FLEXIBILITY CONSIDERATIONS IN PLANNING AND OPERATION OF POWER SYSTEMS

SHRUTI RANJAN

Department of Electrical Engineering
Indian Institute of Technology Delhi
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by

SHRUTI RANJAN

Department of Electrical Engineering

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I dedicate this thesis to my parents and husband for all their unconditional love and support.

Certificate

This is to certify that the dissertation entitled '**Flexibility Considerations in Planning and Operation of Power Systems**', being submitted by **Mrs. Shruti Ranjan** 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.

Mrs. Shruti Ranjan 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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Dr. A. R. Abhyankar
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi 110016, India

Date:

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Abstract

The thesis introduces a paradigm shift from traditional to renewable integrated power systems. The rapid increase in electricity demand and the technical modernization of supply have stressed the power system. The paradigm shift occurs as the power sector adopts renewable sources as excellent options for sources of power. Wind and solar power sources are eminent for their sustainability and cleanliness at a meager cost and are being integrated with the power system. The load keeps changing with time and can even be estimated, but it shows significant fluctuation in real-time. The system operator always desires to maintain the generation-load balance for the secure operation of the power system. The traditional conventional power systems were inherently flexible to cope with the change in load or system component outages. The net load change is served either by adjusting the generation of the generating unit or by adjusting the loads over various time intervals. The integration of variable and uncertain renewable sources has raised uncertainty. Integration of renewable sources has increased the need for flexibility on conventional generators' part, creating considerable challenges for generation-load balance maintenance. This has instigated research on developing/boosting the flexibility of the power system. Flexibility across the power system must be addressed and ensured by flexible generation, transmission, demand-side resources, and system operations. The rise in flexibility needs with the proliferation of renewable energy sources (RES) in the system is seen due to increased supply-side variability and uncertainty, displacing part of the conventional generation capacity. Hence, the power system must comprise quick and efficient ramp-up and down power plants that run at low output levels. It should have transmission networks

that access a broad range of generation and load resources with sufficient capacity and limited bottlenecks to access for better-optimized transmission usage. Smart grids allow customers to respond directly to market signals and control load by enabling demand response, storage, and distribution, thus facilitating demand-side flexibility. Flexible system operations incorporate practices that help extract flexibility from the existing physical system, such as making more frequent decisions closer to real-time, improved use of wind and solar forecasting, and better collaboration with neighbors. Thus, the thesis will discuss the flexibility and the approaches to enhance its assessment.

The thesis introduces the unit commitment framework for temporal flexibility assessment (by conventional generating units) at different levels of renewable penetration. It could be a vital exercise to evaluate the flexibility needs of a power system and to know the cause for limiting the system flexibility in accommodating a large amount of RE and uncertainties increment due to it. Unit commitment (UC) plays an essential role in the secure and reliable operation of the power system as it schedules on/off patterns and the generation output of all generating units to meet the load at minimum operating cost for a given time interval. It would reflect the need for flexibility assessment by the conventional generating unit. The work encourages finding out the impact of RES integration on the flexibility requirement of the thermal generation system. The work comprises modeling the traditional deterministic and stochastic unit commitment model and performing comparative analysis underlining the participation of different generating units for providing generation and flexibility.

The thesis also addresses another critical analysis, i.e., the generation schedule varies dramatically, including uncertainty at different levels of wind energy penetration. In RES-integrated power systems, the power generated by the available RES may be less or greater than the day-ahead (DA) RES schedule due to the random nature of RE. Finding a DA schedule closer to the schedule required in real-time (RT) becomes a challenging task for renewable integrated systems. Conventional thermal generators must be flexible enough to ramp up and down to fulfill the changing net demand. The

