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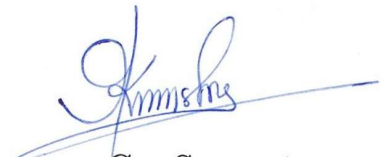
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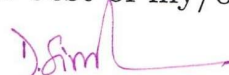
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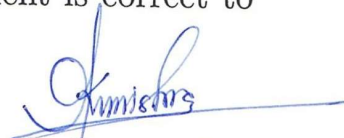
  
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# Acknowledgments

I owe lots of thanks to the people that I have lived around and worked with during the years of my PhD research.

First of all, I express my gratitude to my supervisor **Prof. Devender Singh** and **and co-supervisor Prof. Rakesh Kumar Misra**, Electrical Engineering Department IIT(BHU), Varanasi for his excellent supervision, skilled guidance with lot of patience, **unfailing** support and constant encouragement during my thesis work. I consider it as my **privilege** to have the opportunity to work with him.

I am obliged to Head of the Department and all the faculty members of , Electrical Engineering Department IIT(BHU), Varanasi. I am also obliged to **Mr. Satish Kumar**, Junior Technical Superintendent, Electrical Engineering Department, IIT(BHU), Varanasi.

A very special gratitude goes out to my colleagues and friends with special mention to **Mr. T. Siddartha Reddy**, **Ms. Monika Mishra**, **Ms. Sunidhi Pandey**, **Mr. Basant Kumar Sethi**, **Mr. Debottam Mukherjee**, **Mr. Bablesh Kumar Jha**, **Mr. Abhishek Kumar**, **Ms. Arpita Roy**, and **Ms. Saumya Singh**.

I would like to express my deep sense of gratitude to my parents, my brothers and sister-in-law and my niece for their constant support and encouragement, without which this assignment would have not been completed at all.

Date: 27/06/2022

  
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# Abstract

In the recent decades, Renewable Energy Sources (RESs), mainly Wind Turbines (WT) and Photovoltaics (PV), have become increasingly attractive due to their environmental benefits. With the integration of RESs in the distribution network, the modern era is also witnessing the rapid integration of Electric Vehicles/Plug-in Hybrid Vehicles (EVs/PHEVs) in the power system. Energy Storage Systems (ESSs), either separately installed battery storage systems and/or EVs with Vehicle-to-Grid/Grid-to-Vehicle (V2G/G2V) facilities, accommodate high penetration of RESs by reducing the adverse effects of uncertainties in RESs. ESSs can be effectively used to reduce energy cost, reduce power loss and improve reliability. In addition, advances in Information and Communication Technology (ICT) and smart grid functionalities facilitate end users to participate in energy management through Demand Response (DR) programs. In the new scenario, the Time-of-Use (TOU) pricing offered by the utility based on the availability of RESs generation and wholesale prices influence the customers to change their consumption behavior. The distribution system can be benefited by achieving multiple objectives through optimal scheduling of Distributed Energy Resources (DERs), such as RESs, EVs, Battery Energy Storage Systems (BESSs) and DR programs. Nevertheless, the presence of various energy resource operators, consumers and prosumers with different needs and objectives increases the complexities in operational planning of distribution network. Therefore, an energy management with optimum decisions is needed for coordination of all production and consumption units and maximum utilization of available resources.

Considering the restructuring of the distribution network and the active involvement of multiple operating agents with some conflicting and some non-conflicting goals, integrated scheduling of different DERs controlled by different operators/aggregators is presented in this thesis. The following three aspects have been accomplished under this approach: 1) Day-ahead multi-objective integrated scheduling of DGs, PHEVs and BESSs

in the distribution system with centralized and decentralized approaches. 2) Cooperative scheduling of a network connected Multi-Microgrid (MMG) system with decentralized approach along with internal pricing approach to emphasize the flexibility of Parking Lot (PL) operators and BESSs aggregators. 3) Development of a three-level hierarchical decision making based energy management framework for a distribution system with Multi-Microgrid.

