

**MODELING AND OPERATION OF LOCAL ELECTRICITY
MARKETS FOR FUTURE POWER DISTRIBUTION
NETWORKS**

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Modeling and Operation of Local Electricity
Markets for Future Power Distribution Networks

by

Bevin K C

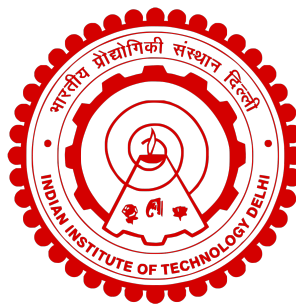
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Certificate

This is to certify that the thesis titled “**Modeling and Operation of Local Electricity Markets for Future Power Distribution Networks**”, submitted by **Bevin K C**, to the Indian Institute of Technology, Delhi, is worthy of consideration for the award of the degree of **Doctor of Philosophy** and is a record of bona fide research work carried out by him. He has worked under my supervision and guidance, and has fulfilled the requirements for the submission of this thesis.

To the best of my knowledge, the results contained in this thesis have not been submitted elsewhere in part or full for the award of any degree or diploma.



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Abstract

The global demand for electricity has surged in recent years, prompting a critical evaluation of the energy landscape and a transition towards renewable energy sources to mitigate environmental challenges. This shift is underscored by ambitious targets set by countries worldwide, emphasizing a move away from traditional fossil fuel based power generation methods. The impending expansion of the transportation sector further emphasizes the need for sustainable alternatives, placing a burden on the electricity sector to adopt low-emission solutions. Despite initial investments favoring large-scale power plants, there is a growing recognition of the importance of small-scale renewable generation for ensuring network reliability. However, the share of local generation remains low since the revenue gained by small-scale generators is only the Feed-in Tariff (FIT), which is very less compared to the cost of buying electricity from the grid. The solution to this issue leads to the emergence Local Electricity Market (LEM). These small-scale markets allow prosumers to sell excess energy to other prosumers within a local community to get better electricity price than the FIT. However, there are lots of challenges in the implementation of such markets.

Since these are small-scale markets confined to a small geographic location, the number of participants at any point in time is usually low. This results in a lack of liquidity for the participants to trade efficiently. The traditional price discovery methods, such as double auction and bilateral trading, face integration challenges

in decentralized systems relying on blockchain technology. Additionally, market settlement in LEM must ensure the reliable operation of power distribution networks, addressing issues like network constraint violations and voltage imbalance. Further, privacy concerns within the LEM highlight the need for innovative solutions to safeguard prosumer data.

This thesis aims to tackle the aforementioned challenges through innovative approaches. To address the lack of liquidity in small-scale markets, a new market design utilizing Automated Market Maker (AMM) with liquidity pools is introduced. In this framework, a liquidity pool is established by aggregating energy commitments from energy storage units capable of delivering and absorbing energy as needed. This enables prosumers to trade directly with the liquidity pool, eliminating the need to search for individual counterparties. Moreover, the market model incorporates an additional transaction approval stage to verify network constraints and compensate for additional losses incurred in the distribution network.

Another critical challenge addressed pertains to the unbalanced nature of voltages in distribution networks. To provide voltage support in unbalanced settings, this thesis introduces Flexible Step Voltage Regulator (FSVR), an enhancement over traditional Step Voltage Regulator (SVR). The FSVR offers superior performance in unbalanced settings by independently controlling both voltage magnitude and angle, unlike traditional SVRs that only control voltage magnitude.

Furthermore, the market model employing AMM is extended to accommodate three-phase unbalanced networks. As unbalanced distribution networks become increasingly loaded, transactions within LEM may lead to violations of network

constraints. This issue is mitigated by integrating the FSVR into the unbalanced distribution network managed by AMM.

Additionally, the thesis ensures the privacy of prosumer bids within the LEM by employing techniques from the cryptography domain. Prosumer bids are encrypted using Paillier encryption, which is homomorphic in nature, allowing computations to be performed on encrypted data. This facilitates Secure Multi-party Computation (SMC), enabling the market operator to conduct market clearing without decrypting prosumer bids. Network congestion management and loss compensation mechanisms are implemented in the market model to ensure its suitability for power system applications. All proposed solutions are validated through numerical simulations performed on standard distribution networks.

