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Day-Ahead Scheduling of Power System Incorporating Network Topology Optimization and Dynamic Thermal Rating

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ABSTRACT The integration of large-scale stochastic renewable energy, the aging of transmission facilities, and the growth of load demand all contribute to the increasing congestion levels of transmission systems. Such factors pose considerable stress on the economical and secure operation of power systems and the accommodation of large-scale renewable energies. However, under the smart grid circumstance, some cutting-edge transmission technologies can bring potential cost-effective solutions to leverage the potential capacity of existing transmission infrastructures. Such technologies can help the utilities to deal with the rapid change of operating conditions of the power system in a more flexible manner. For example, the network topology optimization (NTO) technology can change the transmission topology based on the operating conditions, which increases the flexibility of the transmission system. Dynamic thermal rating (DTR) can evaluate the maximum transmission capacity of transmission lines dynamically according to the weather condition parameters around the conductor. These two cost-effective technologies are promising in improving the congestion mitigation performance and can contribute to the efficient utilization of transmission network–so they will bring potential economic and reliability benefits. This paper incorporates NTO and DTR in the network-constrained unit commitment (NCUC) framework to study their synergistic effect on the power system day-ahead schedule. Case studies are performed on a modified RTS-79 system. The numerical results verify that the coordination of NTO and DTR may help decrease the generation cost and wind power curtailment.

INDEX TERMS Day-ahead scheduling, network-constrained unit commitment, network topology optimization, dynamic thermal rating, wind power curtailment.

NOMENCLATURE

A. INDICES

b	Index for the buses from 1 to N_b.
g	Index for the generators from 1 to N_g.
l	Index for the lines from 1 to N_l.
d	Index for the loads from 1 to N_d.
t	Index for time intervals from 1 to T.
i	Index for busbars in a substation. $i \in \{1, 2\}$
e	Index for the end of line. $e \in \{fr, to\}$

B. SETS

WR_l	Set of weather regions which line l goes through.
D_b/G_b	Set of the loads/generators at bus b.
$L_{fr,b}/L_{to,b}$	Set of the lines whose power are assumed from/to bus b.

C. PARAMETERS

C_g	Generation cost for generator g.
C_g^{SU}/C_g^{SD}	Start-up/shut-down cost of generator g.
C_g^{NL}	No-load cost for generator g.

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C_{WC}	Wind power curtailment cost.
C_{LC}	Load curtailment cost.
β^{max}	Maximum allowed voltage angle.
M	A significantly large number.
$WP_{b,t}$	Power output of wind farm at time t.
P_l^{max}	Upper bound of transmission capacity.
P_g^{min}/P_g^{max}	Lower/upper limit of power output for generator g.
D_t^{sys}	The total system load at time t.
$P_{d,t}^{max}$	The value of load d at time t.
X_l	Impedance of transmission line l.
SRR_t	Spinning reserve requirement at time t.
RA_g	Hourly ramp rate for generator g.
$MBST$	Maximum number of substations in bus splitting state per time interval.
$MLST$	Maximum number of switched out lines per time interval.
$T_g^{min,up}$	Minimum up time for generator g.
$T_g^{min,down}$	Minimum down time for generator g.
J_{conv}	Convection heat loss rate.
J_{radi}	Radiated heat loss rate.
J_{solar}	Solar heat gain rate.
C_{hc}	Total heat capacity for the conductor.
$R(K_c)$	AC resistance of conductor for temperature K_c.
K_c	Transmission line temperature.
α	Solar absorptivity.
Q_{se}	The radiated heat intensity of total solar and sky corrected for elevation.
γ	Effective angle of incidence for the sun's ray.
A'	Projected area of conductor.
D_0	Outside diameter of conductor.
ε	Emissivity.
K_a	Ambient air temperature.
K_{angle}	Wind direction factor.
N_{Re}	Dimensionless Reynolds number.
k_f	Thermal conductivity for air.
μ_f/ρ_f	Absolute viscosity/density of air.
S_w	Speed of air stream at conductor.
P_{WT}	Power output of wind turbine generator.
P_r	Rated power output of wind turbine generator.
v_{ci}, v_r, v_{co}	Cut-in, rated and cut-out wind speed.
a_1, a_2, a_3	Parameter for wind power output curve.