The first aspect is investigated as a multi-objective energy management framework that proposes a combined formulation of energy cost,  $CO_2$  emissions, real power loss and load flattening by considering the integration of PHEVs (G2V and V2G modes), BESSs, and DGs. A  $\varepsilon$ -constraint method is used to obtain Pareto optimal front and optimal scheduling from the distribution utility point of view. A case of the decentralized multi-agent optimization problem in the  $\varepsilon$ -constraint domain has also been formulated.

The second aspect is investigated by proposing a decentralized approach to maximize economic benefits among network-connected Microgrids (MGs) through cooperative scheduling. The cooperative scheduling is based on price signals generated using Shapley value method to encourage MGs to share power among themselves for economic benefits. A microgrid operator (MGO) generates an energy trading status-based time-variable tariff for the PL operators and BESSs aggregators to promote the active participation of PLs and BESSs in the MG's energy management. The uncertainties related to load demand and RESs are modeled using scenario-based methods while the uncertainty associated with PHEV is modeled using copula theory-based estimation.

The third aspect is addressed through a three-level hierarchical decision based multi-objective energy management framework is developed through which multiple operating agents, such as Distribution Utility (DU), MGOs and End-User Aggregators (EUAs), actively engage in energy management to achieve their respective goals. This phase also examines the impact of risk-averse and risk-seeker decisions of MGOs on the operating cost of DU.

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# Nomenclature

## List of Abbreviations

ADN	Active Distribution Network
AER	All Electric Range
BC	Battery capacity
BESS	Battery Energy Storage System
BSS	Battery Swapping Stations
D-BESS	Distributed Battery Energy Storage System
DER	Distributed Energy Resource
DG	Distributed Generation
DL	Dispatchable Load
DNO	Distribution Network Operator
DR	Demand Response
DSM	Demand-Side Management
DU	Distribution Utility
DWDM	Dantzig-Wolfe Decomposition Method
EMS	Energy Management System
EUA	End-User Aggregator

EV	Electric Vehicle
FC	Fuel Cell
G2PL	Grid to Parking Lot
G2V	Grid to Vehicle
GHG	Greenhouse Gas
ICT	Information and Communication Technology
IED	Intelligent Electronic Devices
IGDT	Info-Gap Decision Theory
MCS	Monte-Carlo Simulation
MG	Microgrid
MGA	MGs Aggregator
MGO	Microgrid Operator
MMG	Multi-Microgrid
MT	Micro Turbine
NHTS	National Household Travel Survey
PAR	Peak to Average Ratio
PCC	Point of Common Coupling
PDF	Probability Density Function
PHEV	Plug-in Hybrid Electric Vehicle
PL	Parking Lot
PL2G	Parking Lot to Grid
PLO	Parking Lot operator

POF	Pareto Optimal Front
PV	Photovoltaic
RES	Renewable Energy Source
SDWD	Stochastic Dantzig-Wolfe Decomposition
SG	Smart Grid
SoC	State-of-Charge
SR	Spinning Reserves
SVM	Shapley Value Method
TOU	Time-of-Use
V2G	Vehicle to Grid
WT	Wind Turbines

## List of Variables and Parameters

$\delta_t^{kj}$	Bus voltage angle difference between $k^{th}$ and $j^{th}$ bus at time $t$
$\eta_c, \eta_d$	Charging/discharging efficiency of battery
$\Gamma$	Miles driven by PHEV
$\Gamma_{aer}$	All-electric range of PHEV
$\mu, \lambda, \sigma$	Dual variables
$\nu^{k,j}$	1 if transmission line connected between bus $k$ and $j$ , otherwise 0
$\nu_{t,s}, \nu_{t,s}^{exc,m}, \nu_{t,s}^{MT}$	Binary variables
$\overline{P_{t,s}^{MT}}$	Maximum available capacity of MT at time $t$ under scenario $s$

