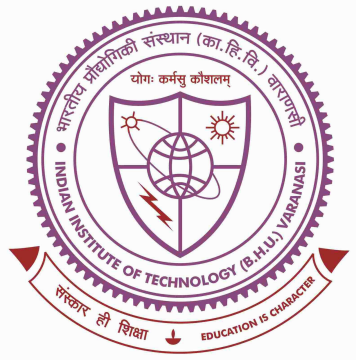
Peer-to-peer Energy Transactions in Active Distribution Network: A Game-theoretic Approach



Thesis submitted in partial fulfillment
for the award of degree

Doctor of Philosophy

by

Monika Mishra

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2024

Dedicated

To

My Beloved Family and Loved Ones

CERTIFICATE

It is certified that the work contained in the thesis titled **Peer-to-peer Energy Transactions in Active Distribution Network: A Game-theoretic Approach** by **Monika Mishra** has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

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DECLARATION

I, **Monika Mishra**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Prof. Rakesh Kumar Misra** and **Prof. Devender Singh** from August-2020 to November-2024, at the Department of Electrical Engineering, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports, dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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It is certified that the above statement made by the student is correct to the best of my/our knowledge.

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Monika Mishra

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Monika Mishra

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Nomenclature

List of Abbreviations

ADMM	Alternating Methods of Multipliers
B2B	Building-to-building
B2C	Building-to-community
BESS	Battery energy storage system
C2C	Community-to-community
DER	Distributed energy resource
DR	Dual residual
DSM	Demand-side management
DSO	Distribution System Operator
GNE	Generalised Nash Equilibrium
HVAC	Heating, ventilation, and air conditioning
KS	Kalai-Smorodinsky
LMP	Locational marginal price
MDR	Mid-market rate
P2P	Peer-to-peer
PR	Primal residual

RES	Renewable energy source
RTDS	Real-time digital simulator
SDR	Supply and demand ratio
SG	Smart grid
SOC	State of charge
SPG	Solar power generation
VC	Virtual community
WPG	Wind power generation
ZEB	Zero energy building

List of Variables and Parameters

$\#^{rt}$	Variables used in real-time scheduling
ϵ^{CE}	Charges due to carbon emission
ϵ^{LS}	Fraction of Load Supplied
η_n^{ch},η_n^{dis}	Charging/discharging efficiency of the battery of VC n
η_n^{loss}	Self-discharge related parameter of the battery of VC n
$\kappa_{d,t}$	Binary variables
λ^P, λ^D	Primal residual and Dual residual
$\Lambda_{d,t}^{DG,P}$,$\Lambda_{d,t}^{DG,Q}$	Active and reactive power bids of DG in dollars per kW unit
Λ_t^{dis}	Weighted coefficient for discomfort due to load shifting at hour t
$\Lambda^{G,P}$,$\Lambda^{G,Q}$	Price of active and reactive power exchange of DSO with main Grid
Λ_t^{im}, Λ_t^{ex}	Price of power import/export from/to utility

Λ^{UTI}	Battery utilization coefficient
$\Lambda_{d,t}^{DG_{in}^{rt}}$,$\Lambda_{d,t}^{DG_{dc}^{rt}}$	DG bidding price for increment and decrement in power in real-time compared to day-ahead values
$\Lambda_{d,t}^{M_{Bid}}$,$\Lambda_{d,t}^{S_{Bid}}$	Bidding prices offered by DGs in main market and supplementary operations
μ,$\lambda^{\#}$	Dual variables of respective equations
$\Omega_{d,t}^{M}$,$\Omega_{d,t}^{S}$	Variables of DSO for clearing the main energy market and supplementary operations
π^{b2b}, π^{b2c},π^{c2c}	incentives in dollars for B2B, B2C, and C2C energy transactions
ρ^{b2b}, ρ^{b2c},ρ^{c2c}	Hourly prices in dollars per kW unit for B2B, B2C, and C2C energy transactions
$\rho_{t,k}^{LMP}$	Locational marginal price of k^{th} bus
σ,ω,δ	Auxiliary variables, dual multipliers, penalty parameters respectively
τ,ν	Given constants
c_d^a, c_d^b, c_d^c	Cost coefficients of DG
$d_{n,m}^{c2c}$	distance between VC n and VC m
f	Generation shift factors
h^a,h^b,h^c	Constants for HVAC loads
i,j,n,m,t,k,k',l,d	Indices $\in \mathbb{N}$
K^{b2b},K^{c2c}	Ratio of savings in optimum case and in best case
K_d	Cost coefficient of distance
$L_{n,i,t}^{max}$,$L_{n,i,t}^{min}$	Maximum/minimum limit for load shifting
M	A very large number

