

**ALGORITHMS FOR ELECTRIC VEHICLE
SCHEDULING IN SMART DISTRIBUTION NETWORKS**

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DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING

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by

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DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING

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Certificate

This is to certify that the thesis entitled “**Algorithms for Electric Vehicle Scheduling in Smart Distribution Networks**”, submitted by **Mr. Bakul Kandpal** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of the original, bona fide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of my knowledge.

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Abstract

The adoption of electric vehicles (EVs) has taken a quick pace. This can be credited to reduction in battery costs and improvement in charging infrastructure, and also in part to shift of consumer choices towards environment-friendly products. As commonly established, rapid increase in EVs will bring several challenges to power grid operations. Few of those challenges being increased demand peaks, intermittency of charging loads, voltage unbalance and voltage deviations in power network, and expensive upgrade required for fast charging infrastructure. In particular, uncoordinated charging of EVs would bring unpredictability in power system operations thereby leading to financial losses to the utility. On the contrary, smart control of EV chargers can curtail, shift or throttle charging demand to reach optimal grid operation. Such intelligent charging, through application programming interfaces (APIs), can be used to shape load profiles of charging stations. Moreover, charging stations with integrated distributed energy resources (DER) can also become prosumers with surplus energy for trading with peers. Every EV user would also have distinct preferences on energy prices, permitted rate of charging or discharging, battery degradation, and information exchange. Further, smart charging algorithm for EVs can suffer from scaling issues where sudden arrival or departure of EVs can bring about additional burden of algorithmic update with new found information. It is also promptly assumed that EVs are always responsive and accept the smart charging signals with no fault. In practice, due to random EV mobility, volatile battery charging characteristics or charging component failures, some EVs would be unable to accept the assigned charging signals dispatched to them. Also, the use of DERs for charging purposes can induce demand-generation mismatch owing to intermittency of photovoltaic (PV) or wind generation plants.

This thesis aims to provide operational and short-term planning of EV energy management to solve the problems stated above, while covering micro-economic aspects,

particularly related to the interactions between EV fleet managers, i.e. EV aggregators (EVAs) and EV owners for finalizing quantity and price of power trade. In particular, social welfare maximization charging strategies for fleets of EVs are proposed, which ease grid operation using vehicle to grid (V2G) support EVs. Further, uncertainty handling optimization techniques are presented to hedge against any randomness in grid loads or DER generation. In particular, using recursive optimization integrated with robust models of EV-PV uncertainties, the proposed methods ensure least welfare loss to EVs or EVAs under a range of unpredictable load-generation scenarios. Moreover, a framework of parallel-operating and fast converging distributed algorithms is also proposed which aims at increased EV user-privacy, improved convergence properties and optimal operation under communication disruptions between EVAs and EVs. Under the proposed methods, PV utilization is maximized by capturing the time correlation of EV charging demands and available PV generation. Moreover, formulation of a peer-to-peer (P2P) market is developed, where EVAs can transact their surplus DER generation to an competitively matched peer considering power loss sensitivity of a low-voltage (LV) distribution network. Finally, this thesis develops privacy preservation methods to mask any coordination signals to be exchanged over decentralized scheduling algorithms, thereby encouraging improved EV user participation in ancillary service demand response (DR) programs.

Various numerical simulations, run for multiple EVAs under CIGRE LV distribution network, show that the proposed methods exhibit low network losses under constrained EV charging, mitigate load unbalance and reduce demand peaks using V2G action, while reduce sub-optimality due to uncertain EV mobility and PV generation. Moreover, the proposed DR strategies help the EVA to proactively reduce financial cost of grid power procurement, while providing fair and rational payoffs based on the power extraction/injection of EVs combined with their battery degradation costs.

