EFFICIENT AND OPTIMAL OPERATIONAL PLANNING OF ACTIVE DISTRIBUTION SYSTEMS

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by

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I dedicate this thesis to my parents for their unconditional love, support, and faith in me

Certificate

This is to certify that the dissertation entitled '**Efficient and Optimal Operational Planning of Active Distribution Systems**', being submitted by **Ms. Shaziya Rasheed** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering at Indian Institute of Technology Delhi, New Delhi.

Ms. Shaziya Rasheed has worked under our supervision and has fulfilled the requirements for the submission of this dissertation, which to our knowledge has reached the requisite standard. The results obtained here have not been submitted to any other University or Institute for the award of any degree.

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Abstract

The research work presented in this thesis discusses various complex issues associated with distribution networks for their operations and planning. The existing approaches in this respect need significant revision, and thus the work in this thesis primarily aims at developing new efficient approaches to serve this need. The objective is to provide better methodologies for efficient and optimal operational planning of active distribution systems.

The upcoming demand and innovations like digitization, deregulation of power systems, integration of distributed energy resources (DERs), two-way power flow, new technical and business configurations, new players in the marketplace, privatization, and new technologies are compelling to advance distribution operations. However, the transitioning of traditional distribution architecture towards advance and smart active distribution system raises many technical challenges to the utilities. It makes the operations and planning of the distribution system operator more difficult and complex. This motivates the development of methodologies for efficient operational planning of distribution systems to achieve economical, secure, and reliable service.

Network reconfiguration is an important tool for the optimal operation of the distribution system. Depending upon the objective functions and constraints, it provides an optimal configuration of the network. The use of realistic voltage-dependent parameters is crucial in power system analysis and optimization. The impact of voltage-dependent load model on network reconfiguration is established in this thesis. Additionally, the impact of feeder bus/es voltage on network reconfiguration in the case of transmission-distribution coupled networks is also observed in this thesis.

The growing interest in renewable energy sources (RESs) is raising concern over their uncertain behavior. Installing storage devices (SDs) could be a viable solution to handle uncertainty. Moreover, future load and market/grid price are also uncertain and cannot be predicted accurately. Integrating RES and SDs poses more challenges to the operations of the distribution utilities, which demands an efficient modeling technique and framework considering the uncertainties. This thesis addresses the difficulty posed due to the mathematical formulation of SDs and distribution network reconfiguration (DNR), altogether, including the challenges associated with uncertain parameters.

With the progress of competition among companies, the involvement of new market players, and new technologies and business configurations, strategies are needed by every participant/player to survive in the market. Players are needed to make decisions for the anticipated electricity market outcomes. For this, multiplayer power transaction problem is proposed in this thesis to find the Nash equilibrium state. Within the distribution system operator (DSO) framework, there could be alternative arrangements to enable market participation by all entities, including privately owned DERs. In many cases, retailers and similar aggregating agencies facilitate this. Even before finalizing the modalities of the market at the distribution level, it is essential to know about the possible market outcome and its impact on the operational decisions of DSO and vice-versa. This thesis presents a simulation framework and associated case studies, where the market outcome and DSO's operational activities are carried out in tandem to establish a realistic and feasible outcome.

Further, the encouragement to deploy more renewable energy sources and storage devices (R&SD) is giving an opportunity to retailers to install their own DERs. In such cases, a market framework must be designed to maintain the rational behavior of an electricity market. This thesis has modeled the stated scenario for which simulation frameworks of the retail market are proposed considering R&SD owned by retailers in consideration with DSO's operations. The simulation results show the importance of optimal allocation of energy resources in association with rational competition within retailers.

The proposed methodologies have been extensively tested on multiple test systems and detailed discussions on case study results have been presented. The results of test systems illustrate the effectiveness of the proposed methodologies for better operational planning of the active distribution systems.