Independent system operator (ISO) clears the market to maximize social welfare in the multi-settlement market system typically used in US centralized dispatch models. The locational marginal price (LMP) is obtained for both DA and RT markets. As market clearing incorporates load forecast, uncertainties dwell in its mechanism and confirm the need to appropriately adapt the DA market clearing strategies with uncertainties in wind power generation and load forecast. Hence, ensuring operational flexibility by developing the UC model to create a DA schedule close to the RT schedule could be of great importance. The thesis proposes the best day-ahead schedule essential for the secured operation of wind-integrated power systems. This thesis investigates the role of real-time adjustment cost in the unit commitment framework and analyses its impact on the scheduling of generating units. The work is accomplished by developing a unit commitment framework with real-time adjustment costs in a deterministic and stochastic manner for integrated wind systems; and by carrying out a comprehensive comparison between unit commitment models with and without real-time adjustment costs. The work ascertains the need and impact of real-time adjustment cost on the contribution of different generating units in providing generation and flexibility at various levels of wind energy penetration.

Majorly the location and the type of RES suitable to integrate into the power system are based on geographical details and load patterns. The penetration of RES in the system may affect the voltage stability or build congestion in particular lines of the system. As voltage stability and congestion are substantial concerns, analyzing the power system parameters would also play a significant role while planning for integrating RE into the system. Hence, integrating RES at suitable sites will help to get locational flexibility of the system. The thesis lights on the fact that the proliferation of renewable energy sources into the traditional power system raises concern about the site selection for integrating RES at the transmission level. Besides the geographical information and load pattern, the system parameters must be considered to select the site. This thesis provides a proposal in three steps: in the first step, the problem is modeled for identifying the buses suitable for integrating RES in terms of voltage stability. The second step determines the best sites or buses based on network constraints. The final step is combining the above two approaches and finding the most suitable and unsuitable sites for RES integration into the power system by accounting for both methods. Thus, the work facilitates the determination of the best and worst locations for RES integration and the crucial lines or buses responsible for limiting the RE.

The thesis brings forward another issue, i.e., the network's power-transferring capability may limit any generating units' scheduling. Similarly, it can restrict renewable energy utilization due to the RES location in the system. Strengthening the transmission corridors is required to support the maximum dispatch of renewable power. The network must be expanded with minimum additional lines to extract maximum renewable energy from the possible installed RE. Thus, the thesis provides transmission expansion planning to help in identifying congested lines and corridors and gives an idea about system flexibility and the need for new corridors. The work is demonstrated on a real power system network. It identifies the critical lines and the number of circuits for expansion planning in normal and contingency states in a deterministic and stochastic manner. It would provide locational or transmission flexibility, which further helps in delivering operational flexibility. The thesis addresses flexible generation, transmission, and system operations and ensures flexibility across the power system.

