Energy Systems (2020) 11:1–19
https://doi.org/10.1007/s12667-018-0306-8

ORIGINAL PAPER

Flexible line ratings in stochastic unit commitment for power systems with large-scale renewable generation

Jiaying Shi[1] · Shmuel S. Oren[1]

Received: 13 March 2018 / Accepted: 7 September 2018 / Published online: 21 September 2018

Abstract
The thermal ratings of overhead transmission lines are typically conservative, which leads to underutilization of transmission assets. In this paper, we propose an optimization model that accounts for the inherent flexibility in line ratings of thermal restricted transmission lines. We determine, in a stochastic unit commitment framework, when and which line can and should adopt higher ratings (calculated based on anticipated weather conditions and loading) as part of the recourse actions. Such recourse decisions in the second stage models the capability of the transmission system to provide flexibility to mitigate the variability of renewable generation. Flexible line ratings in the recourse help improve first-stage commitment decisions. Numerical tests conducted on both IEEE 118 system and a network representing the Central European System demonstrate that with flexible line ratings recourse, the expected operation cost can be substantially reduced without degrading reliability.

Keywords Line ratings · Power systems · Renewable generation · Stochastic unit commitment · Topology control

Abbreviations

Sets:

T	Set of time periods $\{1, 2, \ldots, 24\}$.
G	Set of generators.
N	Set of buses/nodes.
$N(i)$	Set of buses/nodes that have transmission lines connected to bus i.
GF	Set of fast generators.

This work is supported by the National Science Foundation under the EAGER program NSF Award no 1549572.

✉ Shmuel S. Oren
oren@ieor.berkeley.edu

[1] Department of Industrial Engineering and Operations Research, The Tsinghua-Berkeley Shenzhen Institute, University of California, Berkeley, CA 94709, USA

GS	Set of slow generators.
RG	Set of renewable generators.
S	Set of scenarios.
Z	Set of control zones.

Indices:

t	Time period indices; $t \in T$.
i, j	Bus/node indices; $i, j \in N$.
g	Generator indices; $g \in G$.
s	Scenario indices; $s \in S$.

Parameters:

h_g	Start-up cost of generator g.
k_g	No-load cost of generator g.
c_g	Fuel cost of generator g.
ρ_i	Penalty cost of load shedding on bus i.
$\hat{t}_{ij}^{H}$	Maximal consecutive time periods of high rating for line ij.
$\hat{t}_{ij}^{N}$	Minimal normal rating time periods for line ij after adopting high rating.
$F_{ij}^{\max,\text{normal}}$	Normal flow capacity of line ij.
$F_{ij}^{\max,\text{high}}$	High flow capacity of line ij.
B_{ij}	Susceptance of line ij.
π_s	The probability of scenario s.
$P_g^{\max}$	Maximal production level of generator g.
$P_g^{\min}$	Minimal production level of generator g.
$D_{i,t}$	Load on bus i at time t.
$D_{i,t}^{net}$	Net load on bus i at time t.

Variables

$u_{g,t(,s)}$	Commitment of generator g at time t (in scenario s).
$\sigma_{g,t(,s)}$	Start-up indicator of generator g at time t (in scenario s).
$P_{g,t(,s)}$	Production level of generator g at time t (in scenario s).
$\gamma_{g,t}$	Reserve of generator g at time t.
$F_{ij,t,s}$	Active power flow on line ij at time t in scenario s.
$\theta_{ij,t,s}$	Voltage angle of bus i at time t in scenario s.
$r_{ij,t,s}^{Off}$	Indicator of line ij being off at time t in scenario s.
$r_{ij,t,s}^{N}$	Indicator of line ij adopting normal rating at time t in scenario s.
$r_{ij,t,s}^{H}$	Indicator of line ij adopting higher rating at time t in scenario s.
$L_{i,t,s}$	Load shedding on bus i at time t in scenario s.

1 Introduction

The growth of renewable generation brings new challenges to power system operations. The intermittent and variable nature of renewable generation may lead to extreme ramping requirements, over-generation and reliability degradation. The California System Operator (CAISO), for instance, experienced an increase of 10.9 GW in net load over 3 h on Feb. 1, 2016. Moreover, for wind power, which contributes most to the share of renewable generation, there can be a wide mismatch between production and actual load in terms of seasonal and daily patterns. The wind production is usually high when the demand is low and solar power peaks around mid-day. This can lead to over generation risk during the day, which may require out of market intervention to maintain reliability. In CAISO, the net load dropped to 11.63 GW at around 2 pm on May 15, 2016, about three hours after the first peak of the net load. f With the deeper penetration of renewables in power systems, the ISOs need a more flexible mix of resources that can be adjusted quickly to meet the sharp changes in both the demand side and the supply side.

To maintain system reliability, the ISOs must continuously match the demand for electricity with the supply on a second-by-second basis. Historically, the ISOs directed conventional controllable generation units to increase or decrease their output according to the variable but predictable demand. Also, steep changes of generation are not totally new to power system operators. Power systems is a complicated system consisted of thousands of components. The unexpected failures of any component referred to as contingencies, which can lead to overloading, frequency changes or voltage violations, could happen anytime. To retain normal operating conditions of power systems, the operators need to take control actions such as adjusting the output of generators, switching on/off transmission lines, or temporarily increasing the capacity of transmission lines by relaxing the flow constraints.

With more renewable generation integrated into the system, the system operators also need to exploit more flexibility, which we define in this paper as the ability to deploy variable resources to meet variable demand, from the system, to balance the variable supply and demand. Flexibility in power systems can be obtained from generation, transmission, and load control. On the generation side, more reserves from conventional units can be scheduled to ensure that the planning of units outputs can withstand the uncertainty introduced by renewable generation. However, this might undermine the goals of utilizing environmentally friendly resources to supply electricity. It can also be costly to have more reserve from conventional units. On the demand side, demand response and storage which is still expensive at the current stage can also serve as flexible resources. In the transmission system, there are three aspects of flexibility. The operators can alter the topology of the system through switching on/off transmission lines. Secondly, they can also change the flow limit of high-voltage transmission lines to allow generations with lower costs to be dispatched to mitigate the uncertainty. The impedance of transmission facilities could also be controlled using FACTS equipment. The first two aspects utilize existing transmission assets and require no additional equipment. In this paper, we will focus on harvesting flexibility from transmission systems through topology control (equivalent to setting ratings to be zero and impedance to be infinity) and by strategically changing the thermal ratings of transmission lines, denoted as flexible line ratings in this paper, for limited lengths of time. By doing so we exploit the heating and cooling characteristics of the lines. With the flexibility provided by the existing transmission infrastructure, system operators do not need to have more expensive conventional units in order to deepen the penetration of renewable generation.

