW)	Cleared Power (MW)
Bus 2	Seller	15.00	15.00
Bus 3	Buyer	12.00	12.00
Bus 5	Seller	20.00	20.00
Bus 6	Seller	25.00	7.00
Bus 8	Seller	15.00	15.00
Bus 9	Buyer	15.00	15.00
Bus 10	Buyer	10.00	10.00
Bus 11	Buyer	8.00	8.00
Bus 14	Buyer	12.00	12.00

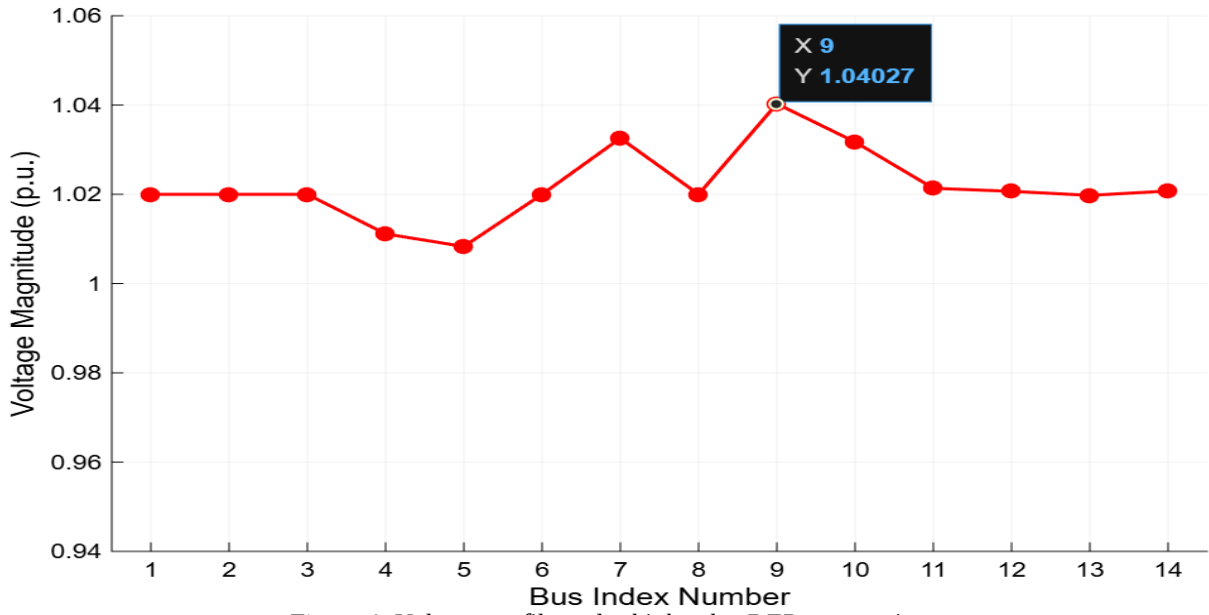


Figure 4: Voltage profile under high solar DER penetration

System performance was evaluated across contrasting loading conditions. At 50% demand, local generation demands are low. It can be seen from Table 7 that high-cost Seller 8 remained offline (0.00 MW), and Seller 5 ramped down to 0.40 MW. Reduced power flows resulted in higher overall line voltages, peaking at 1.03938 at Bus 9 and 1.02054 p.u. at Bus 14 as seen in Figure 5. At 150% demand, all local generators (Sellers 2, 5, 6, and 8) reached their capacity limits (75.00 MW total generation). Heavy power flow caused increased line drops, lowering Bus 14 voltage to 1.00265 p.u. as seen in Figure 5. To prevent thermal overload on feeder branches, Buyer 11 was curtailed to 1.50 MW (out of 12.00 MW demanded), demonstrating that the algorithm prioritizes physical line limits over unconstrained market clearing. Under the 150% peak load scenario, total cleared prosumer generation reaches its aggregate capacity limit of 75.00 MW (15.00 + 20.00 + 25.00 + 15.00 MW). Summing the cleared buyer allocations, Bus 3 (18.00 MW), Bus 9 (22.50 MW), Bus 10 (15.00 MW), Bus 11 (1.50 MW post-curtailment), and Bus 14 (18.00 MW) yields exactly 75.00 MW, confirming power balance consistency across the market.

