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*To*

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It is certified that the work contained in the thesis titled **Multi-agent Energy Management Systems for Active Distribution System** by **Amit Singh** has been carried out under my/our supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

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# DECLARATION

I, **Amit Singh**, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of **Prof. Devender Singh** and **Prof. Rakesh Kumar Misra** from July-2017 to June-2022, at the Departement 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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# 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.

# Contents

# List of Tables

# List of Figures

# 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 discharing |
| $\rho^{emi}$ | 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 |
| $P^{immax,m}$, $P^{exmax,m}$ | 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 $s$ |

| | |
|---|---|
| $P^{L}_{t,s}$, $P^{SL}_{t,s}$ | Elastic load before/after load shifting at time $t$ under scenario $s$ |
| $P^{MT}_{t,s}$ | MT power at time $t$ under scenario $s$ |
| $P^{W}_{t,s}$, $P^{PV}_{t,s}$ | Wind/Solar power availability at time $t$ under scenario $s$ |
| $Q^{L,k}_{t}$ | 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 |
| $S^{up,b}_{t,s}$, $S^{do,b}_{t,s}$ | D-BESS contribution in up/down-SR |
| $S^{up,MT}_{t,s}$, $S^{do,MT}_{t,s}$ | 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 $s$ |
| $SoC^{ev}_{t_{arri}}$, $SoC^{ev}_{t_{depa}}$ | 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 |
| $u^{BESS}_{w}$, $u^{EV}_{w}$, $u^{PL}_{w}$ | Weight factor for $w^{th}$ proposal |
| $V^{max}$, $V^{min}$ | Maximum/minimum limits of bus voltage |
| $V^{k}_{t}$ | $k^{th}$ bus voltage at time $t$ |
| $w$ | Proposal index in DWDM |
| $x^{k}_{m}$, $x^{k}_{sop}$, $x^{k}_{DG}$ | Status of MG/SOP/DG connected to bus $k$ |
| $Z^{BESS}_{w}$, $Z^{EV}_{w}$, $Z^{PL}_{w}$ | 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 |