$\phi_t^m$	Profit/loss allocated to $m^{th}$ MG at time $t$
$\pi_s$	Probability of scenario $s$
$\psi_t(S)$	Profit/loss of coalition $S$ at time $t$
$\psi_t(S - \{m\})$	Profit/loss of coalition $S$ without $m^{th}$ MG participation at time $t$
$\rho^{dg,m}, \rho^{dg,du}$	Dispatchable DG operating cost coefficient of $m^{th}$ MGO and DU
$\rho^d$	Penalty for battery discharging
$\rho^{emi}$	Green house gases emission tariff
$\rho^{min,base}, \rho^{max,base}, \rho^{avg,base}$	Minimum/maximum/average limits of base price offered by DU to MGOs
$\rho^{min,m}, \rho^{max,m}, \rho^{avg,m}$	Minimum/maximum/average limits of offered price of $m^{th}$ MGO to EUAs
$\rho_t^c, \rho_t^d$	Electricity purchase/feed-in tariff for consumers and prosumers
$\rho_t^g$	Main grid electricity tariff
$\rho_t^{base}$	Base price decided by DU at hour $t$
$\rho_t^{c,du}, \rho_t^{d,du}$	Power import/export tariff of DU for MGOs
$\rho_t^{cur,dg}$	DG curtailment price
$\rho_t^{du}$	DU power exchange price for MGOs at hour $t$
$\rho_t^{im,m}, \rho_t^{ex,m}$	Power import/export tariff for $m^{th}$ MG
$\rho_t^m$	Tariff of $m^{th}$ MGO for EUAs at hour $t$
$\rho_t^{n_B,n}$	DR load price corresponding to step $n_B$ of $n^{th}$ EUA at hour $t$

$\rho_t^{up}, \rho_t^{do}$	Up/down-SR tariff
$\underline{\Delta P}, \overline{\Delta P}$	Minimum/maximum limit of load shift
$\Upsilon$	Fraction of miles driven in electric mode
$\zeta$	Load curtailment limit
$A^{sop,k}$	Loss coefficient for SOP converter connected at bus $k$
$B^{kj}, G^{kj}$	Susceptance/conductance of branch between $k^{th}$ and $j^{th}$ bus
$d^{max,n_B,n}$	Maximum limit of power corresponding to step $n_B$ of $n^{th}$ EUA
$d_t^{n_B,n}$	Fraction of scheduled DR load corresponding to step $n_B$ of $n^{th}$ EUA at hour $t$
$E_t^{b,n}, E_t^{ev,n}$	Battery energy level of BESS/PHEV of $n^{th}$ EUA at hour $t$
$E_{t,t'}$	Load elasticity coefficient
$n$	Index of EUA
$N_s, N_{ev}, N_{bess}$	Total number of scenarios/PHEVs in PL/D-BESSs
$N_{bus}, N_{branch}$	Total number of buses and branches in distribution system
$N_{EUA}, N_{MG}, N_{sop}$	Total number of EUAs/MGs/SOPs
$P^{cmax}, P^{dmax}$	Maximum charging/discharging rate of battery
$P^{DGmax,m}, P^{DGmax,du}$	Dispatchable DG power limit of $m^{th}$ MGO and DU
$P^{evmax}$	Maximum limit of PHEVs demand
$P^{imax,m}, P^{exmax,m}$	Maximum limit of power import/export for $m^{th}$ MG
$P^{max,du}$	Power exchange limit for DU
$P^{max,m}$	$m^{th}$ MGO power exchange limit
$P^{max,n}$	Maximum limit of power exchange of $n^{th}$ EUA with its MGO