D. VARIABLES

$u_{g,t}$	Status of generator g (0:off; 1:on).
$m_{g,t}$	Start-up variable of generator.
$n_{g,t}$	Shut-down variable of generator.
$P_{g,t}$	Power output of generator g at time t.
$P_{g,i,t}$	Generation output of generator g delivered to busbar i at time t.
$P_{d,i,t}$	The amount of d-th load being satisfied on busbar i of substation at time t.
$P_{l,t}$	Power flow of line l at time t.
$P_{l,e,i,t}$	Power flow delivered to busbar i from the end e of line l at time t.
$WC_{b,t}$	Wind power curtailment at time t.
$\beta_{b,t}$	Voltage angle of bus b at time t.
$\beta_{b,i,t}$	Angle of the voltage for busbar i of substation b at time t.
$\beta_{l,e,t}$	Angle of the voltage of transmission line l for end e at time t.
$\beta_{l,e,i,t}$	Angle of the voltage at busbar i connected with end e of transmission line l at time t.
$y_{b,t}$	Binary variable relevant to the connection of busbars in subatation b.
$y_{l,t}$	Binary variable indicating the switching state of transmission line l at time t.
$y_{g,t}/y_{d,t}$	Binary variable indicating which busbar the generator/load connects to.
$y_{l,e,t}$	Binary variable indicating which busbar the endpoint e of line is connected to.
$R_{g,t}$	Spinning reserve of generator g.

I. INTRODUCTION

The increasing concerns on the energy crisis and environmental pollution call for the widespread utilization of renewable energies in electric power industry. Based on the technical documents published by the U.S. Department of Energy (DOE), it is predicted that wind power will supply 20 % of the total electric power demand in the U.S. by 2030 [1]. However, the traditional fixed transmission network is not designed to accommodate such large-scale renewable energy penetrations [2]. Meanwhile, the power grid is faced with the considerable load growth and the aging transmission infrastructures. So the congestion level of power system is increased dramatically, which increases the generation cost of power system and restricts large-scale renewable energy integration severely [2], [3]. As building new transmission corridors to relieve the congestions is very expensive and time-consuming, finding cost-effective ways to leverage the potential of existing transmission systems becomes a major concern for utilities, which will help guarantee the efficient operation of the power system and bring about considerable socioeconomic benefits.

It is mentioned in Sec.1223 of USA Energy Policy Act of 2005 that the advanced transmission technology is defined as the technologies that can increase the capacity, efficiency, or reliability of an existing or new transmission facility [4]. Several emerging transmission technologies which can increase the transmission capacity of the transmission system, such as flexible AC transmission systems (FACTS) [5], high-voltage DC technology (HVDC), advanced conductor technology, are listed in this report [4]. Other novel energy storage devices can also contribute to the mitigation of transmission congestions and the increase of power system flexibility, such as pumped hydro, superconducting magnetic energy storage (SMES) and compressed air energy storage (CAES) [4]. However, the deployment of some technologies like FACTS devices and the construction of large-scale energy storage demand massive investment. So some new transmission technologies which can tap the potential of existing transmission equipment are very attractive and are more likely to be extensively implemented in real-world. Therefore, this paper will focus on two promising technologies including DTR and NTO, which may enhance the congestion mitigation performance and boost the system transmission capacity in a cost-effective manner. As these technologies will have far-reaching influences on multiple aspects of power systems, a comprehensive study should be performed to study their potential impacts on power system operations such as optimal scheduling.

Network-constrained unit commitment is an essential procedure to devise the scheduling scheme in the day-ahead electricity market [6]. Security analysis can also be further implemented to perform the security-constrained unit commitment (SCUC). The objective of this optimization problem is to obtain a unit commitment and generation scheduling scheme with the minimum generation cost and ancillary service costs, etc. [7]. The operational constraints, such as power balance constraint, network flow limit and power output restrictions for generators should also be satisfied simultaneously. In general, NCUC model is a large-scale mixed-integer optimization problem [6]. Extensive optimization algorithms have been developed and applied to solve these models including the branch and bound method, priority listing, heuristic methods, mixed-integer programming (MIP), dynamic programming (DP), and Lagrangian relaxation (LR) [8]. The abovementioned novel transmission technologies can have significant influences on the operational performance of power grids and enlarge the solution domain of power system scheduling problems. They should be comprehensively incorporated into the NCUC model to quantify their operational benefits.