सार

इस थीसिस में प्रस्तुत शोध कार्य वितरण नेटवर्क के संचालन और योजना से जुड़े विभिन्न जटिल मुद्दों पर चर्चा करता है। इस संबंध में मौजूदा दृष्टिकोणों में महत्वपूर्ण संशोधन की आवश्यकता है, और इस प्रकार इस थीसिस में काम का मुख्य उद्देश्य इस आवश्यकता को पूरा करने के लिए नए कुशल दृष्टिकोण विकसित करना है। इसका उद्देश्य सक्रिय वितरण प्रणालियों की कुशल और इष्टतम परिचालन योजना के लिए बेहतर कार्यप्रणाली प्रदान करना है।

आगामी मांग और नवाचार जैसे डिजिटलीकरण, बिजली प्रणालियों का विनियमन, वितरित ऊर्जा संसाधनों (डीईआर) का एकीकरण, दो-तरफा बिजली प्रवाह, नई तकनीकी और व्यावसायिक विन्यास, बाजार में नए खिलाड़ी, निजीकरण और नई प्रौद्योगिकियां वितरण संचालन कार्यों को आगे बढ़ाने के लिए मजबूर कर रही हैं। हालाँकि, पारंपरिक वितरण वास्तुकला का उन्नत और स्मार्ट सक्रिय वितरण प्रणाली की ओर परिवर्तन उपयोगिताओं के लिए कई तकनीकी चुनौतियाँ खड़ी करता है। यह वितरण प्रणाली ऑपरेटर के संचालन और योजना को अधिक कठिन और जटिल बनाता है। यह किफायती, सुरक्षित और विश्वसनीय सेवा प्राप्त करने के लिए वितरण प्रणालियों की कुशल परिचालन योजना के लिए कार्यप्रणाली के विकास को प्रेरित करता है।

वितरण प्रणाली के इष्टतम संचालन के लिए नेटवर्क पुनर्विन्यास एक महत्वपूर्ण उपकरण है। उद्देश्य कार्यों और बाधाओं के आधार पर, यह नेटवर्क का एक इष्टतम विन्यास प्रदान करता है। बिजली प्रणाली विश्लेषण और अनुकूलन में यथार्थवादी वोल्टेज-निर्भर मापदंडों का उपयोग महत्वपूर्ण है। इस थीसिस में नेटवर्क पुनर्विन्यास पर वोल्टेज-निर्भर लोड मॉडल का प्रभाव स्थापित किया गया है। इसके अतिरिक्त, ट्रांसमिशन-डिस्ट्रीब्यूशन युग्मित नेटवर्क के मामले में नेटवर्क पुनर्विन्यास पर फीडर बस/ईएस वोल्टेज का प्रभाव भी इस थीसिस में देखा गया है।

नवीकरणीय ऊर्जा स्रोतों (आरईएस) में बढ़ती रुचि उनके अनिश्चित व्यवहार पर चिंता बढ़ा रही है। अनिश्चितता से निपटने के लिए स्टोरेज डिवाइस (एसडी) स्थापित करना एक व्यवहार्य समाधान हो सकता है। इसके अलावा, भविष्य का लोड और बाजार/ग्रिड कीमत भी अनिश्चित है और इसका सटीक अनुमान नहीं लगाया जा सकता है। आरईएस और एसडी को एकीकृत करने से वितरण उपयोगिताओं के संचालन में अधिक चुनौतियां पैदा होती हैं, जो अनिश्चितताओं को देखते हुए एक कुशल मॉडलिंग तकनीक और ढांचे की मांग करती है। यह थीसिस एसडी के गणितीय सूत्रीकरण और वितरण नेटवर्क पुनर्विन्यास (डीएनआर) के कारण उत्पन्न कठिनाई को संबोधित करती है, जिसमें अनिश्चित मापदंडों से जुड़ी चुनौतियां भी शामिल हैं।

कंपनियों के बीच प्रतिस्पर्धा की प्रगति, नए बाजार खिलाड़ियों की भागीदारी, और नई प्रौद्योगिकियों और व्यावसायिक विन्यासों के साथ, बाजार में सक्रिय रहने के लिए प्रत्येक भागीदार/खिलाड़ी को रणनीतियों की आवश्यकता होती है। खिलाड़ियों को प्रत्याशित बिजली बाजार परिणामों के लिए निर्णय लेने की आवश्यकता होती है। इसके लिए, नैश संतुलन स्थिति को खोजने के लिए इस थीसिस में मल्टीप्लेयर पावर लेनदेन समस्या प्रस्तावित है। वितरण प्रणाली ऑपरेटर (डीएसओ) ढांचे के भीतर, निजी स्वामित्व वाले डीईआर सहित सभी संस्थाओं द्वारा बाजार भागीदारी को सक्षम करने के लिए वैकल्पिक व्यवस्था हो सकती है। कई मामलों में,