सार

थीसिस पारंपरिक से नवीकरणीय एकीकृत बिजली प्रणालियों में एक आदर्श बदलाव का परिचय देती है। बिजली की मांग में तेजी से वृद्धि और आपूर्ति के तकनीकी आधुनिकीकरण ने बिजली व्यवस्था पर जोर दिया है। प्रतिमान परिवर्तन तब होता है जब बिजली क्षेत्र नवीकरणीय स्रोतों को बिजली के स्रोतों के लिए उत्कृष्ट विकल्प के रूप में अपनाता है। पवन और सौर ऊर्जा स्रोत कम लागत पर अपनी स्थिरता और स्वच्छता के लिए प्रसिद्ध हैं और इन्हें बिजली प्रणाली के साथ एकीकृत किया जा रहा है। मांग समय के साथ बदलता रहता है और इसका अनुमान भी लगाया जा सकता है, लेकिन यह वास्तविक समय में महत्वपूर्ण उतार-चढ़ाव दिखाता है। प्रणाली प्रचालक हमेशा बिजली प्रणाली के सुरक्षित संचालन के लिए उत्पादन - मांग संतुलन बनाए रखने की इच्छा रखता है। पारंपरिक पारंपरिक बिजली प्रणालियाँ मांग में परिवर्तन या प्रणाली घटक आउटेज से निपटने के लिए स्वाभाविक रूप से लचीली थीं। शुद्ध मांग परिवर्तन या तो उत्पादन इकाई की उत्पादन को समायोजित करके या विभिन्न समय अंतरालों पर मांग को समायोजित करके किया जाता है। परिवर्तनशील और अनिश्चित नवीकरणीय स्रोतों के एकीकरण ने अनिश्चितता बढ़ा दी है। नवीकरणीय स्रोतों के एकीकरण ने पारंपरिक उत्पादक के हिस्से में लचीलेपन की आवश्यकता को बढ़ा दिया है, जिससे उत्पादन-मांग संतुलन रखरखाव के लिए काफी चुनौतियां पैदा हो गई हैं। इसने विद्युत प्रणाली के लचीलेपन को विकसित करने/बढ़ाने पर अनुसंधान को प्रेरित किया है। बिजली प्रणाली में लचीलेपन को लचीले उत्पादन, पारेषण, मांग-पक्ष संसाधनों और प्रणाली संचालन द्वारा संबोधित और सुनिश्चित किया जाना चाहिए। प्रणाली में नवीकरणीय ऊर्जा स्रोतों (आरईएस) के प्रसार के साथ लचीलेपन की जरूरतों में वृद्धि आपूर्ति-पक्ष परिवर्तनशीलता और अनिश्चितता में वृद्धि के कारण देखी जाती है, जो पारंपरिक उत्पादन क्षमता के हिस्से को विस्थापित करती है। इसलिए, बिजली प्रणाली में त्वरित और कुशल रैंप-अप और डाउन बिजली संयंत्र शामिल होने चाहिए जो कम उत्पादन स्तर पर चलते हैं। इसमें संचरण संजाल होना चाहिए जो बेहतर-अनुकूलित संचरण उपयोग के लिए पर्याप्त क्षमता और सीमित बाधाओं के साथ उत्पादन और मांग संसाधनों की एक विस्तृत श्रृंखला तक पहुंच हो। स्मार्ट ग्रिड ग्राहकों को सीधे बाजार संकेतों पर प्रतिक्रिया करने और मांग प्रतिक्रिया, भंडारण और वितरण को सक्षम करके मांग को नियंत्रित करने की अनुमति देता है, जिससे मांग-पक्ष लचीलेपन की सुविधा मिलती है। लचीले प्रणाली संचालन में ऐसी प्रथाएं शामिल होती हैं जो मौजूदा भौतिक प्रणाली से लचीलापन निकालने में मदद करती हैं, जैसे वास्तविक समय के करीब अधिक बार निर्णय लेना, पवन और सौर पूर्वानुमान का बेहतर उपयोग और पड़ोसियों के साथ बेहतर सहयोग। इस प्रकार, थीसिस अपने मूल्यांकन को बढ़ाने के लिए लचीलेपन और दृष्टिकोण पर चर्चा करेगी।

थीसिस नवीकरणीय प्रवेश के विभिन्न स्तरों पर अस्थायी लचीलेपन मूल्यांकन (पारंपरिक उत्पादन इकाइयों द्वारा) के लिए इकाई प्रतिबद्धता ढांचे का परिचय देती है। बिजली प्रणाली की लचीलेपन की जरूरतों का मूल्यांकन करना और बड़ी मात्रा में आरई को समायोजित करने में प्रणाली लचीलेपन को सीमित करने और इसके कारण अनिश्चितताओं में वृद्धि का कारण जानना एक महत्वपूर्ण अभ्यास हो सकता है। इकाई प्रतिबद्धता (यूसी) बिजली प्रणाली के सुरक्षित और विश्वसनीय संचालन में एक आवश्यक भूमिका निभाती है क्योंकि यह एक निश्चित समय अंतराल के लिए न्यूनतम परिचालन लागत पर मांग को पूरा करने के लिए सभी उत्पादन इकाइयों के प्रतिमान और उत्पादन को सूची करती है। यह पारंपरिक उत्पादन इकाई द्वारा लचीलेपन मूल्यांकन की आवश्यकता को प्रतिबिंबित करेगा। यह कार्य थर्मल उत्पादन प्रणाली की लचीलेपन की आवश्यकता पर आरईएस एकीकरण के प्रभाव का पता लगाने को प्रोत्साहित करता है। कार्य में पारंपरिक नियतिवादी और स्टोकेस्टिक इकाई प्रतिबद्धता मॉडल को मॉडलिंग करना और उत्पादन और लचीलापन प्रदान करने के लिए विभिन्न उत्पादन इकाइयों की भागीदारी को रेखांकित करते हुए तुलनात्मक विश्लेषण करना शामिल है।