N_n^b	Number of buildings in the VC n
N^c	Number of VCs
$P_{k,t}^D$,$Q_{k,t}^D$	Active and reactive power demand at k^{th} bus
$P_{k,t}^G$,$Q_{k,t}^G$	Active and reactive power generation at k^{th} bus
$P_{n,i,j,t}^{b2b}$,$\pi_{n,i,j,t}^{b2b}$	Power imported by building i from building j and the respective payment
$P_{n,i,t}^{b2c}$,$\pi_{n,i,t}^{b2c}$	Power imported by building i from its VC n and the respective payment
$P_{n,m,t}^{c2c}$,$\pi_{n,m,t}^{c2c}$	Power imported by VC n from VC m and the respective payment
$P_{d,t}^{DG,min}$,$P_{d,t}^{DG,max}$	Active power limits of DGs
$P_{d,t}^{DG}$,$Q_{d,t}^{DG}$	Active and reactive power supplied by d^{th} DG
$P^{G,min}$,$P^{G,max}$	Minimum and maximum limits of active power generations
$P_{1,t}^G$,$Q_{1,t}^G$	Active and reactive power bought from the main Grid
P_l^{max}	Line limits for active power flow at line l
$P_{d,t}^{DG'^{rt}}$,$P_{d,t}^{DG'^{rt}_{in}}$,$P_{d,t}^{DG'^{rt}_{dc}}$	DG power, incremented power and decremented power in pseudo model compared to day-ahead values
$P_{d,t}^{DG'}$,$P_{n,t}^{net'}$	Auxiliary variable for net power injection by DG and VCs, respectively
$P_{d,t}^{DG^{rt}}$	DG power supplied in real-time compared to day-ahead values
$P_{d,t}^{DG_{in}^{rt}}$,$P_{d,t}^{DG_{dc}^{rt}}$	DG power increment and decrement in real-time compared to day-ahead values
$P_{n,t}^{net}$	Net power exchange of n^{th} VC with the utility and other VCs
$P_{d,t}^{DG^{aux}}$	Auxiliary variable
$P_{n,i,t}^b$,$P_{n,i,t}^s$	Power import/export from/to utility

$P_{n,i,t}^{HVAC}$	Electrical power input for HVAC loads
$P_{n,i,t}^{ls}$,$L_{n,i,t}$	Shifted load and Actual load respectively
$P_{n,i}^{max}$,$P_{n,i}^{min}$	Power exchange limit of building i from VC n
$P_{n,t}^{ch}$,$P_{n,t}^{dis}$	Charging/discharging power of battery
$P_{n}^{ch_{max}}$,$P_{n}^{ch_{min}}$	Maximum/minimum limit for charging power of the battery of VC n
$P_{n}^{dis_{max}}$,$P_{n}^{dis_{min}}$	Maximum/minimum limit for discharging power of the battery of VC n
$Q_{d,t}^{DG,min}$,$Q_{d,t}^{DG,max}$	Reactive power limits of DGs
$Q^{G,min}$,$Q^{G,max}$	Minimum and maximum limits of reactive power generations
q^{xb},$q^{\pi b}$	Current power/price strategy set of buildings
q^{xc},$q^{\pi c}$	Current power/price strategy set of VCs
$R_{n,i,t}$	Total renewable generation by building i of VC n
$toll_1$,$toll_2$	Tolerances
V^{min},V^{max}	Minimum and maximum limits of voltages
X,b	Network Parameters
$x^{\#}$	Binary parameters used for indicating connections
X^B,X^C	Strategy set for buildings and VCs
SOC_n^{max},SOC_n^{min}	Maximum/minimum limit for SOC of the battery of VC n
$SOC_{n,t}$	State of charge of the battery of the VC n at hour t
$T_{p_{n,i,t}}^{HVAC}$,$T_{p_{n,i,t}}^{O}$	Temperature of inside and outside environment
$T_{p_{n,i,t}}^{min}$, $T_{p_{n,i,t}}^{max}$	Temperature limits for HVAC loads