खुदरा विक्रेता और समान एकत्रीकरण एजेंसियां इसकी सुविधा प्रदान करती हैं। वितरण स्तर पर बाजार के तौर-तरीकों को अंतिम रूप देने से पहले भी, संभावित बाजार परिणाम और डीएसओ के परिचालन निर्णयों पर इसके प्रभाव के बारे में जानना आवश्यक है और इसके विपरीत भी। यह थीसिस एक सिमुलेशन ढांचा और संबंधित केस अध्ययन प्रस्तुत करती है, जहां यथार्थवादी और व्यवहार्य परिणाम स्थापित करने के लिए बाजार के परिणाम और डीएसओ की परिचालन गतिविधियों को एक साथ किया जाता है।

इसके अलावा, अधिक नवीकरणीय ऊर्जा स्रोतों और भंडारण उपकरणों (आर&एसडी) को तैनात करने के प्रोत्साहन से खुदरा विक्रेताओं को अपने स्वयं के डीईआर स्थापित करने का अवसर मिल रहा है। ऐसे मामलों में, बिजली बाजार के तर्कसंगत व्यवहार को बनाए रखने के लिए एक बाजार ढांचा तैयार किया जाना चाहिए। इस थीसिस ने बताए गए परिदृश्य को मॉडल किया है जिसके लिए डीएसओ के संचालन को ध्यान में रखते हुए खुदरा विक्रेताओं के स्वामित्व वाले आर&एसडी पर विचार करते हुए खुदरा बाजार के सिमुलेशन ढांचे का प्रस्ताव किया गया है। सिमुलेशन परिणाम खुदरा विक्रेताओं के भीतर तर्कसंगत प्रतिस्पर्धा के साथ ऊर्जा संसाधनों के इष्टतम आवंटन के महत्व को दर्शाते हैं।

प्रस्तावित पद्धतियों का कई परीक्षण प्रणालियों पर बड़े पैमाने पर परीक्षण किया गया है और केस अध्ययन परिणामों पर विस्तृत चर्चा प्रस्तुत की गई है। परीक्षण प्रणालियों के परिणाम सक्रिय वितरण प्रणालियों की बेहतर परिचालन योजना के लिए प्रस्तावित पद्धतियों की प्रभावशीलता को दर्शाते हैं।

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Nomenclature

n	Total number of buses
m	Total number of branches
n_f	Total number of feeder buses
i, j, k	Index to represent bus/node
l	Index to represent branch/line
f	Index to represent feeder bus/node
t	Time step
$\phi(i)$	Set of lines connected with node i
b_{ij}	Susceptance of line connecting node i and j
g_{ij}	Conductance of line connecting node i and j
$P^t_{gen_i}$	Real power produced by generator at node i at time step t
$Q^t_{gen_i}$	Reactive power produced by generator at node i at time step t
$P^t_{load_i}$	Real power load demand at node i at time step t
$Q^t_{load_i}$	Reactive power load demand at node i at time step t
Ψ^t_b/P^t_b	Power quantity/price for bilateral transaction

P_{feeder}^t	Power drawn from substation/feeder at time step t
P_{dch}^t	Power drawn by SD from grid at time step t
P_{ch}^t	Power injected by SD to grid at time step t
γ_k	Self discharging component of SD connected at node k
Δt	Time span
μ_x	Mean value of uncertain quantity x
σ_x	Standard deviation of uncertain quantity x
ϱ_k^t	Binary variable to define the status of SD connected at node k at time step t
ε_k^t	stored energy of SD connected at node k at time step t
$\wp_i^l$	Variable associated with line l connected to node i in SOCP model
Ω_l	Binary variable related to line l shows connectivity of radiality constraints
β_{ij}	Binary variable related to line l connecting node i and j used to define network radiality constraints
I_l^t	Current flows in line l at time step t
Ψ_m^t/P_m^t	Power quantity/price for transaction from market
$\mathfrak{U}_i^t$	Variable associated with node i in SOCP model represents $1/sqrt(2)$ times of square of voltage magnitude
$\Re_{ij}, \Im_{ij}$	Variable associated with line ij in SOCP model
$\langle \bullet \rangle_{min}$	Minimum permissible limit of a variable $\langle \bullet \rangle$
$\langle \bullet \rangle_{max}$	Maximum permissible limit of a variable $\langle \bullet \rangle$