थीसिस एक अन्य महत्वपूर्ण विश्लेषण को भी संबोधित करती है, यानी, पवन ऊर्जा प्रवेश के विभिन्न स्तरों पर अनिश्चितता सहित, उत्पादन कार्यक्रम नाटकीय रूप से भिन्न होता है। आरईएस-एकीकृत बिजली प्रणालियों में, आरई की यादृच्छिक प्रकृति के कारण उपलब्ध आरईएस द्वारा उत्पन्न बिजली अगले दिन (डीए) आरईएस अनुसूची

से कम या अधिक हो सकती है। वास्तविक समय (आरटी) में आवश्यक अनुसूची के करीब डीए अनुसूची ढूंढना नवीकरणीय एकीकृत प्रणालियों के लिए एक चुनौतीपूर्ण कार्य बन जाता है। बदलती शुद्ध मांग को पूरा करने के लिए पारंपरिक उष्णता सम्बन्धी उत्पादक को ऊपर और नीचे रैंप करने के लिए पर्याप्त लचीला होना चाहिए। इंडिपेंडेंट सिस्टम ऑपरेटर (आईएसओ) आमतौर पर अमेरिकी केंद्रीकृत प्रेषण मॉडल में उपयोग किए जाने वाले बहु-निपटान बाजार प्रणाली में सामाजिक कल्याण को अधिकतम करने के लिए बाजार को साफ करता है। स्थानीय सीमांत मूल्य (एलएमपी) डीए और आरटी दोनों बाजारों के लिए प्राप्त किया जाता है। चूंकि बाजार समाशोधन में मांग पूर्वानुमान शामिल होता है, अनिश्चितताएं इसके तंत्र में रहती हैं और पवन ऊर्जा उत्पादन और मांग पूर्वानुमान में अनिश्चितताओं के साथ डीए बाजार समाशोधन रणनीतियों को उचित रूप से अनुकूलित करने की आवश्यकता की पुष्टि करती हैं। इसलिए, आरटी अनुसूची के करीब डीए अनुसूची बनाने के लिए यूसी मॉडल विकसित करके परिचालन लचीलापन सुनिश्चित करना बहुत महत्वपूर्ण हो सकता है। थीसिस पवन-एकीकृत बिजली प्रणालियों के सुरक्षित संचालन के लिए आवश्यक सर्वोत्तम दिन-आगे के कार्यक्रम का प्रस्ताव करती है। यह थीसिस इकाई प्रतिबद्धता ढांचे में वास्तविक समय समायोजन लागत की भूमिका की जांच करती है और उत्पादन इकाइयों के अनुसूची पर इसके प्रभाव का विश्लेषण करती है। एकीकृत पवन प्रणालियों के लिए नियतात्मक और स्टोकेस्टिक तरीके से वास्तविक समय समायोजन लागत के साथ एक इकाई प्रतिबद्धता ढांचे को विकसित करके कार्य पूरा किया जाता है; और वास्तविक समय समायोजन लागत के साथ और उसके बिना इकाई प्रतिबद्धता मॉडल के बीच एक व्यापक तुलना करके। यह कार्य पवन ऊर्जा प्रवेश के विभिन्न स्तरों पर उत्पादन और लचीलापन प्रदान करने में विभिन्न उत्पादन इकाइयों के योगदान पर वास्तविक समय समायोजन लागत की आवश्यकता और प्रभाव का पता लगाता है।