The idea of utilizing the flexibility provided by transmission systems through switching on/off lines and temporarily adopting higher (emergency) ratings is not new to power system operations. System operators use such approaches as post-contingency control actions to control contingency and alleviate violations which may jeopardize system reliability [13,17]. Topology control has been studied as an action against overloading and voltage violations since the 1980s [2,18]. Recent research showed that, in addition to help in relieving post-contingency violations, it could also assist in achieving N-1-1 reliability. Extensive studies [7,9,10,19,20] have been conducted on utilizing topology control to reduce the operating cost in deterministic settings. Our previous study on both the IEEE 118 system [23] and a commercial scale network representing the Central European System [22] shows that topology control, modeled as a recourse action in a two-stage stochastic unit commitment problem, improves the day-ahead scheduling of conventional units in the presence of uncertain renewable generations.

The capacity of short-distance high-voltage overhead transmission lines is commonly determined by their thermal conditions [25]. We recognize that thermal line rating, sometimes is only proxies to stability limits. For instance, the capacity of long-distance, extra-high-voltage (EHV) lines is determined by the lines surge impedance loading instead of their actual thermal limits. However, the total length of the long-distance EHV lines only takes a small fraction of the whole system. Furthermore, for transmission lines whose ratings are determined by stability concerns, we can easily screen them out by checking whether the emergency limit equals the normal limit. Hence, in the remaining part of this paper, we only consider overhead lines whose ratings are limited by thermal considerations.

The thermal limit of transmission lines depends on meteorological conditions such as wind speed, ambient temperature, solar radiation, and wind angle. The meteorological parameters are selected in a conservative way. According to [25], when calculating the thermal ratings, the 98% of the expected worst-case values are selected for key environmental parameters. Furthermore, the assumptions suppose that adverse operating conditions all occur at the same time. Bucher [3] conducted a sensitivity analysis of the ampacity of a Drake 26/7 ACSR line with respect to different meteorological conditions. The results showed that the influence of ambient conditions could be substantial. In some cases, the ampacity was more than twice as high as in the base case. The conservativeness in selecting the ambient parameters will lead to under-utilization of transmission facilities and congestions.

In the operations of power systems, system operators might utilize higher ratings for some transmission line temporarily as post-contingency actions. With the presence of renewable generation, extreme scenarios of renewable generation are similar to contingencies in real-time operations. The recourse decision of flexible line rating we proposed in this paper is an analog to utilizing higher ratings of transmission lines temporarily as post-contingency control actions. We assume no costs are incurred in flexible line rating since we only exploit the underutilized ampacity of transmission lines without harming the transmission infrastructure. We identify our major contribution in this paper as proposing a two-stage stochastic programming model which mobilizes the inherent transmission system flexibility through anticipating the capability of using a less conservative line rating when making the commitment decisions of slow units. Specifically, we study the benefits of modeling flexible line ratings as recourse actions in a two-stage stochastic unit commitment problem. The decisions we would like to optimize are the first-stage commitment decisions which are made when ambient conditions that are required to calculate dynamic line ratings are not available. The flexible line rating decisions are recourse actions in the second stage when the uncertainty of renewable generation is realized. Compared with stochastic unit commitment with topology control recourse (TCSUC) explored in [23] and [22], we include here the flexible line rating in the recourse in addition to switching decisions for topology control. The proposed model allows anticipation of the capability to optimally select when and which line should adopt higher ratings subject to security constraints, which limit the time interval of higher ratings, in addition to allowing lines to be switched off. Moreover, we force a subsequent cooling off period during which the line will adopt more conservative static ratings. In contrast with dynamic line ratings in existing literature, the proposed model in this paper requires no information on real-time ambient conditions of transmission lines. In flexible line ratings, we harvest flexibility from transmission system based on three facts: the line ratings are calculated using conservative ambient parameters; the actual current flow on a transmission line that generates heat is smaller than the ratings for most of the time; and it takes time to heat the transmission lines. When we optimize the commitment decisions of slow units, the proposed model takes the flexibility of transmission systems provided by flexible line ratings into consideration. By doing this, less conservative commitment decisions become feasible. Obviously, such recourse actions increase the computational burden, so it is fair to say that we are harnessing the computational power to produce transmission system flexibility.

The remainder of the paper is organized as follows. In Sect. 2, we first review how static line ratings are calculated in practice, then summarize existing literature on dynamic ratings, and proposed flexible line ratings. In Sect. 3, we present the mathematical formulation of stochastic unit commitment with flexible line rating recourse. In Sect. 4, we provide a demonstration study based on both the IEEE 118 system and a network representing the Central European system. And Sect. 5 concludes the paper.

2 Line ratings of overhead transmission lines

Transmission owners and system operators determine static ratings for transmission facilities based on fixed meteorological and operating conditions. According to the PJM Transmission Operations Manual [17], three sets of thermal limits listed in a non-decreasing order are provided for all monitored equipment: normal limit, emergency limit (long-term and short-term limit) and load dump limit. System operators make dispatching decisions according to the normal limits. However, transmission facilities can stand for emergency limit within a pre-specified period of time without violating the safety codes or jeopardizing the conductor. There are totally 16 sets of the three ratings provided for each monitored transmission facility. Eight ambient temperatures are used with a set or the night and a set for the day period. Transmission owners and the RTOs security analysis programs must be able to handle all 16 sets of ratings and allow the operating personnel to select appropriate sets for system operation. In this section, we will review how static line ratings are calculated, illustrate what is dynamic line ratings, and propose flexible line ratings for power systems with renewable generations.

2.1 Static line ratings

In thermal-limited overhead transmission lines, the maximum current that can flow is determined by the maximum allowable temperature of the conductor. The temperature of a line should not be too high to avoid excessive sags and possible thermal damage to the conductor. Both IEEE [11] and CIGRE [12] have standards to provide guidance for calculating the ampacity and the temperature of the bare overhead transmission lines.

In both standards, the thermal behavior of conductors is modeled using a heat balance equation (HBE) which is used to model the fact that the heat gain of a conductor should equal the heat loss at any time. The HBE can be expressed as:

$$q_c + q_r + m \cdot C_p \frac{dT}{dt} = q_s + I^2 R(T) \tag{1}$$

where q_c is the convection heat loss, q_r is the radiated heat loss, $m \cdot C_p$ measures the thermal inertia of the conductor, q_s is the heat gain from the sun, and $R(T)$ is the resistant of the conductor at temperature. This first order differential equation models how the temperature of a bare conductor responds to changes in the current and the ambient environment. For steady-state consideration, we can set the derivative term to be zero. Given the maximum allowable temperature and the ambient weather conditions, we can utilize the steady-state HBE to calculate a static thermal rating for the conductor. The CIGRE report [21] provides guidelines for the selection of weather conditions to calculate line ratings. Conventionally, in the day-ahead operations of power systems and in most of the existing literature, static line ratings are utilized as parameters to model the capacity for lines.