In power system dispatch, the thermal rating is an important property for transmission line and should be carefully considered. Traditional thermal ratings of transmission lines are restricted by various fixed conservative weather conditions, which is known as static thermal rating (STR) [9], [10]. However, actual natural environmental conditions are not static and they will keep on changing. So the actual transmission capacity of overhead lines (OHL) could be underestimated under STR circumstance. As a consequence, to evaluate the transmission capacity of OHLs more accurately, the utilities operators are considered to use DTR based on the real-time environmental information [9]. The actual rating of transmission line can be determined by thermal rate monitor equipment. Based on the field test in [11], the DTR can improve the OHL's thermal rating during 96% of the time. The increment rate varies from 15% to 50% and it could even be up to 150 % under some specific circumstances [11], [12]. More importantly, for the implementation of DTR, the cost of equipment and software used to monitor the transmission corridor is less than 2% of the expenses to achieve the equivalent gain by means of traditional transmission line upgrade techniques [10], [13]. Therefore, DTR is an ideal cost-effective technology which can help realize the potential transmission capacity and postpone the transmission line expansion or upgrade. DTR has been involved in many research directions of the power system sector. In [14] and [15], DTR is deployed as an effective congestion management tool to alleviate transmission congestion and increase the security margin of the power system. In [16], the sequential Monte Carlo (SMC) simulation method is applied to evaluate the impact of DTR on power system reliability and the results show that DTR can increase the network reliability. The DTR incorporated stochastic transmission expansion planning is performed in [17] and DTR is verified to reduce new transmission lines to be built. In power system scheduling aspect, the DTR prediction studies make it possible to consider this technology in day-ahead scheduling problem to obtain more economic dispatching scheme under deregulated electricity market [18]–[21]. DTR is incorporated in SCUC framework in [22] to enhance the system security and obtain technical/economic performances. In [23], stochastic optimization is further applied in the SCUC model in the presence of wind power integration. DTR is validated to reduce the wind power spillage. However, the existing literature about DTR incorporated NCUC problem are mostly based on the fixed transmission topology. The coordination of DTR with other novel transmission topology control technologies in the NCUC problem still remains to be studied.

Transmission topology reconfiguration is another promising power flow control technology which can help leverage potential transmission capacity and mitigate the transmission congestions [24]. The topology control technology can help the utilities to gain operational benefit under normal operating conditions. It can also be deployed as a corrective control measure to mitigate line overloading and voltage violations under contingencies or emergency situations. The transmission line switching and the substation busbar splitting are two common ways to implement the topology control technology [24]. For the line switching, it has been involved in many studies in the aspects of power system contingency analysis, reliability evaluation, congestion management, expansion planning and economic dispatch, etc. In the unit commitment aspect, optimal transmission switching is incorporated into day-ahead unit commitment and economic dispatch in [25], and it is verified that optimal transmission switching (OTS) can help reduce the congestion cost and lower generation cost significantly. In [26], N-1 reliability is further considered in the co-optimization problem of OTS and unit commitment. Stochastic optimization is applied in the OTS incorporated unit commitment problem to test the economic performance of power system in [27]. When it comes to the bus-splitting mechanism, the substation reconfiguration is integrated in the power flow calculation for the purpose of congestion management in [28]. In [29], busbar switching is incorporated into a corrective switching algorithm to relieve the overloads and voltage violations due to the faults in power grid. In [30], a network optimization model is established considering busbar splitting to study its contribution to the congestion mitigation and generation cost reduction. As an effective congestion management measure, to the best of the authors' knowledge, bus splitting mechanism hasn't been considered in the NCUC problem in the existing literature thus far. Hence, the potential impact of bus splitting mechanism on the power system scheduling and renewable energy accommodation should be further studied systematically. Meanwhile, the coordination of bus splitting mechanism integrated network topology optimization and other cost-effective smart transmission technologies should also be explored in a more comprehensive manner.

Wind power accommodation is another important factor that should be considered in the day-ahead scheduling problem. Generally, the regions which have abundant wind resources are not suitable for human habitation. Therefore, some large-scale wind power bases are usually built in remote areas which are far away from load center. For example, in China there are more than twenty large scale wind farm bases, each of which has a total installed capacity of about 1GW, have been planned or are being constructed in the north and west areas since the year of 2011. A large percentage of wind power will be transmitted to the heavy load centers in the southeast coastal areas of China [31]. However, the transmission network is relatively weak in the remote areas. The insufficient transmission capacity may lead to the congestions in the power grid [2]. The construction of new transmission corridor requires massive investment and long construction cycle [2], which makes power transmission capability usually unable to keep pace with the constructions of wind power bases [32]. This situation restricts the delivery of clean renewable power and its accommodation in a wider area of electric power system, especially during the time when the wind speed is relatively high and wind farms are under rated power generating state. As a result, novel and cost-effective operating strategies are demanded to enhance the utilization efficiency of renewable energy in the presence of transmission congestions.

Since both NTO and DTR have compelling congestion mitigation performance which can help the utilities to utilize the existing transmission infrastructure more efficiently, they should be incorporated in the NCUC framework to quantify their overall impact on power system scheduling and wind power accommodation. However, there was little existing literature for studying the DTR incorporated NCUC or SCUC problem with topology control technology integration. Meanwhile, the bus-splitting mechanism (which is a promising topology control measure) has not been considered in the NCUC problem yet. Therefore, this paper studies the NTO and DTR incorporated NCUC problem with wind power integration. The main contributions of this paper are summarized as follows:

(1) The comprehensive network topology optimization technology including both optimal transmission switching and substation busbar splitting mechanism is incorporated into the NCUC framework to study its impact on power system scheduling.