$P^{MTmax}, P^{MTmin}$	MT maximum/minimum power limit
$P_t^m$	Power exchange of $m^{th}$ MGO with DU at hour $t$
$P_t^n$	Power exchange of $n^{th}$ EUA with MGO at hour $t$
$P_t^{0,n}, P_t^{DR,n}$	EUA consumer load before/after DR at hour $t$
$P_t^{c,b}, P_t^{d,b}$	Charging/discharging power of $b^{th}$ BESS at time $t$
$P_t^{c,ev}, P_t^{d,ev}$	Charging/discharging power of $ev^{th}$ PHEV at time $t$
$P_t^{DGmax,dg}, P_t^{DGmin,dg}$	Maximum/minimum limit of output power of $dg^{th}$ DG at time $t$
$P_t^{dg}$	DG output power at time $t$
$P_t^g$	Power exchange from main grid
$P_t^{k,j}, Q_t^{k,j}$	Active/reactive power flow in line between $k$ and $j$ buses at hour $t$
$P_t^{L,k}$	Active power load at $k^{th}$ bus at time $t$
$P_t^{loss,l}$	Active power loss in $l^{th}$ branch at time $t$
$P_t^{loss,sop,k}$	SOP power loss connected at $k$ bus at hour $t$
$P_t^{sop,k}, Q_t^{sop,k}$	Active/reactive power of sop converter connected at bus $k$ at hour $t$
$P_{t,s}^{c,b}, P_{t,s}^{d,b}$	Charging/discharging power of $b^{th}$ BESS at time $t$ under scenario $s$
$P_{t,s}^{c,ev}, P_{t,s}^{d,ev}$	Charging/discharging power of $ev^{th}$ PHEV at time $t$ under scenario $s$
$P_{t,s}^{im,m}, P_{t,s}^{ex,m}$	$m^{th}$ MG import/export power at time $t$ under scenario $s$
$P_{t,s}^{in,PL}, P_{t,s}^{out,PL}$	Power import/export by parking lot at time $t$ under scenario $s$

$P_{t,s}^L, P_{t,s}^{SL}$	Elastic load before/after load shifting at time $t$ under scenario $s$
$P_{t,s}^{MT}$	MT power at time $t$ under scenario $s$
$P_{t,s}^W, P_{t,s}^{PV}$	Wind/Solar power availability at time $t$ under scenario $s$
$Q_t^{L,k}$	Reactive power load at $k^{th}$ bus at time $t$
$RD^{dg,du}, RU^{dg,du}$	Ramp down/up power limit of dispatchable DG of DU
$RD^{dg,m}, RU^{dg,m}$	Ramp down/up power limit of dispatchable DG of $m^{th}$ MGO
$RU^{MT}, RD^{MT}$	Ramp-up/down limit of MT
$S^{max,k,j}$	Line loading limit
$S_{t,s}^{up,b}, S_{t,s}^{do,b}$	D-BESS contribution in up/down-SR
$S_{t,s}^{up,MT}, S_{t,s}^{do,MT}$	MT contribution in up/down-SR
$SoC^{max}, SoC^{min}$	Maximum/minimum SoC limit
$SoC_t$	State-of-Charge at time $t$
$SoC_{t,s}$	State-of-Charge at time $t$ under scenario $s$
$SoC_{t_{arri}}^{ev}, SoC_{t_{depa}}^{ev}$	SoC level at arrival/departure time of $ev^{th}$ PHEV
$SU^{MT}, SD^{MT}$	Startup/shutdown ramp limit of MT
$t_{arri}, t_{depa}$	Arrival/departure time of PHEV
$u_w^{BESS}, u_w^{EV}, u_w^{PL}$	Weight factor for $w^{th}$ proposal
$V^{max}, V^{min}$	Maximum/minimum limits of bus voltage
$V_t^k$	$k^{th}$ bus voltage at time $t$
$w$	Proposal index in DWDM
$x_m^k, x_{sop}^k, x_{DG}^k$	Status of MG/SOP/DG connected to bus $k$
$Z_w^{BESS}, Z_w^{EV}, Z_w^{PL}$	Energy cost of BESS/EV/PL aggregator for $w^{th}$ proposal

$b$	BESS index
$ev$	PHEV index
$k,j$	System bus indices
$l$	Distribution system branch index
$m$	MG index
$s$	Scenario index
$t$	Time index