2.2 Dynamic line ratings

In the HBE, the weather conditions influence both the heat gain and the heat loss of the conductor. The loading conditions of the line also have impacts on the actual temperature of the transmission line. Since the static rating is determined based on very conservative assumptions of weather conditions, and for most of the time the lines are not operating at their ratings, the actual capacity of the line should be higher than the normal rating. Dynamic line ratings adapt the prevalent weather conditions, real-time conductor temperatures and actual loading of transmission lines.

Davis [5] first proposed dynamic ratings in 1977. Since then, different aspects of dynamic ratings have been studied, including assessing impacts of dynamic line rating on system security in the operating environment [6,8] and probabilistic forecast of dynamic ratings [14]. In the literature, researchers have explored how to include dynamic line ratings in both day-ahead and real-time operations to reduce the cost of transmission constrained power systems, especially for those with large-scale renewables integration. In [15], the authors include the heat balance equation in security constrained unit commitment. Representative scenarios of weather conditions are selected as parameters in the formulation. They utilize a convex approximation of the differential equation. In [24], the authors presented an approach for how to include dynamic line ratings in an N-1 secure dispatch optimization. The evolution of the conductor temperature is simulated using the basic Euler forward method, and the power flow is then guided by constraints on the conductor temperature rather than by the traditional static line ratings on power flow. In [4], the authors incorporate dynamic line ratings in security constrained economic dispatch. In the proposed approach, the real-time ratings are first calculated and then used to update the parameters in the security constrained economic dispatch. In practice, Oncor is the first transmission owner that was able to integrate the dynamic ratings directly into the Electric Reliability Council of Texas (ERCOT) security constrained economic dispatch model [25]. According to the report of ENTSO-E, many TSOs use dynamic line rating in testing and operations. But, currently, dynamic line ratings are only used for information, alarms to the dispatchers and others. Further study is still required to fully incorporate dynamic line ratings in system operations and planning.

2.3 Flexible line ratings

To incorporate dynamic line ratings into the operations of power systems, we need to have real-time measurements of the meteorological and operation conditions or accurate enough forecast for those conditions. However, it is costly to install sensors and communication systems at the operating center for all lines. Even if we have all the required equipment installed, we still need weather forecast or use of selected scenarios in day-ahead operations to adopt dynamic line ratings. If the weather forecast or selected scenario leads to a conservative line rating profile or if we simply utilize static ratings, it will result in conservative and costly commitment decisions.

In this paper, we propose to utilize flexible line ratings as a recourse action in stochastic unit commitment as illustrated in Fig. 1. An acceptable higher rating $F_{ij}^{\max,\text{high}}$ than the normal static line rating $F_{ij}^{\max,\text{normal}}$ is calculated based on anticipated weather conditions and loading conditions. Based on the HBE, the conductor has thermal inertia so that the temperature of the line will not increase immediately. By limiting the time t_{ij}^{H} $(\leq \hat{t}_{ij}^{H})$ of adopting high ratings and mandate normal or even lower ratings afterward for a certain period of time t_{ij}^{N} $(\leq \hat{t}_{ij}^{H})$, we actually allow the lines to be heated and then cool down. This will avoid excessive sagging and thermal damage caused by high conductor temperature. When flexible ratings are adopted in stochastic unit commitment for power systems with intermittent renewable resources, we allow second stage decisions on when to allow the line ratings to be higher than the normal static ratings. Moreover, in this paper, we also include the switching of transmission lines in the definition of flexible line ratings, which means the rating of a line is allowed to be zero when it is switched off. Hence, there are at most three states

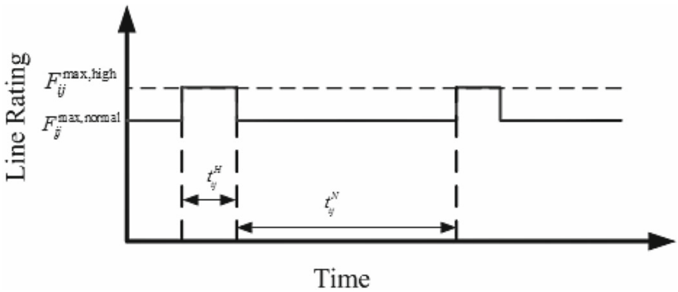


Fig. 1 Illustration of flexible line ratings

of a transmission line: off, adopting normal rating, or adopting a higher rating. Noted that the normal rating of transmission lines are calculated conservatively assuming severe ambient conditions, we do not require lower ratings after allowing higher ratings. But such a state of utilizing a lower rating could be modeled in the same way and easily incorporate in the proposed model. The three states of transmission lines are modeled as recourse actions in our two-stage stochastic model. By allowing such recourse actions in the second stage, we actually solve a relaxation of the stochastic unit commitment without such recourse actions. Including flexible line ratings will make more aggressive, i.e. less conservative, first stage decisions feasible.

3 Mathematical formulation

As with the formulation of stochastic unit commitment with topology control recourse in our previous paper [23], in this paper, we also divide the set of conventional generation resources(G) into a set of slow units(GS) and a set of fast units(GF). This dichotomy is primarily based on the fuel type of generators following the same logic illustrated in [16]. Fast units can be synchronized to, or disconnected from the power network within a shorter period of time than slow units. The uncertainty of renewable generation is captured by a discrete set of scenarios that are treated as a negative load in the proposed model. We use the algorithm in [16] to simulate renewable generation and select representative scenarios. We formulate the day-ahead scheduling problem as a mixed-integer two-stage stochastic program. The first stage of the problem represents day-ahead decisions and the second stage represents the real-time recourse in response to the revealed uncertainty of renewable generation. In the model, the commitments of slow generators are first-stage decisions that are made before the realization of renewable generation. Other decisions including fast generator commitments, production of all generators, and the line status decisions are second-stage decisions. The commitment of fast units and the dispatch of generators production are co-optimized with the flexible line ratings decisions in the recourse. For brevity, we present a compact formulation of the proposed model in this paper that emphasizes the constraints related to flexible line ratings. The detailed generation and system operation constraints can be found in our previous paper [23]. The compact formulation of stochastic unit commitment with flexible line rating recourse (FLRSUC) can be expressed as:

(FLRSUC) :

$$\min \sum_{t\in T}\sum_{s\in S}\pi_s(\sum_{g\in GF}(h_g\sigma_{g,t,s}+k_g u_{g,t,s}+c_g P_{g,t,s})+\sum_{g\in GS}c_g P_{g,t,s}$$

$$+\sum_{i\in N}\rho_i L_{i,t,s})+\sum_{t\in T}\sum_{g\in GS}(h_g\sigma_{g,t}+k_g u_{g,t}) \tag{2}$$

$$\text{s.t.}(\mathbf{u}_{GS},\sigma_{GS})\in\Delta_{GS} \tag{3}$$

$$(\mathbf{u}_{GF,s},\mathbf{P}_{G,s},\mathbf{L}_s)\in\Delta_{GF}(\mathbf{W}_s,\mathbf{u}_{GS},F_s),\forall s\in S \tag{4}$$

$$r^{Off}_{ij,t,s}+r^{N}_{ij,t,s}+r^{H}_{ij,t,s}=1,\forall ij\in M,t\in T,s\in S \tag{5}$$

$$-M_{ij}r^{Off}_{ij,t,s}\le F_{ij,t,s}-B_{ij}(\theta_{i,t,s}-\theta_{j,t,s})$$

$$\le M_{ij}r^{Off}_{ij,t,s},\forall i,j\in N,t\in T,s\in S \tag{6}$$

$$-F_{ij,t,s}\le F^{\max,\text{normal}}_{ij}r^N_{ij,t,s}+F^{\max,\text{high}}_{ij}r^H_{ij,t,s},$$

$$\forall i,j\in N,t\in T,s\in S \tag{7}$$

$$F_{ij,t,s}\le F^{\max,\text{normal}}_{ij}r^N_{ij,t,s}+F^{\max,\text{high}}_{ij}r^H_{ij,t,s},$$

$$\forall i,j\in N,t\in T,s\in S \tag{8}$$

$$\sum_{k=0}^{\min(|T|-t,\hat{t}^H_{ij})}r^H_{ij,t+k,s}\le\hat{t}^H_{ij},\forall ij\in M,t\in T,s\in S \tag{9}$$

$$\sum_{k=0}^{\min(|T|-t,\hat{t}^N_{ij})}(1-r^H_{ij,t+k,s})\ge\min(|T|-t,\hat{t}^N_{ij})(r^H_{ij,t-1,s}-r^H_{ij,t,s}),$$

$$\forall ij\in M,t\in T,2\le t\le|T|-1,s\in S \tag{10}$$

$$\sum_{ij\in M}r^{\text{Off}}_{ij,t,s}\le r^{Off}_{\max},\forall t\in T,s\in S \tag{11}$$

$$\sum_{ij\in M}r^H_{ij,t,s}\le r^H_{\max},\forall t\in T,s\in S \tag{12}$$

$$r^{\text{Off}}_{ij},r^N_{ij,t,s},r^H_{ij,t,s}\in\{0,1\},\forall ij\in M,t\in T,s\in S \tag{13}$$

In the above formulation, we minimize the expected operating cost including production cost, no-load cost, start-up cost and the penalty cost for load shedding, as expressed (2). For brevity, we adopt set notations to represent constraints related to conventional units. Set constraint (3) represents the on/off transition constraints, minimum up-time constraints and minimum down-time constraints of slow units. Set constraint (4) include the on/off transition constraints, minimum up-time constraints and minimum down-time constraints of fast units. It also includes the ramping constraints, generation capacity constraints and the market clearing constraints of all units. The status of transmission line ij are represented by binary decision variables $r^{\text{Off}}_{ij,t,s}$, $r^N_{ij,t,s}$, and $r^H_{ij,t,s}$. Transmission line ij is switched off when $r^{\text{Off}}_{ij,t,s}=1$ at time t in scenario s. It adopts normal rating at time t in scenario s if $r^N_{ij,t,s}=1$. If $r^H_{ij,t,s}=1$, the line utilize a higher rating than its normal rating, which is computed using less conservative ambient parameters. At each time period, the line must be in one status, which is achieved in constraint (5). Constraints (6) is the modified DC power flow. In (6), M_{ij} is a large enough number. Constraints (7) and (8) is the line flow capacity constraint. Similar as in TCSUC, the voltage angles of bus i and bus j are coupled only if the line ij is on. If $r^{\text{Off}}_{ij,t,s} = 1$, we have $F_{ij,t,s} = 0$. Otherwise, the flow is within the capacity of the line. When $r^{H}_{ij,,t,s}$equals to one, the line flow can exceed the normal rating, but still capped by $F^{\max,\text{high}}_{ij}$. Constraint (9) limits the number of consecutive time periods that a line can adopt higher ratings. Constraint (10) mandates a normal rating or switched off for a certain amount of time after the higher rating is utilized. This constraint is only active when $r^{H}_{ij,t-1,s} = 1$ and $r^{H}_{ij,t,s} = 0$ since the line status variables are binary. When $r^{H}_{ij,t-1,s} - r^{H}_{ij,t,s} = 1$, the line status transit from adopting higher rating to adopting normal rating or being switched off. Constraint (10) then enforce the cooling period to be long enough. Constraint (11) and constraint (12) limit the number of lines switched off and the number of lines utilizing higher ratings in each time period and each scenario. For switching decisions, previous literature [7] and [23] shows that the marginal benefit of enabling additional lines to be switched decrease significantly after a small portion of lines is allowed to be switched off. For line rating decisions, by limiting the number of lines adopting higher ratings in each time period, we can enhance the reliability of the system. Moreover, by including these constraints in the model can limit the search space of the line status decisions hence reduce the complexity of solving FLRSUC. Simulation and stability analysis should be conducted after solving the problem to ensure stability and reliability of the system.

4 Numerical tests

To demonstrate that flexible line ratings could mitigate the uncertainty and variability of renewable generation, we conduct numerical tests on both the IEEE 118 system and on a network representing the Central European System. For a commercial scale system with thousands of transmission lines and thousands of conventional generators, the total number of decision variables could be over 1 million if we directly solve the problem formulated as in Sect. 3. In the numerical tests of this paper, we take $F^{\max,\text{high}}_{ij} = 1.1 F^{\max,\text{normal}}_{ij}$, which is still relatively conservative compared with the value calculated using real time ambient conditions. However, significant cost reduction is obtained in both test cases.

We use a laptop with an Intel Core i7 2.6 GHz CPU and 12 GB RAM for numerical tests. CPLEX 12.5 is utilized as the solver for the mixed-integer stochastic programming problem. We solve the problem of each zone for all scenarios simultaneously with a good warm start to reduce the solving time. The warm start solution is created following two steps: we first solve SUC; we then solve the flexible line ratings problem for each scenario with the commitment decisions fixed in SUC. The warm start solution of binary decision variables is composed of the solutions of the two steps. To solve such a mixed integer programming problem for a practical system, we

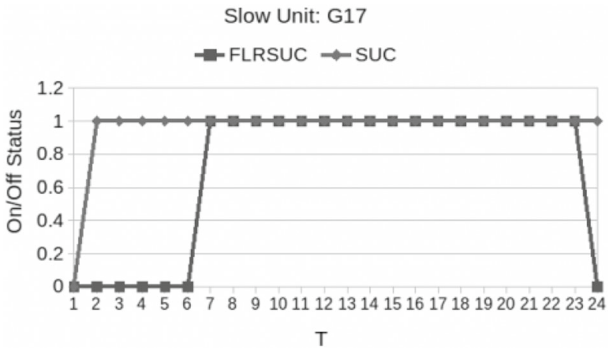


Fig. 2 Commitment of slow unit G17

proposed a heuristic that decomposes the system into zones as shown in our paper [22]. Specifically, we utilize the heuristic to decompose the network representing the Central European System into five zones and solved the sub-problem for each zone. In both test cases, we compare the costs with and without flexible line ratings recourse in the two-stage stochastic unit commitment.