(2) The coordination of NTO and DTR in NCUC and their impact on power system scheduling performance are studied systematically. Both technologies are promising cost-effective measures to utilize the potential transmission capacity of existing transmission infrastructures.

(3) The operational performance of NTO and DTR for the enhancement of large-scale wind power accommodation in the presence of transmission congestions is analyzed comprehensively, which provides novel solving strategies for fully utilizing the generation of large wind farms.

(4) Comparative analysis is performed to study different topology control mechanisms including both OTS and NTO on the power system scheduling outcomes.

(5) The impact of meteorological features for different weather regions are considered in the DTR and NTO incorporated NCUC problem, which is a realistic problem for the application of DTR in practice. It can help derive a more accurate power system scheduling scheme when both technologies are implemented.

The rest of the paper is organized as follows: The network topology optimization modeling is illustrated in section II; the model of dynamic thermal rating technology is introduced in section III; the DTR and NTO incorporated NCUC framework is shown in section IV; the solution method is presented in section V; case studies are performed in section VI and conclusions are drawn in section VII.

II. NETWORK TOPOLOGY OPTIMIZATION MODELING

Traditionally, the transmission system is considered to have a fixed transmission topology. With the technological advancement enabled by smart technologies, integration of emerging load demands like massive EVs as well as the rapidly growing renewable energy integration, power system is faced with more complicated operating conditions. Since these stochastic operation conditions are usually not fully considered in the transmission planning stage, the fixed transmission topology cannot be optimal for all the operation conditions of power system. Therefore, the envisaged smart grid calls for a more flexible transmission system.

There are multiple ways to make the transmission system dispatchable and improve its flexibility, such as FACTS devices, on-load tap changer transformer, topology reconfiguration, etc. These technologies can help leverage potential transmission capability and improve the operational efficiency, which can bring some operational benefits. This section is focused on the emerging transmission topology optimization technology including both transmission switching and substation busbar splitting, which are verified to be effective congestion mitigation measures and can improve the system transmission capacity [27], [28].

The outlook of dispatchable transmission system is proposed in [33] and the pioneering study about OTS is given in [34]. Based on the transmission line switching technology, the switching states of lines can be dispatchable which can be represented by binary control variables. For example, the line is switched in when $y_l = 1$; otherwise, when $y_l = 0$, the line is switched out.

The busbar splitting technology within substations is also considered to form a comprehensive system topology control modeling. Substation has the voltage classes transformation function, which enables it to be crucial infrastructure to establish tight relationship between generation resources, transmission equipment and the load demand. A widely recommended and extensively deployed substation structure scheme called breaker-and-a-half arrangement, which has good flexibility and reliable operational performance, is used in this study to model the substation modeling for busbar splitting. The breaker-and-a-half substation scheme is shown in Fig. 1. It can be seen that the substation has two busbars and they are connected with transmission lines, generators and the loads etc. The topology reconfiguration can be realized by switching the on/off states of circuit breakers. A generalized model for substations can be summarized from this substation arrangement scheme, which is shown in Fig. 2 [30]. For example, in substation 1, the transmission lines, loads and the generators can be connected with either of the busbars determined by the binary control variable $y_{l,fr}/y_{l,to}$, y_d and y_g, respectively. Meantime, the two busbars can also be connected or separated, which are controlled by the variable y_b. The control variables with respect to two topology control technologies and connectivity relationship of the elements are summarized in Table 1.

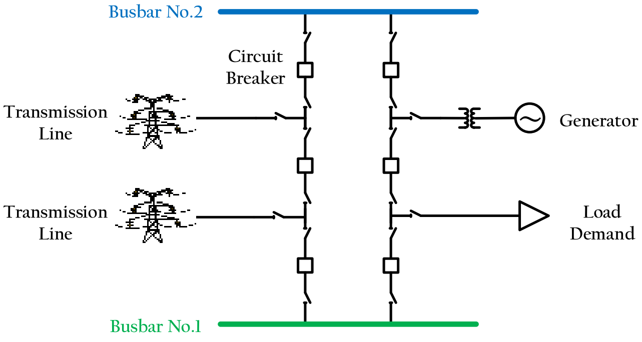

FIGURE 1. Breaker-and-a-half substation scheme.