सार

विश्व के अनेको देशों में इलेक्ट्रिक वाहनों ईवी को अपनाने में तेजी आई है। इसका श्रेय बैटरी की लागत में कमी और चार्जिंग इंफ्रास्ट्रक्चर में सुधार, और कुछ हद तक पर्यावरण के अनुकूल उत्पादों की ओर उपभोक्ता की पसंद में बदलाव को भी दिया जा सकता है। ईवी के अपनाने में तेजी से वृद्धि पावर ग्रिड संचालन के लिए कई चुनौतियां लाएगी। उन चुनौतियों में बिजली की मांग में वृद्धि, चार्जिंग लोड की अनिश्चितता, वोल्टेज असंतुलन और बिजली नेटवर्क में वोल्टेज विचलन, और फास्ट चार्जिंग इंफ्रास्ट्रक्चर के लिए आवश्यक महंगे अपग्रेड शामिल हैं। विशेष रूप से, ईवी की असंगठित चार्जिंग बिजली प्रणाली के संचालन में अप्रत्याशितता लाएगी जिससे उपयोगिता को वित्तीय नुकसान होगा। इसके विपरीत, ईवी चार्जर का स्मार्ट नियंत्रण इष्टतम ग्रिड संचालन तक पहुंचने के लिए चार्जिंग मांग को कम, शिफ्ट या थ्रॉटल कर सकता है। एप्लिकेशन प्रोग्रामिंग इंटरफेस एपीआई के माध्यम से इस तरह की बुद्धिमान चार्जिंग का उपयोग चार्जिंग स्टेशनों के लोड प्रोफाइल को आकार देने के लिए किया जा सकता है। इसके अलावा, एकीकृत वितरित ऊर्जा संसाधनों डीईआर वाले चार्जिंग स्टेशन भी साथियों के साथ व्यापार करने के लिए अधिशेष ऊर्जा वाले अभियोजक बन सकते हैं। प्रत्येक ईवी उपयोगकर्ता की ऊर्जा की कीमतों, चार्जिंग या डिस्चार्जिंग की अनुमत दर, बैटरी की गिरावट और सूचनाओं के आदान-प्रदान पर अलग-अलग प्राथमिकताएँ होंगी। इसके अलावा, ईवीएस के लिए स्मार्ट चार्जिंग एल्गोरिदम स्केलिंग के मुद्दों से ग्रस्त हो सकता है जहां ईवी के अचानक आगमन या प्रस्थान नई जानकारी के साथ एल्गोरिदमिक अपडेट का अतिरिक्त बोझ ला सकता है। यह भी तुरंत मान लिया जाता है कि ईवी हमेशा उत्तरदायी होते हैं और स्मार्ट चार्जिंग सिग्नल को बिना किसी गलती के स्वीकार करते हैं। व्यवहार में, यादृच्छिक ईवी गतिशीलता, अस्थिर बैटरी चार्जिंग विशेषताओं या चार्जिंग घटक विफलताओं के कारण, कुछ ईवी उन्हें भेजे गए चार्ज सिग्नल को स्वीकार करने में असमर्थ होंगे। इसके अलावा, चार्जिंग उद्देश्यों के लिए डीईआर का उपयोग फोटोवोल्टिक पीवी या पवन उत्पादन संयंत्रों की आंतरायिकता के कारण बिजली की मांग (उत्पादन में बेमेल को प्रेरित कर सकता है।

इस शोषग्रन्थ का उद्देश्य उपरोक्त समस्याओं को हल करने के लिए ईवी ऊर्जा प्रबंधन की परिचालन और अल्पकालिक योजना प्रदान करना है, सूक्ष्म आर्थिक पहलुओं को ध्यान में रखते करते हुए, विशेष रूप से ईवी बेड़े प्रबंधकों, यानी ईवी एग्रीगेटर्स ईवीए और ईवी मालिकों के बीच बातचीत से संबंधित अंतिम रूप देने के लिए बिजली व्यापार की मात्रा और कीमत को निर्धारित किया गया है। विशेष रूप से, ईवी के बेड़े के लिए महत्तम सामाजिक कल्याण अधिकतमकरण चार्जिंग रणनीतियों का प्रस्तावित है, जो वाहन से ग्रिड की ऊर्जा को समर्थन वाले ईवी का उपयोग करके ग्रिड संचालन को आसान बनाते हैं। इसके अलावा, ग्रिड लोड या डीईआर उत्पादन में किसी भी यादृच्छिकता के खिलाफ बचाव के लिए अनिश्चितता से निपटने की अनुकूलन तकनीक प्रस्तुत की जाती है। विशेष रूप से, ईवी पीवी अनिश्चितताओं के मजबूत मॉडल के साथ एकीकृत पुनरावर्ती अनुकूलन का उपयोग करते हुए, प्रस्तावित तरीके अप्रत्याशित लोड (जेनरेशन परिदृश्यों की एक श्रृंखला के तहत ईवीएस या ईवीए को कम से कम कल्याणकारी नुकसान सुनिश्चित करते हैं। इसके अलावा, समानांतर (ऑपरेटिंग और फास्ट कन्वर्जिंग डिस्ट्रीब्यूटेड एल्गोरिदम का एक ढांचा भी प्रस्तावित किया गया है, जिसका उद्देश्य ईवी उपयोगकर्ता (गोपनीयता में वृद्धि, अभिसरण गुणों में सुधार