4.1 IEEE 118 test case

There are 118 buses, 186 transmission lines and 19 conventional generators in the system. Among the 19 conventional generators, 4 are slow units, and 15 are fast units.

Using the NREL Western Wind Resources Dataset, we simulated 1000 scenarios of 24 h wind power output [16]. If we solve the stochastic unit commitment without flexible line ratings (SUC), the expected cost is \$36507. When flexible line ratings are modeled as a recourse action (FLRSUC), the expected cost is \$29481 that is 19.2% lower than the expected cost of SUC. It took less than four hours for CPLEX on the laptop to solve the problem given a warm start.

We compare the commitment of slow units. In the optimal solution of SUC and FLRSUC, only the scheduling of G17 is different. As shown in Fig. 2, G17 stays off for six more hours in FLRSUC than in SUC. Figures 3 and 4 show the cost comparison of slow units and fast units. In the two figures, we divide the cost components in FLRSUC by the corresponding cost components of SUC. The numbers in the figures show ratios of cost components in FLRSUC to those of SUC. The numbers of start-ups of slow units in FLRSUC and SUC are the same, so the start-up costs of slow units are the same. When flexible line ratings are allowed, less expected generations are provided by slow units. However, the average fuel cost of generation from slow units is reduced with flexible line ratings. Fast units generate more power in FLRSUC with lower costs as shown in Fig. 4. Since in this test case, most of the generation capacity is from fast units, fast units contribute more to the cost reduction.

To understand how flexible line ratings could influence the dispatch, we can take a part of the IEEE 118 test case containing 4 buses and 5 lines as an example. The topology of this part of the system is shown in Fig. 5 The load connected to Bus 90 is

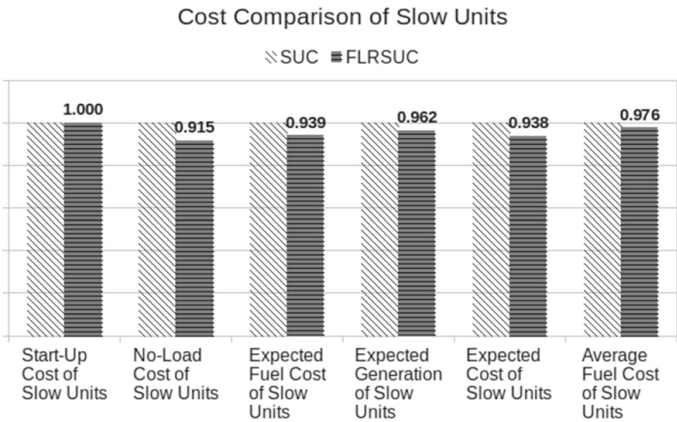


Fig. 3 Cost comparison of slow units in IEEE 118 test case

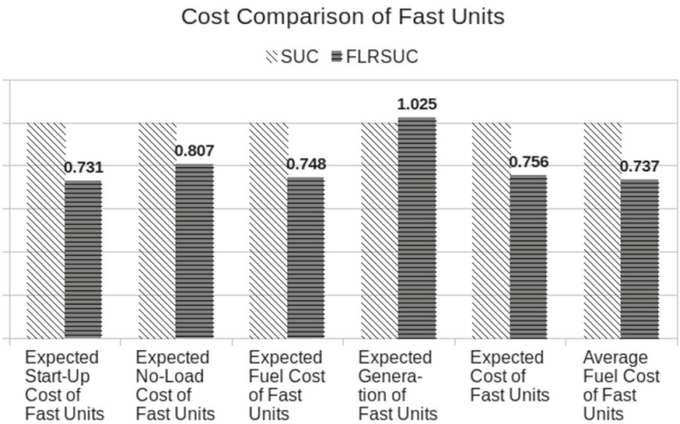


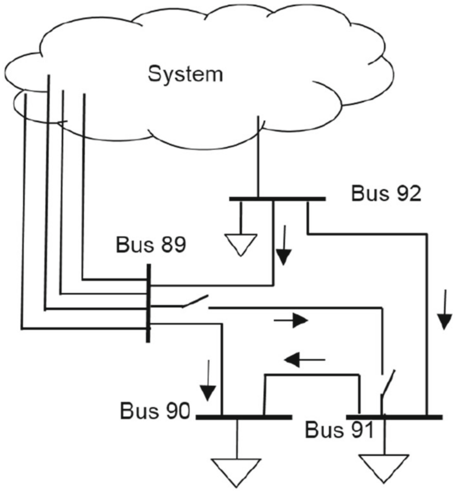
Fig. 4 Cost comparison of fast units in IEEE 118 test case

much larger than that of other buses. Bus 89 and Bus 92 are connected to the rest of the network. Without flexible line ratings, the bottleneck of this part of the system is the line connecting Bus 89 and Bus 92.

From Fig. 6 we can see that without flexible line ratings, the flow on line Bus92-Bus89 reaches the static rating for 10 h. Due to this congestion, units with lower costs could not be dispatched. When flexible line ratings are included in the second stage as decisions, line Bus89-Bus91 is off for 15 h. Line Bus92-Bus89 adopts higher line ratings in two hours. The peak flow of line Bus92-Bus89 is around 230 MW, which is only 105% of the normal static rating. The congestion on line Bus92-Bus89 is relieved, and better dispatch is allowed with flexible line ratings.