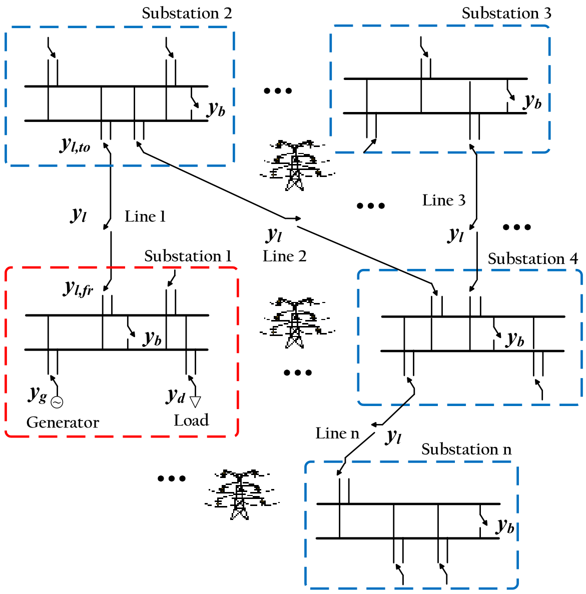

FIGURE 2. Generalized model for substations.

TABLE 1. Control variables in network topology optimization modeling.

Technology	Elements	Switching states	Variable values
Busbar Splitting	Busbar	Connected	y_b=1
	Busbar	Separated	y_b=0
	Line	Connected to Busbar1	$y_{l,fr}/y_{l,to}$=0
	Line	Connected to Busbar2	$y_{l,fr}/y_{l,to}$=1
	Load	Connected to Busbar1	y_d=0
	Load	Connected to Busbar2	y_d=1
	Generator	Connected to Busbar1	y_g=0
	Generator	Connected to Busbar2	y_g=1
Line Switching	Line	Switched in	y_l=1
	Line	Switched out	y_l=0

By combining the line switching technology and the bus splitting technology, the comprehensive NTO model can be incorporated in the day-ahead scheduling to study its impact on the power system dispatch. Comparing to some transmission technologies like FACTS which require a great deal of investments for purchasing new equipment, these topology control mechanisms implemented by state switching of circuit breakers are cost-effective measures to mitigate the transmission congestions and tap the potential transmission capacity of the existing transmission infrastructures. The detailed NTO model will be incorporated into the NCUC model, which is illustrated in detail in Section IV.

III. DYNAMIC THERMAL LINE RATING TECHNOLOGY

Traditionally, the thermal rating of transmission line is evaluated by some fixed environmental parameters, which is called STR. The conservatively assumed static meteorological conditions include low wind speed (0.61m/s), high ambient temperature (40 °C) and full sun radiation (1000W/m^2), etc. [10]. The actual operation condition of a transmission line may vary from time to time. Therefore, these conservative weather conditions may lead to the underestimate of overhead line thermal ratings. When a power system is faced with the increasing congestion and more complicated operational conditions, it is of great value for the system operator to leverage the potential transmission capacity by means of the DTR technology during some favorable weather conditions under the deregulated power market.

The implementation of DTR can be realized by the installation of appropriate weather monitor equipment. The main meteorological conditions to be measured include wind velocity, wind direction, ambient temperature, solar radiation, etc. [10]. Based on the weather condition prediction studies for DTR illustrated in [18]–[21], DTR can be incorporated into the power system scheduling model to mitigate the transmission congestions and reduce the generation cost. If DTR is properly deployed in the power system planning stage, it can also help reduce the number of lines to be built or postpone their construction, which will bring economic benefit to the Independent Transmission System Operation (ITSO).

Multiple professional international organizations have published technical standards for the thermal rating calculation of transmission lines, such as CIGRE Technical Brochure 601 [35], IEC/TR 61597 [36] and IEEE Standard 738 [37]. The technical criteria of IEEE Standard 738 are used in this study to evaluate the DTR of OHLs. The non-steady-state heat balance equation (HBE) is shown as follows [37]:

$$J_{conv} + J_{radi} + C_{hc}\frac{dK_c}{dt} - I^2R(K_c) - J_{solar} = 0 \tag{1}$$

where $\frac{dK_c}{dt}$ represents the derivative of conductor temperature with time. The radiation heat loss J_{radi}, convection heat loss J_{conv}, heat from solar radiation J_{solar} and the conductor Joule heat $I^2\ R(K_c)$ are also considered in this equation.

The time interval of day-ahead scheduling is usually one hour. Although transient heat balance equation can evaluate the dynamic thermal rating of OHLs more precisely, considering the thermal time constant of OHLs is usually in the range of 10 to 20 min [38], so the error introduced by assuming the steady-state equation is likely to be very small [38]–[40]. Therefore, the steady-state heat balance expression in IEEE Standard 738 [37] is adopted in this study, which is shown in (2).

$$J_{conv} + J_{radi} - I^2R(K_c) - J_{solar} = 0 \tag{2}$$

In the above expression, the heat gained from the solar radiation J_{solar} can be calculated by (3) [37].

$$J_{solar} = \alpha Q_{se} \sin(\gamma) A' \tag{3}$$

The radiated heat loss J_{radi} can be calculated by (4) [37].