और ईवीए और ईवी के बीच संचार व्यवधान के तहत इष्टतम संचालन है। प्रस्तावित विधियों के तहत, ईवी चार्जिंग मांगों और उपलब्ध पीवी उत्पादन के समय के सहसंबंध को अन्तर्हित करके पीवी उपयोग को अधिकतम किया जाता है। इसके अतिरिक्त, एक पीयर टू पीयर पीरपी बाजार विकसित किया गया है, जहां ईवीए कम वोल्टेज LV वितरण नेटवर्क की बिजली हानि संवेदनशीलता पर विचार करते हुए प्रतिस्पर्धात्मक रूप से मिलान किए गए पीयर के लिए अपने अधिशेष डीईआर उत्पादन को लेन देन कर सकते हैं। अंत में, यह थीसिस विकेंद्रीकृत शेड्यूलिंग एल्गोरिदम पर आदान प्रदान किए जाने वाले किसी भी समन्वय संकेतों को गोपनीयता सुरक्षित रखने के लिए गोपनीयता संरक्षण विधियों को विकसित करती है, जिससे सहायक सेवा मांग प्रतिक्रिया कार्यक्रमों में बेहतर ईवी उपयोगकर्ता भागीदारी को प्रोत्साहित किया जा सकता है।

CIGRE LV वितरण नेटवर्क के अंतर्गत कई ईवी के लिए चलाए जाने वाले विभिन्न संख्यात्मक सिमुलेशन, दिखाते हैं कि प्रस्तावित तरीके बाध्य ईवी चार्जिंग के तहत कम नेटवर्क नुकसान प्रदर्शित करते हैं, लोड असंतुलन को कम करते हैं और वर्ग कार्रवाई का उपयोग करके बिजली की अधिकतम मांग को कम करते हैं, जबकि अनिश्चित ईवी गतिशीलता के कारण उप इष्टतमता को कम करते हैं और पीवी पीढ़ी। इसके अलावा, प्रस्तावित डीआर रणनीतियाँ ईवीए को ग्रिड से बिजली खरीदने की वित्तीय लागत को सक्रिय रूप से कम करने में मदद करती हैं, जबकि ईवी के बिजली निष्कर्षण इंजेक्शन के आधार पर उचित और तर्कसंगत अदायगी प्रदान करते हुए उनकी बैटरी अवक्रमण लागत के साथ संयुक्त होती हैं।

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Abbreviations

AC	Alternating Current
ADN	Active Distribution Network
ADMM	Alternating Direction Method of Multipliers
API	Application Programming Interface
BESS	Battery Energy Storage System
BMS	Battery Management System
CVAR	Conditional Value at Risk
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generation
DR	Demand Response
DSO	Distribution System Operator
EMS	Energy Management System
EV	Electric Vehicle
EVA	Electric Vehicle Aggregator
EVSE	Electric Vehicle Supply Equipment
LP	Linear Program
LMP	Locational Marginal Pricing
LSF	Loss Sensitivity Factor
LV	Low Voltage
MILP	Mixed Integer Linear Program
MILP	Mixed Integer Non-Linear Program
MPC	Model Predictive Control
NILM	Non-Intrusive Load Monitoring
OPF	Optimal Power Flow
P2P	Peer-to-peer