सार

हाल के वर्षों में विद्युत की वैश्विक मांग में बढ़ोतरी आई है, जिससे ऊर्जा परिदृश्य का एक महत्वपूर्ण मूल्यांकन और पर्यावरणीय चुनौतियों को कम करने के लिए अक्षय ऊर्जा स्रोतों की ओर बदलाव को बढ़ावा मिला है। यह बदलाव दुनिया भर के देशों द्वारा निर्धारित महत्वाकांक्षी लक्ष्यों द्वारा रेखांकित किया गया है, जिसमें पारंपरिक जीवाश्म ईंधन आधारित विद्युत उत्पादन के तरीकों से दूर जाने पर जोर दिया गया है। परिवहन क्षेत्र का आसान विस्तार टिकाऊ विकल्पों की आवश्यकता पर जोर देता है, जिससे विद्युत क्षेत्र पर कम उत्सर्जन समाधान अपनाने का बोझ पड़ता है। बड़े पैमाने के विद्युत संयंत्रों के पक्ष में शुरुआती निवेश के बावजूद, नेटवर्क विश्वसनीयता सुनिश्चित करने के लिए छोटे पैमाने पर अक्षय उत्पादन के महत्व की मान्यता बढ़ रही है। हालाँकि, स्थानीय उत्पादन की हिस्सेदारी कम बनी हुई है क्योंकि छोटे पैमाने के जनरेटर द्वारा प्राप्त राजस्व केवल फीड-इन टैरिफ (एफआईटी) है, जो ग्रिड से विद्युत खरीदने की लागत की तुलना में बहुत कम है। इस समस्या के समाधान से स्थानीय विद्युत बाजार (एलईएम) का उदय हुआ। ये छोटे पैमाने के बाजार उपभोक्ताओं को एफआईटी से बेहतर बिजली कीमत पाने के लिए स्थानीय समुदाय के अन्य उपभोक्ताओं को अतिरिक्त ऊर्जा बेचने की अनुमति देते हैं। हालाँकि, ऐसे बाजारों के कार्यान्वयन में बहुत सारी चुनौतियाँ हैं।

चूँकि ये छोटे पैमाने के बाजार हैं जो एक छोटे भौगोलिक स्थान तक सीमित हैं, इसलिए किसी भी समय प्रतिभागियों की संख्या आमतौर पर कम होती है। इसके परिणामस्वरूप प्रतिभागियों के लिए कुशलतापूर्वक व्यापार करने के लिए तरलता की कमी हो जाती है। पारंपरिक मूल्य खोज विधियाँ, जैसे दोहरी नीलामी और द्विपक्षीय व्यापार, ब्लॉकचेन तकनीक पर निर्भर विकेंद्रीकृत प्रणालियों में एकीकरण चुनौतियों का सामना करती हैं। इसके अतिरिक्त, एलईएम में बाजार निपटान को नेटवर्क बाधा उल्लंघन और वोल्टेज असंतुलन जैसे मुद्दों को संबोधित करते हुए, बिजली वितरण नेटवर्क के विश्वसनीय संचालन को सुनिश्चित करना चाहिए। इसके अलावा, एलईएम के भीतर गोपनीयता संबंधी चिंताएं उपभोक्ता डेटा की सुरक्षा के लिए नवीन समाधानों की आवश्यकता पर प्रकाश डालती हैं।

इस थीसिस का उद्देश्य नवीन दृष्टिकोणों के माध्यम से उपरोक्त चुनौतियों से निपटना है। छोटे पैमाने के बाजारों में तरलता की कमी को दूर करने के लिए, तरलता पूल के साथ स्वचालित बाजार निर्माता (एएमएम) का उपयोग करने वाला एक नया बाजार डिजाइन पेश किया गया है। इस ढांचे में, आवश्यकतानुसार ऊर्जा वितरित करने और अवशोषित करने में सक्षम ऊर्जा भंडारण इकाइयों से ऊर्जा प्रतिबद्धताओं को एकत्रित करके एक तरलता पूल स्थापित किया जाता है। यह उपभोक्ताओं को तरलता पूल के साथ सीधे व्यापार करने में सक्षम बनाता है, जिससे व्यक्तिगत समकक्षों की खोज करने की आवश्यकता समाप्त हो जाती है। इसके अलावा, बाजार मॉडल नेटवर्क बाधाओं को सत्यापित करने और वितरण नेटवर्क में होने वाले अतिरिक्त नुकसान की भरपाई के लिए एक अतिरिक्त लेनदेन अनुमोदन चरण को शामिल करता है। एक अन्य महत्वपूर्ण चुनौती वितरण नेटवर्क में वोल्टेज की असंतुलित प्रकृति से संबंधित है। असंतुलित सेटिंग्स में वोल्टेज समर्थन प्रदान करने के लिए, यह थीसिस फ्लेक्सिबल स्टेप वोल्टेज रेगुलेटर (एफएसवीआर) पेश करती है, जो पारंपरिक स्टेप वोल्टेज रेगुलेटर (एसवीआर) पर एक वृद्धि है। एफएसवीआर पारंपरिक एसवीआर के विपरीत, जो केवल वोल्टेज परिमाण को नियंत्रित