In FLRSUC, a subset of wind generation scenarios is selected to represent the uncertainty in order to reduce the complexity and to make the problem easier to solve. To evaluate the performance of the first-stage commitment decisions generated using the reduced scenario set with or without flexible line ratings, we conduct an out-of-

Fig. 5 A part of the IEEE 118 test case



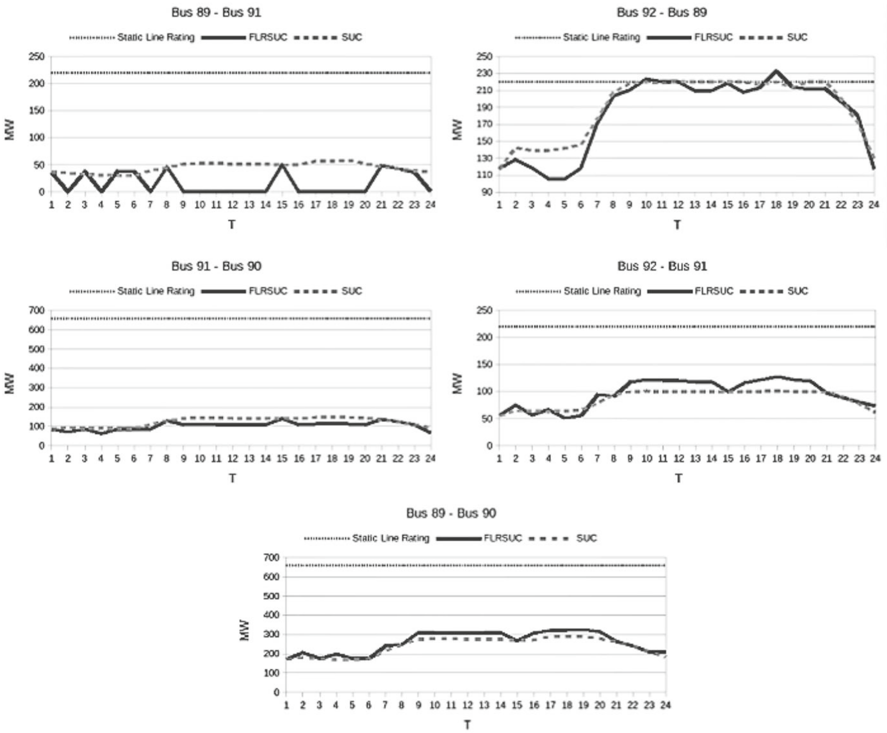


Fig. 6 Line flows in the part of the IEEE 118 test case in scenario 3

sample test of the model on a larger set of scenarios. In the evaluation, we fixed the first stage decisions as the optimal commitment of slow units in SUC/FLRSUC. We generate 1000 wind generation scenarios using Monte Carlo simulation. In the 1000

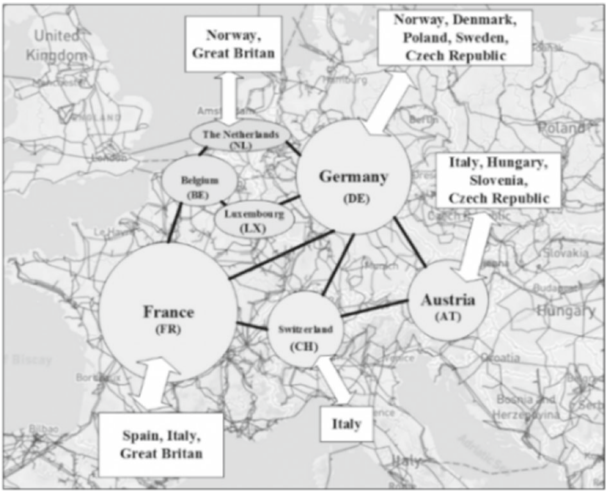


Fig. 7 Central European system

test cases, we solve SUC and FLRSUC and compare the costs. In all 1000 tests, when flexible line ratings are allowed in the second stage, the cost is less than when there are no flexible line ratings. The average cost reduction is above 18% with flexible line ratings. This means flexible line ratings enable better slow unit commitment decisions in the first stage.

4.2 Central European test case

We also test the idea of utilizing flexible line ratings as recourse actions on a network representing the Central European System [1] as shown in Fig. 7. There are 679 buses, 667 conventional units, 1036 transmission lines and 1437 renewable units in this test case. The connections between the Central European System and other countries outside the system are modeled as fixed imports and exports. The loading conditions and the renewable generation profiles are the same as in the second test case in our paper [22].

We select 10 scenarios to represent the uncertainty of renewable generation. There are around 1 million continuous decision variables and over 900,000 binary decision variables in FLRSUC. Even for a single scenario sub-problem, there are over 120,000 binary decision variables. To reduce the complexity of solving this problem, we adopt the heuristic in [22]. We decompose the system into five zones. The detailed information for each zone is listed in Table 1. In the sub-problem of the largest zone FR+CH, there are around 450,000 binary decision variables and over 500,000 continuous variables. The solution time for this zone is around 18 h using CPLEX on a laptop with an Intel i7 CPU and 12 GB memory.

We compare the cost of SUC, TCSUC (the second test case in [22]) and FLRSUC. The results are shown in Table 2. From the results, we can see that with flexible line ratings modeled as recourse actions, the operating cost can be further reduced than in

Table 1 System zonal information

	AT	BE+LX	DE	FR+CH	NL
Buses	36	27	228	364	24
Lines	42	25	312	594	26
Fast Units	11	25	94	26	19
Slow Units	25	46	254	113	46
Peak Load (MW)	8044.9	1 .4e4	65018	76371	13959
Max. Gen. Cap. (MW)	7656.8	1.7e4	1.1e5	9.4e4	24690

Table 2 Test results of central European system

	SUC (MEUR)	TCSUC (MEUR)	FLRSUC (MEUR)	Cost Saving of FLRSUC (MEUR)
AT	7.0057	6.8244	6.7980	0.2077
BE+LX	6.2083	6.2083	6.1850	0.0233
DE	14.2089	14.0540	13.9496	0.2593
FR+CH	17.3961	16.0753	15.5977	1.7984
NL	10.5475	10.3793	10.3642	0.1833
Total	55.3665	53.5141	52.8945	2.472

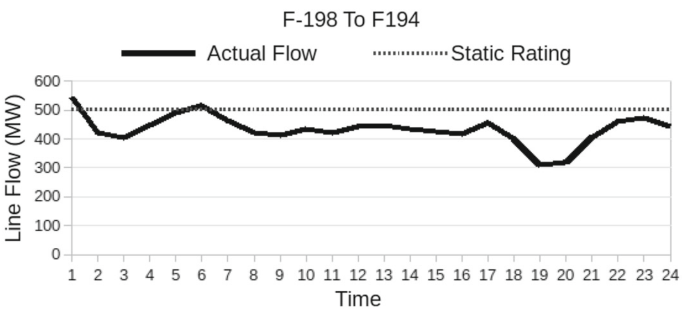


Fig. 8 Line flow of transmission line F-198 to F-194 in scenario one

TCSUC. Compared with SUC, the cost reduction of FLRSUC for the entire system is around 4.5%. The zone FR+CH has the largest cost saving. The cost reduction is above 10%. In the remaining part of this section, we will take FR+CH as an example. In BE+LX, no cost saving is observed in TCSUC. With flexible line ratings, the cost is slightly reduced.