Table 7: P2P Market Dispatch under off-peak, base case and peak scenarios

Participant Index	Off-Peak (50% Load) Cleared (MW)	Baseline (100% Load) Cleared (MW)	Peak (150% Load) Cleared (MW)
Seller 2	15.00	15.00	15.00
Buyer 3	6.00	12.00	18.00
Seller 5	0.40	16.84	20.00
Seller 6	13.10	25.00	25.00
Seller 8	0.00	0.16	15.00
Buyer 9	7.50	15.00	22.50
Buyer 10	5.00	10.00	15.00
Buyer 11	4.00	8.00	1.500 (Curtailed)
Buyer 14	6.00	12.00	18.00

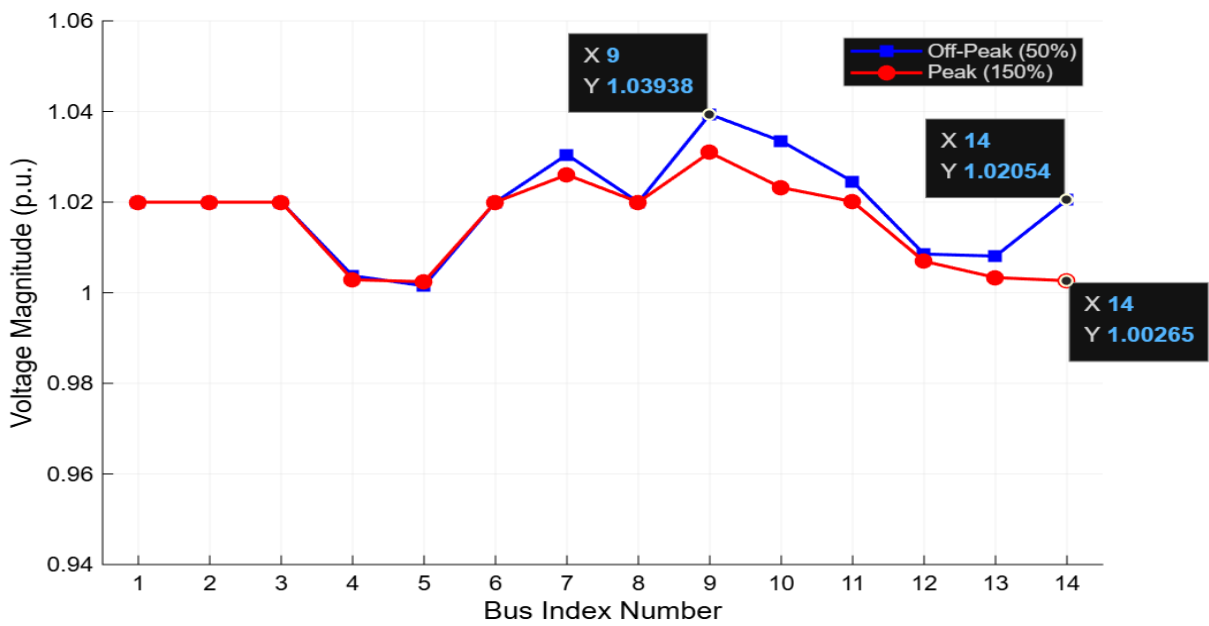


Figure 5: Voltage profile under off-peak and peak scenarios

3.4. IPM Solver Computational Convergence Performance

For the base-case P2P market clearing took 12 iterations to converge within 0.048 seconds, while CED involved 10 iterations to converge within 0.039 seconds. For the N-1 contingency, it took 15 iterations to converge within 0.062 seconds. For high DER penetration, it took 11 iterations to converge within 0.045 seconds. For the off-peak demand, it took 9 iterations to converge within 0.038 seconds, while for peak demand it took 18 iterations to converge within 0.076 seconds. The KKT residual ($\epsilon < 10^{-6}$) for all scenarios.

4. CONCLUSION

This paper presented a security-constrained Peer-to-Peer (P2P) energy market framework designed to bridge the gap between decentralized market clearing and physical distribution network security. By integrating non-linear AC power-flow equations, nodal-voltage boundaries, and branch thermal-capacity limits into a social-welfare maximisation objective, the proposed model ensures that all cleared bilateral trades are physically executable. The non-convex optimisation problem was solved using an Interior Point Method (IPM) with logarithmic barrier penalties, ensuring robust numerical convergence while strictly adhering to operational limits.

Validation on a modified IEEE 14-bus test system demonstrated the operational and economic superiority of the proposed framework over traditional Centralised Economic Dispatch (CED). The P2P market achieved a net economic welfare improvement differential of 375.54 m.u./h while reducing total

required system generation from 57.97 MW to 57.83 MW, yielding a 0.14 MW reduction in active power losses through localised power matching. Furthermore, the market enabled 100% community self-sufficiency for local demand, requiring only 0.83 MW of slack grid power exchange to compensate for network losses. Nodal voltage profiles remained strictly within statutory bounds (0.95 to 1.05 p.u.), yielding a less stressed average nodal voltage of 1.0206 p.u. compared to 1.0430 p.u. under CED.

Rigorous stress testing confirmed the algorithm's adaptability under dynamic grid conditions. During a 25 MW generator contingency at Bus 6, the IPM algorithm seamlessly re-cleared local reserves to maintain system stability. Under a 150% peak load surge, the framework intelligently curtailed demand at Bus 11 to 1.50 MW, proving that physical grid limits are strictly prioritized over unconstrained trade clearing. Overall, the framework provides distribution network operators with a scalable tool to unlock localised DER capacity without compromising grid reliability. Future work will expand this framework to multi-period operational horizons with energy storage degradation models and extend the formulation to unbalanced three-phase distribution systems.

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