मुख्य रूप से बिजली प्रणाली में एकीकृत करने के लिए उपयुक्त स्थान और आरईएस का प्रकार भौगोलिक विवरण और मांग प्रतिमान पर आधारित है। प्रणाली में आरईएस का प्रवेश वोल्टेज स्थिरता को प्रभावित कर सकता है या प्रणाली की विशेष लाइनों में भीड़ पैदा कर सकता है। चूंकि वोल्टेज स्थिरता और भीड़ बड़ी चिंताएं हैं, इसलिए प्रणाली में आरई को एकीकृत करने की योजना बनाते समय बिजली प्रणाली मापदंडों का विश्लेषण भी महत्वपूर्ण भूमिका निभाएगा। इसलिए, उपयुक्त स्थलों पर आरईएस को एकीकृत करने से प्रणाली का स्थानिक लचीलापन प्राप्त करने में मदद मिलेगी। थीसिस इस तथ्य पर प्रकाश डालती है कि पारंपरिक बिजली प्रणाली में नवीकरणीय ऊर्जा स्रोतों का प्रसार संचरण स्तर पर आरईएस को एकीकृत करने के लिए स्थल चयन के बारे में चिंता पैदा करता है। भौगोलिक जानकारी और मांग प्रतिमान के अलावा, स्थल का चयन करने के लिए प्रणाली मापदंडों पर भी विचार किया जाना चाहिए। यह थीसिस तीन चरणों में एक प्रस्ताव प्रदान करती है: पहले चरण में, वोल्टेज स्थिरता के संदर्भ में आरईएस को एकीकृत करने के लिए उपयुक्त बसों की पहचान करने के लिए समस्या का मॉडल तैयार किया गया है। दूसरा चरण संजाल बाधाओं के आधार पर सर्वोत्तम स्थलों या बसों का निर्धारण करता है। अंतिम चरण उपरोक्त दो दृष्टिकोणों को संयोजित करना और दोनों तरीकों को ध्यान में रखते हुए बिजली प्रणाली में आरईएस एकीकरण के लिए सबसे उपयुक्त और अनुपयुक्त स्थलों को ढूंढना है। इस प्रकार, कार्य आरईएस एकीकरण के लिए सर्वोत्तम और सबसे खराब स्थानों और आरई को सीमित करने के लिए जिम्मेदार महत्वपूर्ण लाइनों या बसों के निर्धारण की सुविधा प्रदान करता है।

थासिस एक और व्यापक खोज है, अर्थात, संजाल की विद्युत-स्थानान्तरण क्षमता किसी भी उत्पादन इकाई के अनुसूची को सीमित कर सकती है। इसी तरह, प्रणाली में आरईएस स्थान के कारण सांस्कृतिक ऊर्जा उपयोग उपयोग को प्रतिबंधित कर सकता है। नवीकरणीय ऊर्जा के अधिकतम प्रेषण को समर्थन देने के लिए संचरण गलियारों को मजबूत करना आवश्यक है। संभावित स्थापित आरई से अधिकतम नवीकरणीय ऊर्जा निकालने के लिए संजाल को न्यूनतम अतिरिक्त लाइनों के साथ विस्तारित किया जाना चाहिए। इस प्रकार, थीसिस भीड़भाड़ वाली लाइनों और गलियारों की पहचान करने में मदद करने के लिए संचरण विस्तार योजना प्रदान करती है और प्रणाली लचीलेपन और नए गलियारों की आवश्यकता के बारे में एक विचार देती है। कार्य को वास्तविक विद्युत प्रणाली संजाल पर प्रदर्शित किया जाता है। यह नियतात्मक और प्रसंभाव्य तरीके से सामान्य और आकस्मिक स्थितियों में विस्तार योजना के लिए महत्वपूर्ण लाइनों और सर्किटों की संख्या की पहचान करता है। यह स्थानीय या संचरण लचीलापन प्रदान करेगा, जो आगे परिचालन लचीलापन प्रदान करने में मदद करता है। थासिस लचीली