Figure 8 shows an example of a transmission line that utilized higher ratings in two time periods. The line flow is above the normal static rating at time period one and time period six. After exceeding the normal rating, the flow goes below the normal ratings, and the transmission line gets cooled down. Figure 9 compares the average number of lines switched off per hour in TCSUC and in FLRSUC. In some of the scenarios, more lines are switched off with flexible line ratings while in other scenarios, fewer

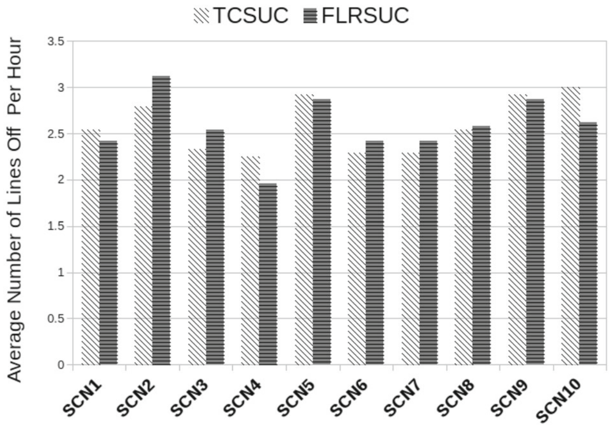


Fig. 9 Average number of lines switched off per hour in TCSUC and FLRSUC in zone FR+CH

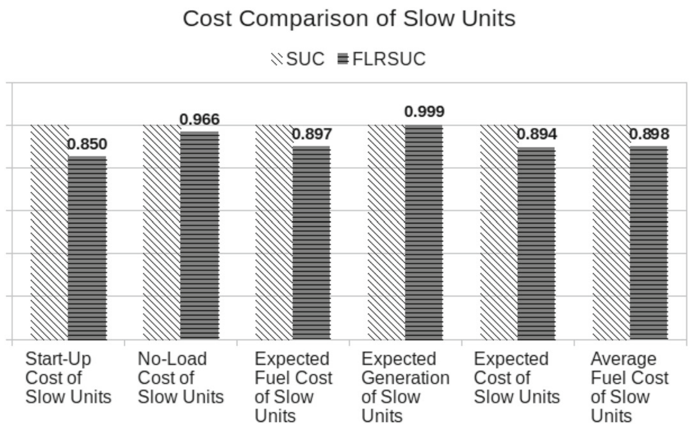


Fig. 10 Cost comparison of slow units in zone FR+CH

lines are switched off. The switching of transmission lines will re-dispatch the flow in the network. This may cause the overflow of some transmission lines after the switching and make the topology of the network infeasible in TCSUC. With flexible line ratings modeled as recourse actions, the program can optimally choose when and on which line higher ratings will be utilized. The overflow caused by switching might become feasible in this case, and the operating cost can be reduced. On the other hand, the switching decisions are co-optimized with the rating decisions. In the cases where increasing the ratings of line facilitate better commitment units and dispatch of generation, we might not need to switch off lines.

The comparison of detailed cost information in zone FR+CH is shown in Figs. 10 and 11. To compare different cost components of slow units and fast units, we scale each component, dividing it by the corresponding value of SUC. The values in the figures represent the cost component in FLRSUC corresponding to that of SUC. From Fig. 10, we can see that flexible line ratings in the second stage facilitate more aggressive first

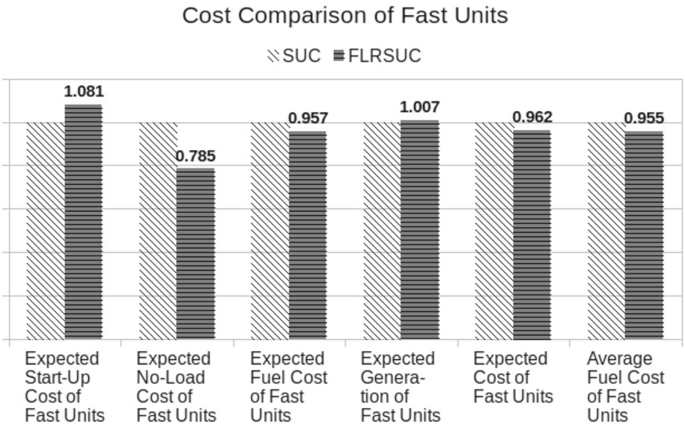


Fig. 11 Cost comparison of fast units in zone FR+CH

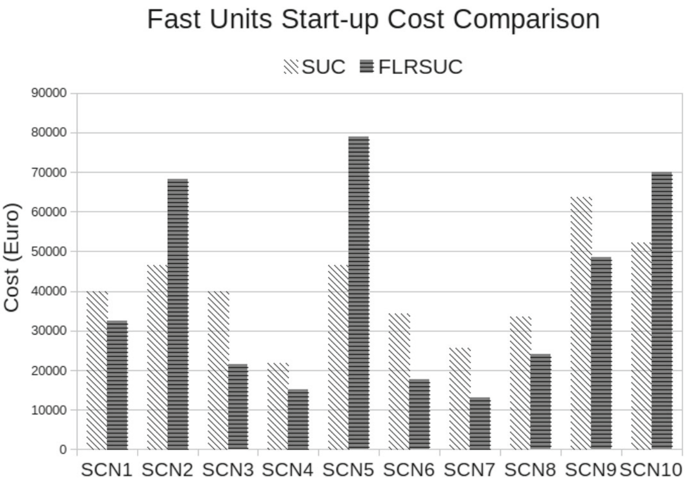


Fig. 12 Start-up cost comparison of fast units in FR+CH

stage commitment decisions of slow units. The start-up cost, no-load cost, and the expected fuel cost of slow units are reduced. The expected generation from slow units decreased by less than 0.1%. However, both the expected cost of slow units and the average per MW fuel cost of slow units decreased by over 10%. Moreover, almost the same amount of generation from slow units is dispatched in the second stage. As shown in Fig. 11, due to the aggressive first stage decisions, the expected start-up cost of fast generators increases by around 8%. Moreover, the expected generation of fast units increases by 0.7%. Figure 12 shows start-up cost of fast units in each scenario of SUC and FLRSUC. The start-up cost is higher in FLRSUC in three out of the total ten scenarios. The probability of those three scenarios is around 0.43 hence the expected start-up cost of fast units in FLRSUC is higher. The expected no-load cost and the expected fuel cost was reduced when flexible line ratings are included as recourse actions. The expected cost of fast units and the average fuel cost of fast units are also reduced. Since renewable generation is modeled as a negative load, no comparison is made between SUC and FLRSUC for renewable generation. In other words, the amount of renewable generation remains the same for both cases.