Abbreviations

PAR	Peak to Average Ratio
PLU	Phase Load Unbalance
PTDF	Power Transfer Distribution Factor
PVS	Previous Value Strategy
RES	Renewable Energy Source
RTP	Real Time Prices
SOC	State of Charge
STS	Static Transfer Switches
TOU	Time of Use
TOU	Transactive Energy Markets
V2B	Vehicle to Building
V2G	Vehicle to Grid
V2H	Vehicle to Home

Symbols

R_t	Solar irradiance at time t
α_t, β_t	Shape parameters for beta distribution function
$R_{\omega,t}$	Irradiation at time t for scenario ω
$R_{\omega,t}^{limit}$	Lower bound of confidence interval of irradiation
$R_{\omega,t}^{max}$	Upper bound of confidence interval of irradiation
Π_ω	Probability of occurrence of scenario ω
\mathcal{J}	Multi-objective function for EV scheduling
$SOC_{n,t}$	SOC of n^{th} EV's battery until at time t
$D_{n,t}^{cost}$	Degradation cost of n^{th} EV at time t
E_0^n	Initial energy of n^{th} EV battery at plug-in
α_t^{base}	Base electricity price received from DSO at time t
B^{ev}	EV battery capacity in kWh
P_t^{CBL}	Customer baseline load
P_t^{buil}	Building load at time t
$P_{\omega,t}^{PV}$	PV output at time t for scenario ω
SOC^{des}	Desired state of charge of EV battery by the user
\mathcal{N}	Total number of EVs connected
W	Set of scenarios of solar irradiation
$\mathbf{x}_{\mathcal{N}}$	Concatenated vector of scheduling variables
\mathcal{T}	Set of hours for which model is run
$\overline{\mathcal{N}}$	Grand coalition of all N connected EVs
$\overline{\mathcal{S}}, \overline{\mathcal{T}}$	Disjoint sub-coalition of EVs within grand coalition
$\mathcal{C}^{el}(\overline{\mathcal{S}})$	Electricity costs for coalition $\overline{\mathcal{S}}$
$\mathcal{C}^{deg}(\overline{\mathcal{S}})$	Degradation costs for coalition $\overline{\mathcal{S}}$
$\theta_t(\overline{\mathcal{N}})$	Electricity costs to building and N EVs
\mathcal{H}	Cost function for electricity costs based on demand

List of Symbols

γ_{ch}	Charging cost per kWh
γ_{dich}	Discharging incentives per kWh
$\xi_{n,t}^c$	Electricity cost allocated to n^{th} EV for time t
$\xi_{n,t}^d$	Discharging incentive allocated to n^{th} EV for time t
σ_i	Mixed strategy of prosumer i over its actions
π_i^s, π_i^b	Price bid by seller or buyer i
p_i^s, p_i^b	Power quantity bid by seller or buyer i
$\bar{\pi}_i^s, \underline{\pi}_i^b$	Maximum/minimum acceptable price limits
$\bar{p}_i^s, \underline{p}_i^b$	Maximum/minimum acceptable power quantity limits
A_i	Regret matching actions of prosumer i
A_{-i}	Regret matching actions of all prosumer excluding i
a_{ij}	Prosumer i choice of trading with prosumer j
$R_{K,i}(a_{ij})$	Regret value for action a_{ij} till iteration K
$\mathcal{N}_S, \mathcal{N}_B$	Set of sellers and buyers respectively
\mathbf{p}_i^{EV}	Aggregated EV charging variable for timeslots in \mathcal{T}
\mathbf{p}_i^{PV}	Aggregated PV generation for timeslots in \mathcal{T}
Q_i	Set of EV energy constraints of prosumer i
f_k^s, f_k^b	Seller and buyer negotiation objective at iteration k
$\mathbf{p}_{n,k}^{EX}$	Power quantity bid by prosumer n at iteration k
α_n, β_n	Economic parameters of prosumer n
π_{fin}	Final contractual price of prosumer pair
SOC_n^{req}	Energy requirements of EV n in kWh
u_i, Ψ_i	Utility function for prosumer matching/negotiations