$$J_{radi} = 17.8 D_0 \varepsilon \left[\left(\frac{K_c + 273}{100}\right)^4 - \left(\frac{K_a + 273}{100}\right)^4 \right] \tag{4}$$

The calculation of the convection heat loss J_{conv} is also based on [37] and it can be classified into two categories including the forced convection and natural convection. If there is wind around the conductor, the larger value from the following formula (5)-(6) will be adopted for J_{conv}.

$$J_{conv,1} = K_{angle}[1.01 + 1.35 N_{Re}^{0.52}](K_c - K_a)k_f \tag{5}$$

$$J_{conv,2} = 0.754 K_{angle} N_{Re}^{0.6}(K_c - K_a)k_f \tag{6}$$

where N_{Re} is the Reynolds number and it is relevant to the wind speed. The expression for N_{Re} is as follows:

$$N_{Re} = \frac{1}{\mu_f} D_0 \rho_f S_w \tag{7}$$

If the wind speed around the conductor is zero, the natural convection happens and the natural heat loss convection is calculated by equation (8).

$$J_{conv,n} = 3.645 \rho_f^{0.5} D_0^{0.75} (K_c - K_a)^{1.25} \tag{8}$$

By calculating each element in HBE, the thermal rating of an overhead transmission line can be expressed by:

$$I_{max} = \sqrt{\frac{1}{R(K_c)}(J_{conv} + J_{radi} - J_{solar})} \tag{9}$$

The DTR of an overhead transmission line can be evaluated based on the day-ahead predicted meteorological conditions. By comparing the DTR evaluation result with the STR, the thermal rating improvement rate (TRIR) can be obtained by (10).

$$TRIR_l = \frac{I_{max,DTR} - I_{max,STR}}{I_{max,STR}} \tag{10}$$

In the day-ahead scheduling of power system, the rating of transmission line is updated by the product of TRIR and the original line rating. Then the predicted rating based on DTR is incorporated in the NCUC model to implement the power system scheduling.

IV. NETWORK-CONSTRAINED UNIT COMMITMENT FRAMEWORK

Based on the NTO modeling and predicted TRIR obtained by DTR modeling, these two technologies can be incorporated in the network-constrained unit commitment model to quantify their influence on power system scheduling.

The objective function of proposed model is to minimize the total dispatch cost, the wind curtailment cost and the load curtailment cost, which is shown in (11). The dispatch cost includes generating cost, no-load cost, start-up cost and shut-down cost.

$$\begin{aligned} \min \sum\nolimits_{t=1}^{T} \Big\{ & \sum\nolimits_{g=1}^{N_g} (C_g P_{g,t} + C_g^{SU} m_{g,t} + C_g^{SD} n_{g,t} + C_g^{NL} u_{g,t}) \\ & + C_{LC}\left[D_t^{sys} - \sum\nolimits_{d=1}^{N_d} (P_{d,1,t} + P_{d,2,t})\right] + C_{WC} WC_t \Big\} \end{aligned} \tag{11}$$

The NTO model including both bus splitting and transmission line switching technology is incorporated in the NCUC model so as to implement the network topology scheduling [30].

For the transmission lines, it can be switched in or out in line switching technology, which is expressed in (12) and (13). Meantime, it can also be connected to either of the busbars in the relevant substation. Constraints (14) and (15) represent the line connectivity relationships with two busbars.

The power flow calculation at each end of the line is shown in (16)-(17).

$$\left|P_{l,e,1,t}\right| \le y_{l,t} P_{l,t}^{max,DTR} \quad \forall l, e, t \tag{12}$$

$$y_{l,e,t} - y_{l,t} \le 0 \quad \forall l, e, t \tag{13}$$

$$\left|P_{l,e,1,t}\right| \le P_{l,t}^{max,DTR} \left(1 - y_{l,e,t}\right) \quad \forall, e, t \tag{14}$$

$$\left|P_{l,e,2,t}\right| \le P_{l,t}^{max,DTR} y_{l,e,t} \quad \forall l, e, t \tag{15}$$

$$P_{l,t} - P_{l,fr,1,t} - P_{l,fr,2,t} = 0 \quad \forall l, t \tag{16}$$

$$P_{l,t} - P_{l,to,1,t} - P_{l,to,2,t} = 0 \quad \forall l, t \tag{17}$$

The constraints related to generator connection relationships with busbars and corresponding power output are illustrated in (18)-(24). As one generator can inject power to either of two busbars in corresponding substation which has bus splitting capability, the summation of the power delivered to two busbars is the output of this generator, which is shown in (18). The Big-M technique is applied to avoid the product of continuous variables and binary variables, which helps formulate the model as MILP format and reduce the computational burden. When $u_{g,t}$ is equal to 0, constraints (21) and (24) guarantee that there is no power output in this generator; otherwise, the power output can be injected to busbar 1 or busbar 2 based on the value of $y_{g,t}$, which is restricted in (19)-(20) and (22)-(23).