5 Conclusion and future works

We investigate the potential benefits of utilizing flexibility provided by transmission system through flexible line ratings. We present an optimization model for determining when and which line should be switched or utilize higher ratings in the recourse of a stochastic unit commitment problem. By solving the proposed model, we can mobilize enhanced computation and high fidelity formulations, which is becoming cheaper and faster, in order to improve the utilization of system resources and reduce the need for investment in infrastructure resources. Such potential has been demonstrated in the numerical cases in this paper. We found that substantial cost saving could be achieved with such flexible line rating recourse actions in numerical tests where the higher rating of lines is only 10% higher than the normal static rating. The cost reduction is above 19% in the IEEE 118 system while it is around 4.5% in a network representing the Central European System. Results of analysis on both systems show that flexible line ratings recourse serves as a hedging mechanism against the uncertainty brought about by renewable generation and facilitates more aggressive first stage commitment decisions.

This paper is a first step in analyzing the potential benefits of flexible line ratings. Future work will take several directions, including the design and analysis of efficient algorithms or heuristics, the study of the impacts of flexible line ratings on system reliability, and the cost or surplus allocation.

Acknowledgements The authors would like to thank the Lawrence Livermore National Laboratory for granting computing resources on the Sierra and Cab cluster. This work was supported by NSF EAGER Grant ECCS 1549572, ARO grant W911NF-17-1-0555, and by TBSI, at UC Berkeley.

References

1. Aravena, I., Papavasiliou, A.: Renewable energy integration in zonal markets. IEEE Trans. Power Syst. **32**(2), 1334–1349 (2017)
2. Bakirtzis, A.G., Meliopoulos, A.S.: Incorporation of switching operations in power system corrective control computations. IEEE Trans. Power Syst. **2**(3), 669–675 (1987)
3. Bucher, M.A.: On operational flexibility in transmission constrained electric power systems. Ph.D. thesis (2016)
4. Cheung, K.W., Wu, J.: Incorporating dynamic line ratings in real-time dispatch of market and system operations. In: Power and energy society general meeting (PESGM), 2016, pp. 1–5. IEEE (2016). https://doi.org/10.1109/PESGM.2016.7742016
5. Davis, M.W.: A new thermal rating approach: the real time thermal rating system for strategic overhead conductor transmission lines—Part I: general description and justification of the real time thermal rating system. IEEE Trans. Power Appar. Syst. **96**(3), 803–809 (1977). https://doi.org/10.1109/T-PAS.1977.32393

6. Fan. F., Bell. K., Infield. D.: Probabilistic weather forecasting for dynamic line rating studies. In: 2016 Power Systems Computation Conference (PSCC), pp. 1–7 (2016). https://doi.org/10.1109/PSCC.2016.7540854
7. Fisher, E.B., O'Neill, R.P., Ferris, M.C.: Optimal transmission switching. IEEE Trans. Power Syst. **23**(3), 1346–1355 (2008). https://doi.org/10.1109/TPWRS.2008.922256
8. Foss, S.D., Maraio, R.A.: Dynamic line rating in the operating environment. IEEE Trans. Power Delivery **5**(2), 1095–1105 (1990). https://doi.org/10.1109/61.53127
9. Hedman, K., O'Neill, R., Fisher, E., Oren, S.: Optimal transmission switching—sensitivity analysis and extensions. In: 2009 IEEE power energy society general meeting, pp. 1–1 (2009). https://doi.org/10.1109/PES.2009.5275884
10. Hedman, K.W., Ferris, M.C., O'Neill, R.P., Fisher, E.B., Oren, S.S.: Co-optimization of generation unit commitment and transmission switching with N-1 reliability. IEEE Trans. Power Syst. **25**(2), 1052–1063 (2010)
11. IEEE-SA Standards Board: IEEE standard for calculating the current-temperature relationship of bare overhead conductors. IEEE Std 738-2012 (Revision of IEEE Std 738-2006—incorporates IEEE Std 738-2012 Cor 1-2013), pp. 1–72 (2013). https://doi.org/10.1109/IEEESTD.2013.6692858
12. Iglesias, J., Watt, G., Douglass, D., Morgan, V., Stephen, R., Bertinat, M., Muftic, D., Puffer, R., Guery, D., Ueda, S., et al.: Guide for thermal rating calculations of overhead lines. Cigré Paris, France (2014)
13. ISO-NE: New england operating procedure no. 19: transmission operations. Apr **13**, 7–8 (2007)
14. Michiorri, A., Nguyen, H.M., Alessandrini, S., Bremnes, J.B., Dierer, S., Ferrero, E., Nygaard, B.E., Pinson, P., Thomaidis, N., Uski, S.: Forecasting for dynamic line rating. Renew. Sustain. Energy Rev. **52**, 1713–1730 (2015)
15. Nick, M., Alizadeh-Mousavi, O., Cherkaoui, R., Paolone, M.: Security constrained unit commitment with dynamic thermal line rating. IEEE Trans. Power Syst. **31**(3), 2014–2025 (2016). https://doi.org/10.1109/TPWRS.2015.2445826
16. Papavasiliou, A., Oren, S.S.: Multiarea stochastic unit commitment for high wind penetration in a transmission constrained network. Oper. Res. **61**(3), 578–592 (2013)
17. PJM transmission operations: PJM manual 03: transmission operations. PJM, PA, USA (2018)
18. Rossier, C., Germond, A.: Network topology optimization for power system security enhancement. Tech. Rep. (1983)
19. Ruiz, P.A., Foster, J.M., Rudkevich, A., Caramanis, M.C.: On fast transmission topology control heuristics. In: 2011 IEEE power and energy society general meeting, pp. 1–8 (2011). https://doi.org/10.1109/PES.2011.6039833
20. Ruiz, P.A., Rudkevich, A., Caramanis, M.C., Goldis, E., Ntakou, E., Philbrick, C.R.: Reduced mip formulation for transmission topology control. In: 2012 50th annual Allerton conference on communication, control, and computing (Allerton), pp. 1073–1079 (2012). https://doi.org/10.1109/Allerton.2012.6483337
21. Seppa, T.O., Salehian, A.: Guide for selection of weather parameters for bare overhead conductor ratings. CIGRE Technical Brochure **299** (2006)
22. Shi, J., Oren, S.S.: Stochastic unit commitment with topology control recourse for power systems with large-scale renewable integration. IEEE Trans. Power Syst. **33**(3), 3315–3324 (2018)
23. Shi, J., Oren, S.S.: Wind power integration through stochastic unit commitment with topology control recourse. In: 2016 Power systems computation conference (PSCC), pp. 1–7 (2016). https://doi.org/10.1109/PSCC.2016.7541026
24. Tschampion, M., Bucher, M.A., Ulbig, A., Andersson, G.: N- 1 security assessment incorporating the flexibility offered by dynamic line rating. In: Power systems computation conference (PSCC), 2016, pp. 1–7 (2016). https://doi.org/10.1109/PSCC.2016.7540880
25. Wang, W., Pinter, S.: Dynamic line rating systems for transmission lines. US DOE, Washington DC, USA (2014)