करते हैं, वोल्टेज परिमाण और कोण दोनों को स्वतंत्र रूप से नियंत्रित करके असंतुलित सेटिंग्स में बेहतर प्रदर्शन प्रदान करता है।

इसके अलावा, एएमएम को नियोजित करने वाले बाजार मॉडल को तीन-चरण असंतुलित नेटवर्क को समायोजित करने के लिए विस्तारित किया गया है। जैसे-जैसे असंतुलित वितरण नेटवर्क तेजी से लोड होते जा रहे हैं, एलईएम के भीतर लेनदेन से नेटवर्क बाधाओं का उल्लंघन हो सकता है। एएमएम द्वारा प्रबंधित असंतुलित वितरण नेटवर्क में एफएसवीआर को एकीकृत करके इस समस्या को कम किया गया है।

इसके अतिरिक्त, थीसिस क्रिप्टोग्राफी डोमेन से तकनीकों को नियोजित करके एलईएम के भीतर अभियोजक की बोलियों की गोपनीयता सुनिश्चित करती है। प्रॉज्यूर बोलियों को पैलियर एन्क्रिप्शन का उपयोग करके एन्क्रिप्ट किया जाता है, जो प्रकृति में होमोमोर्फिक है, जो एन्क्रिप्टेड डेटा पर गणना करने की अनुमति देता है। यह सुरक्षित मल्टी-पार्टी कंप्यूटेशन (एसएमसी) की सुविधा प्रदान करता है, जो बाजार ऑपरेटर को उपभोक्ता बोलियों को डिक्रिप्ट किए बिना बाजार समाशोधन करने में सक्षम बनाता है। बिजली प्रणाली अनुप्रयोगों के लिए इसकी उपयुक्तता सुनिश्चित करने के लिए नेटवर्क भीड़ प्रबंधन और हानि क्षतिपूर्ति तंत्र को बाजार मॉडल में लागू किया जाता है। सभी प्रस्तावित समाधान मानक वितरण नेटवर्क पर किए गए संख्यात्मक सिमुलेशन के माध्यम से मान्य हैं।

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List of Abbreviations

ADMM Alternating Direction Method of Multipliers

AMM Automated Market Maker

BCF Buyer Clearing Factor

BCFL Buyer Clearing Factor with Losses

CC Cluster Coordinator

CIGRE International Council on Large Electric Systems/ Conseil International des
Grands Réseaux Electriques