$$P_{g,1,t} + P_{g,2,t} = P_{g,t} \quad \forall g, t \tag{18}$$

$$P_{g,1,t} - \left(1 - y_{g,t}\right) P_g^{min} \ge -M\left(1 - u_{g,t}\right) \quad \forall g, t \tag{19}$$

$$P_{g,1,t} - \left(1 - y_{g,t}\right) P_g^{max} \le M\left(1 - u_{g,t}\right) \quad \forall g, t \tag{20}$$

$$-Mu_{g,t} \le P_{g,1,t} \le Mu_{g,t} \quad \forall g, t \tag{21}$$

$$P_{g,2,t} - y_{g,t} P_g^{min} \ge -M\left(1 - u_{g,t}\right) \quad \forall g, t \tag{22}$$

$$P_{g,2,t} - y_{g,t} P_g^{max} \le M\left(1 - u_{g,t}\right) \quad \forall g, t \tag{23}$$

$$-Mu_{g,t} \le P_{g,2,t} \le Mu_{g,t} \quad \forall g, t \tag{24}$$

The load connection constraints are shown in (25) and (26). The load is connected with busbar 1 when $y_{d,t}$ is equal to 0; otherwise, the load is connected to busbar 2.

$$0 \le P_{d,1,t} \le -P_{d,t}^{max} y_{d,t} + P_{d,t}^{max} \quad \forall d, t \tag{25}$$

$$0 \le P_{d,2,t} \le P_{d,t}^{max} y_{d,t} \quad \forall d, t \tag{26}$$

The phase angle difference between two busbars at one substation is constrained by (27). It indicates that if two busbars are connected, there is no angle difference between them. The phase angle constraints for the busbars are shown in (28) and (29); and the angle for the reference bus is shown in (30).

$$\left(1 - y_{b,t}\right) \beta^{max} \ge \left|\beta_{b,1,t} - \beta_{b,2,t}\right| \quad \forall b, t \tag{27}$$

$$-\beta^{max} \le \beta_{b,1,t} \le \beta^{max} \quad \forall b, t \tag{28}$$

$$-\beta^{max} \le \beta_{b,2,t} \le \beta^{max} \quad \forall b, t \tag{29}$$

$$\beta_{1,1,t} = 0 \quad \forall t \tag{30}$$

The power flow calculation for the transmission line in each dispatch time interval is shown in (31). The phase angle relationship between one endpoint of the transmission line and the relevant busbar that it is connected to is shown in (32)-(33). The power balance constraint at each busbar is shown in (34)-(35). The utilized power output of wind farm should also be added in the left-hand side of the equation.

$$\left|-P_{l,t} + \frac{\beta_{l,fr,t} - \beta_{l,to,t}}{X_l}\right| \le M\left(1 - y_{l,t}\right) \quad \forall l, t \tag{31}$$

$$\left|\beta_{l,e,t} - \beta_{l,e,1,t}\right| \le \beta^{max} y_{l,e,t} \quad \forall l, e, t \tag{32}$$

$$\left|\beta_{l,e,t} - \beta_{l,e,2,t}\right| \le \beta^{max}\left(1 - y_{l,e,t}\right) \quad \forall l, e, t \tag{33}$$

$$\sum\nolimits_{l \in L_{to,b}} P_{l,t} + \sum\nolimits_{g \in G_b} P_{g,1,t} = \sum\nolimits_{d \in D_b} P_{d,1,t} + \sum\nolimits_{l \in L_{fr,b}} P_{l,t} \quad \forall b, t \tag{34}$$

$$\sum\nolimits_{l \in L_{to,b}} P_{l,t} + \sum\nolimits_{g \in G_b} P_{g,2,t} = \sum\nolimits_{d \in D_b} P_{d,2,t} + \sum\nolimits_{l \in L_{fr,b}} P_{l,t} \quad \forall b, t \tag{35}$$

In each substation, if two busbars are connected, there is no need for specifying which busbar the elements are connected with. Therefore, some tightening constraints are introduced for simplicity, which are expressed by (36)-(38).

$$y_{g,t} + y_{b,t} - 1 \le 0 \quad \forall g \in G_b, b, t \tag{36}$$

$$y_{d,t} + y_{b,t} - 1 \le 0 \quad \forall d \in D_b, b, t \tag{37}$$

$$y_{l,e,t} + y_{b,t} - 1 \le 0 \quad \forall b, e, t, l \in L_{fr,b} \; or \; l \in L_{to,b} \tag{38}$$