उत्पादन, संचरण और प्रणाली की संचालन को संबोधित करती है और पूरे बिजली प्रणाली में लचीलापन सुनिश्चित करती है।

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Nomenclature

λ	Load parameter
$V_i\delta_i$	Voltage at bus i
X	Bus reactance matrix
δ	Angle of the buses
η	Value for the k^{th} element of state variable x which consists (δ, V)
ϕ_i	Power factor of load at bus i
σ	Scalar value for step size
θ_l, θ_m	Phase angle at bus l and bus m
K_{di}	Multiplier for load change at bus i
K_{gi}	Multiplier for generation change at bus i
P_{di}, Q_{di}	Real and reactive power demand at bus i
P_{di}^0, Q_{di}^0	Real and reactive load at bus i at base condition
P_{gi}, Q_{gi}	Real and reactive power generation at bus i
P_{gi}^0	Real generation at bus i at base condition
P_{Inji}, Q_{Inji}	Real and reactive power injection at bus i

P_{lm}^{0}	Flow on line *lm* at base case
P_{lm}^{max}	Maximum power that can be transferred on line *lm*
V	Voltage magnitude of the buses
x_{lm}	Inductive reactance of line in per unit
$y_{ij}\theta_{ij}$	$(i,j)^{th}$ element of the system admittance matrix Y_{BUS}
ω	Scenarios, 1 to $N\omega$
b	Buses, 1 to B
i	Generating units, 1 to I
j	Startup cost intervals, 1 to J
l	Lines, 1 to L
NB	Buses, 1 to NB
ND	Load, 1 to ND
NF	Lines, 1 to NF
NG	Conventional generating units, 1 to NG
NS	Solar units, 1 to NS
NW	Wind farms, 1 to NW
s	Generating unit cost curve segments, 1 to S
t	Time hours, 1 to T
w	Wind generating units, 1 to W
$(.)^{\omega}$	Scenario value of variable (.)

$(.)^{max}$	Maximum value of variable (.)
$(.)^{min}$	Minimum value of variable (.)
0_n	$(n * 1)$ vector of all zeros
ρ^{ω}	Probability of scenario ω
A_D	$(NB * ND)$ bus-load unit incidence matrix
A_F	$(NB * NF)$ bus-line incidence matrix
A_G	$(NB * NG)$ bus-generating unit incidence matrix
A_i	Fixed generation cost of the generating unit i (\$)
A_S	$(NB * NS)$ bus-solar unit incidence matrix
A_W	$(NB * NW)$ bus-wind unit incidence matrix
B	$(NF * 1)$ vector for susceptance of line
C_G	$(NG * 1)$ vector for generation cost of generating unit NG (Rs.)
CT	$(NF * 1)$ vector for new transmission line NF cost (Rs.)
$d_m(t)$	Demand at bus m (MW)
$G_i^{on\_off}$	On-off status of generating unit i at time $t{=}0$
K_s	Cost curve slope of segment s of generating unit i (\$/MW)
L	$(NF * 1)$ vector for existing transmission line NF
l_{mn}^{max}, l_{mn}^{min}	Maximum and minimum capacity of transmission line between bus m and n, respectively (MW)
MT_i^{dn}	Minimum down time of generating unit i (h)
MT_i^{up}	Minimum up time of generating unit i (h)