DLEM Decentralized Local Electricity Market

DSO Distribution System Operator

ESU Energy Storage Unit

FACTS Flexible AC Transmission System

FIT Feed-in Tariff

FSVR Flexible Step Voltage Regulator

GWO Grey Wolf Optimization

IEEE Institute of Electrical and Electronics Engineers

LEM Local Electricity Market

LV Low Voltage

LP Liquidity Pool

MCP Market Clearing Price

MCV Market Clearing Volume

MO Market Operator

MOV Metal Oxide Varistor

MWT Multi-Winding Transformer

OLTC On-Load Tap Changers

P2P Peer to Peer

PT Prosuer Terminal

PTDF Power Transfer Distribution Factors

SCF Seller Clearing Factor

SMC Secure Multi-party Computation

SPDT Single Pole Double Throw

STATCOM Static synchronous Compensator

SVC Static VAR Compensator

SVR Step Voltage Regulator

TPVCD Three Phase Voltage Control Device

UPFC Unified Power Flow Controller

VUF Voltage Unbalance Factor

List of Symbols

E_{LP}^i	Quantity of E-tokens in the LP after i^{th} transaction
M_{LP}^i	Quantity of M-tokens in the LP after i^{th} transaction
k	Constant AMM product
E_{LP}^*	Quantity of virtual E-tokens in the LP
M_{LP}^*	Quantity of virtual M-tokens in the LP
\mathcal{L}	Liquidity constant
ρ_{LP}^i	Liquidity pool price after i^{th} transaction
E_i	Number of E-tokens involved in i^{th} transaction
M_i	Number of M-tokens involved in i^{th} transaction
ρ_i	Energy price for i^{th} iteration
ρ_{lo}	Lower limit of LP price
ρ_{up}	Upper limit of LP price
ρ_{eq}	Equilibrium price in the LP
$M_{ES}^j(n)$	Quantity of M-tokens with ESU located at node ‘ n ’ after j^{th} transaction
$L_{ES}^j(n)$	Quantity of L-tokens with ESU located at node ‘ n ’ after j^{th} transaction
$M_{PR}^i(n)$	Quantity of M-tokens with prosumer located at node ‘ n ’ after i^{th} transaction
B_i	Number of B-tokens involved in i^{th} transaction
S_i	Number of S-tokens involved in i^{th} transaction
$B_{PR}^i(n)$	Quantity of B-tokens with prosumer located at node ‘ n ’ after i^{th} transaction
$S_{PR}^i(n)$	Quantity of S-tokens with prosumer located at node ‘ n ’ after i^{th} transaction
$ES_i(n)$	Additional E-tokens ESU has to deliver to fulfill i^{th} transaction

$ES_{cont}^i(n)$	Quantity of E-tokens ESU is contracted to deliver after i^{th} transaction
$P_G(n)$	Power generation at node ' n '
$P_D(n)$	Power demand at node ' n '
$V(n)$	Voltage at node ' n '
V_{\min}/V_{\max}	Minimum and maximum limits of voltage
P_{l_max}	Maximum limit of real power flow in line ' l '
$PLoss_i$	Sum of real power losses in all the distribution lines after i^{th} iteration
$\Delta Loss_i$	Real power incurred in the network due to i^{th} transaction
ρ_i^{eff}	Effective energy price for i^{th} iteration after compensating for losses
ρ_{ES}^i	Energy price for ESUs after i^{th} iteration
V_{in_p}	Input voltage for phase ' p '
V_{out_p}	Output voltage for phase ' p '
α_p	Tap setting of SVR for phase ' p '
$\alpha_{a1} \dots \alpha_{c3}$	Equivalent tap-setting for each of the 9 windings of FSVR
V_{w1}, V_{w2}	Rated voltage of two sub-windings in output side
α_{eff}	Effective tap-setting of the FSVR
V_{w_eff}	Effective voltage of output side winding
V_{ir}	Rated voltage of input side winding of FSVR
R_{max}	Maximum voltage regulation
PL_{l_p}	Real power loss in line l for phase ' p '
V_{n_p}	Voltage at Bus ' n ' for phase ' p '
I_{l_p}	Current flowing through line ' l ' for phase ' p '
J_{m_p}	Current injections at Bus ' m ' for phase ' p '
SD_{m_p}	Load demand at Bus ' m ' for phase ' p '
L'	Set of line sections connected to bus ' n '

V_i^-	Negative sequence component of voltage at bus i
V_i^+	Positive sequence component of voltage at bus i
N_b	Number of buses in the network
V_{nom}	Nominal voltage
P_{D_ip}	Real power demand by loads in phase p at bus i
Q_{D_ip}	Reactive power demand by loads in phase p at bus i
λ	Load multiplier factor
\mathcal{N}, \mathcal{G}	Public key components
ϕ, μ	Secret key components
b_{ip}	Quantity of energy i^{th} prosumer is willing to buy at price level ρ
s_{ip}	Quantity of energy i^{th} prosumer is willing to sell at price level ρ
\mathcal{B}_i	Ordered list of buy bids for i^{th} prosumer
\mathcal{S}_i	Ordered list of sell offers for i^{th} prosumer
\mathcal{B}_C	Ordered list of aggregate buy bids for C^{th} cluster
\mathcal{S}_C	Ordered list of aggregate sell offers for C^{th} cluster
K_{gen}	Set of keys generated for a billing cycle
PK^t, SK^t	Public key and secret key selected for trading window ' t '
MCP_C^t	MCP for C^{th} cluster during trading window ' t '
BCF_C^t	BCF for C^{th} cluster during trading window ' t '
SCF_C^t	SCF for C^{th} cluster during trading window ' t '
BCFL_C^t	BCF compensated for losses in C^{th} cluster during trading window ' t '
\mathbf{c}_i^t	Cost of buying energy for i^{th} prosumer during trading window ' t '
\mathbf{r}_i^t	Revenue for selling energy for i^{th} prosumer during trading window ' t '
\mathfrak{C}_i^t	Pseudo-cost for i^{th} prosumer during trading window ' t '
\mathfrak{R}_i^t	Pseudo-revenue for i^{th} prosumer during trading window ' t '