$\eta_{ch,k}$	Discharging efficiency of storage device
$\eta_{dch,k}$	Charging efficiency of storage device
V_i	Voltage magnitude at bus i
Ψ_g^t/P_g^t	Power quantity/price for transaction from grid at time of day charges
P_u^g	Power purchased by u^{th} retailer from WEM
P_u^s	Total load demand for u^{th} retailer
P_{vu}^{sr}	Power purchased from v^{th} RES by u^{th} retailer
P_{wu}^{sdg}	Power purchased from w^{th} DG by u^{th} retailer
P_v^r	Power generated by v^{th} RES
P_w^{dg}	Power generated by w^{th} DG
$\Delta P_{d,i}$	Loss allocated at bus u
$\mathcal{U}_i, \wp_i^l$	Variables associated with conic formulation related with voltage
τ_u	Tariff charged by u^{th} retailer to the consumers
ζ_u	Grid price of electricity for $u^{th} retailer$
x_v^r	Price of power sold by v^{th} RES
x_w^{dg}	Price of power sold by w^{th} DG
A_k, B_k	Cost function parameters of k^{th} DG
$\mathcal{F}_{ji}$	Power flowing in a line connecting bus j and i
f_{ret}^u	Profit incurred by u^{th} retailer
f_R^v	Profit incurred by v^{th} RES

f_{DG}^{w}	Profit incurred by w^{th} DG
$C_w()$	Cost function of w^{th} DG
$f_{obj}^{p}()$	Objective function of a GNEP
$g_{i_p}()$	i_p inequality function(s) of a GNEP
$h_{j_p}()$	j_p equality function(s) of a GNEP
m_p/i_p	Set/number of inequality constraint of a GNEP
n_p/j_p	Set/number of equality constraint of a GNEP
$N/i, j, k$	Set/indices of bus number
$\mathbb{U}/u$	Set/number of retailers
$\mathbb{V}/v$	Set/number of RESs
$\mathbb{W}/w$	Set/number of DGs
N_l/l	Set/number of lines connecting bus u and v
N_g	Set of feeder buses
Z	Set of opened lines for radial configuration
N_g	Set of feeder buses
N	Set of buses
Ω_l	Binary variable, specify '1' when line l is connected and '0' when line l is not connected
$\mathcal{P}_{ij}, \mathcal{Q}_{ij}$	Real and reactive power flowing from bus i to j
$\mathcal{U}_i, \mathcal{J}_{ij}$	Voltage and current related terms used in conic formulation
V_i	Voltage magnitude at bus i

β_{ij}	Binary variable, specify ‘1’ when bus i is the source node of bus j and specify ‘0’, otherwise
$\mathcal{P}_0, \mathcal{Q}_0$	Base real and reactive power consumed by the load at nominal voltage
R_{ij}	Resistance of a line connecting bus i and j
X_{ij}	Reactance of a line connecting bus i and j
c_z, c_i, c_p	Coefficient of constant impedance, constant current, and constant power load model
$I_{ij,max}$	Maximum current limit of a line connecting bus i and j
$V_{i,max}$	Maximum voltage limit at bus i
$V_{i,min}$	Minimum voltage limit at bus i
N_{sd}	Set of buses at which storage devices are installed
N_{R_r}	Set of buses feeded by retailer r
$\varphi\left(l\right)$	Set of line l connected between the bus i and j
f_A	Objective function of algorithm A
f_{B_r}	Objective function of algorithm B for r^{th} retailer
f_{Loss}	Objective function for loss minimization

Acronyms / Abbreviations

DER	Distributed energy resource
DG	Diesel generator
DNR	Distribution network reconfiguration
DSO	Distribution system operator

GNEP	Genralized Nash equilibrium problem
IB	Interfacing bus
KKT	Karush-Kuhn-Tucker
LCP	Linear complementarity problem
MPTP	Multi-player power transaction problem
R&SD	Renewable energy sources and storage devices
RES	Renewable energy source
SD	Storage device
SOCP	Second-order conic programming
WEM	Wholesale electricity market