P_{base}	Base MVA
PG_i^0	Generating unit i output at time $t=0$ (MW)
$PG_i^{max}(t)$	Maximum value of generating unit i output (MW)
$PG_i^{min}(t)$	Minimum value of generating unit i output (MW)
$ramp_i^{up}$	Ramp-up limit of generator i (MW/h)
$SUC_{i,j}^{sw}$	Step-wise cost of generating unit i ($)
$SUC_{i,j}^{tlim}$	Step-wise time duration of generating unit i (h)
$TD_i^{dn,min}$	Time duration for which the generating unit i bounded to be off at the start of the planning horizon (h)
$TD_i^{up,min}$	Time duration for which the generating unit i bounded to be on at the start of the planning horizon (h)
$TG_i^{dn,int}$	Time for which generating unit i has been down, before time $t=0$ (h)
$TG_i^{up,int}$	Time for which generating unit i has been up, before time $t=0$ (h)
$WG_w(t)$	Output of wind generating unit w at time t (MW)
X_{mn}	Reactance of line connecting nodes mn (ohms)
δ	$(NB * 1)$ vector for bus voltage angle (radian)
δ^C	$(NB * 1)$ vector for bus voltage angle after contingency (radian)
$\theta_m(t)$	Voltage angle at bus m at time t (radian)
$ADJC_i$	Real time adjustment cost of generating unit i ($)
$d_m^{new}(t)$	New uncertain demand on bus m at time t due to load deviation (MW)
K	$(NF * 1)$ vector for new transmission line NF

P_D	$(ND * 1)$ vector for load (MW)
P_F	$(NF * 1)$ vector for power flow in line NF (MW)
P_F^C	$(NF * 1)$ vector for power flow in line after contingency NF (MW)
P_G	$(NG * 1)$ vector for generation of generating unit NG (MW)
P_S	$(NS * 1)$ vector for generation of solar unit NS (MW)
P_W	$(NW * 1)$ vector for generation of wind unit NW (MW)
$P_{dev,i}(t)$	Power deviation in schedule of generating unit i at time t (MW)
$PG_i(t)$	Generating unit i output at time t (MW)
$PG_{i,s}(t)$	Generation by generating unit i on segment s at time t (MW)
$PG_i^{DA}(t)$	Day ahead scheduled power of generating unit i at time t (MW)
$PG_i^{RT}(t)$	Uncertain real time schedule power of generating unit i at time t (MW)
$SUC_i(t)$	Start-up cost of generator i at time t (\$)
$u_{i,j}(t)$	Binary variable equal to 1, if generator i is started at time t after being off for j hours; and 0, otherwise
$WG_w^{new}(t)$	New output of wind generating unit w at time t due to deviation in wind power (MW)
$x_i(t)$	Binary variable equal to 1, if generator i is producing at time t; and 0, otherwise
$y_i(t)$, $z_i(t)$	Binary variables for start-up and shutdown of generating unit i at time t, respectively

Acronyms / Abbreviations

2PEM	Two-Point estimate method
ANN	Artificial neural network
ATC	Available transfer capability
BARON	Branch-And-Reduce Optimization Navigator
BB	Branch and bound method
BD	Benders decomposition
CPF	Continuation power flow method
DA	Day-Ahead
DP	Dynamic programming
DUC	Deterministic unit commitment
DUCRTA	Deterministic unit commitment with real-time adjustment cost
FACTS	Flexible AC transmission systems
FFT	Fast fourier transformation
GA	Genetic algorithm
GAMS	General algebraic modeling system
IPM	Interior point method
ISO	Independent system operators
LMP	Locational marginal price
LP	Linear programming
LR	Lagrangian relaxation

MCS	Monte Carlo simulation method
MINLP	Mixed integer non-linear programming
MIP	Mixed integer programming
OPF	Optimal power flow
PDF	Probability distribution function
PEM	Point estimate method
PJM	Pennsylvania-New Jersey-Maryland Interconnection
PSO	Particle swarm optimization technique
PTDF	Power transfer distribution factor
RAC	Reliability assessment and commitment
RES	Renewable energy sources
RT	Real-Time
RTO	Regional transmission organization
STUC	Stochastic unit commitment
SUCRTA	Stochastic unit commitment with real-time adjustment cost
TSM	Tabu search method
UC	Unit commitment
UCRTA	Unit commitment framework with real-time adjustment cost