The maximum numbers of switching actions for bus splitting and line switching for each dispatch interval can also be imposed, which are represented in (39) and (40) respectively.

$$\sum\nolimits_{b=1}^{N_b} \left(1 - y_{b,t}\right) - MBST \le 0 \quad \forall t \tag{39}$$

$$\sum\nolimits_{l=1}^{N_l} \left(1 - y_{l,t}\right) - MLST \le 0 \quad \forall t \tag{40}$$

As for the constraints relevant to the enforcement of DTR, the maximum TRIR for a transmission corridor is restricted by (41). The multiple meteorological conditions for different weather regions are also considered to derive more accurate DTR evaluation outcomes. If a line travels across several weather regions, the least TRIR of multiple regions for this transmission corridor is adopted to guarantee the secure operation. The rating of the lines with DTR enforcement is calculated by (42).

$$TRIR_{l,t} = \min\left\{TRIR_{region,t} \middle| region \in WR_l\right\} \quad \forall l, t \tag{41}$$

$$P_{l,t}^{max,DTR} = \left(1 + TRIR_{l,t}\right) P_{l,t}^{max,STR} \quad \forall l, t \tag{42}$$

Other constraints for the NCUC problem are represented by (43)-(53). The active power output limitation for the generating unit is shown in (43)-(44). The start-up and shut-down auxiliary variables are calculated in (45)-(46). The minimum up time and minimum down time constraints are shown in (47) and (48) respectively. The ramping rate constraints of generating units are shown in (49). Constraints (50)-(52) are relevant to the spinning reserve limitation. The amount of wind power curtailment is limited based on (53).

$$P_g^{min} u_{g,t} \le P_{g,t} \quad \forall g, t \tag{43}$$

$$P_{g,t} \leq P_g^{max} u_{g,t} \quad \forall g, t \tag{44}$$

$$u_{g,t} - u_{g,t-1} = m_{g,t} - n_{g,t} \quad \forall g, t \tag{45}$$

$$m_{g,t} + n_{g,t} - 1 \leq 0 \quad \forall g, t \tag{46}$$

$$\sum_{t=j}^{T_g^{min,up}-1+j} u_{g,t} \geq \left(-u_{g,j-1} + u_{g,j}\right) T_g^{min,up}$$

$$2 \leq j \leq 1 + T - T_g^{min,up} \quad \forall g \tag{47}$$

$$\sum_{t=j}^{T_g^{min,down}-1+j} \left(1 - u_{g,t}\right) \geq \left(-u_{g,j} + u_{g,j-1}\right) T_g^{min,down}$$

$$2 \leq j \leq 1 + T - T_g^{min,down} \quad \forall g \tag{48}$$

$$RA_g \geq \left|P_{g,t} - P_{g,t-1}\right| \quad \forall g, t \tag{49}$$

$$\sum\nolimits_{g=1}^{N_g} R_{g,t} - SRR_t \geq 0 \quad \forall g, t \tag{50}$$

$$R_{g,t} \leq -P_{g,t} + u_{g,t} P_g^{\ max} \quad \forall g, t \tag{51}$$

$$0 \leq R_{g,t} \leq RA_g \quad \forall g, t \tag{52}$$

$$0 \leq WC_{b,t} \leq WP_{b,t} \quad \forall b, t \tag{53}$$

With the enforcement of DTR and transmission network reconfiguration technologies, the search domain in the traditional NCUC optimization problem is expanded. Based on the line rating enhancement performance by DTR, the maximum transmission capacity limitation of OHLs can be relaxed under some favorable meteorological conditions. The flexibility and the congestion mitigation performance of power system are improved, which will help achieve considerable operational benefits.

V. SOLUTION METHOD

To incorporate DTR into the day-ahead NCUC problem, the first step is to evaluate the ratings of transmission lines based on the predicted environmental parameters. The studies for forecasting the dynamic line rating are reviewed in [18]. In [19] and [20], by developing a probabilistic weather forecasting model, the day-ahead ampacity forecasting can be accomplished. The method which is available to predict transmission line ampacity on a day-ahead basis can also be found in [21]. As the major aim of this paper is to quantify the operational benefit of cost-effective smart grid technologies in power system scheduling instead of predicting the weather condition for DTR calculation, the historical weather information from North Dakoda in the U.S. is used here to evaluate DTR of OHLs. The comprehensive solution method for the proposed NCUC problem is shown in Fig. 3.

The day-ahead predicted weather parameters for each weather region are input into the TRIR calculation module to simulate the DTR of the transmission lines. If a transmission line goes through multiple weather regions, the lowest TRIR will be applied in this transmission corridor to guarantee the secure operation of the transmission system.

The wind farm integration is also considered in this study so as to study the influence of cost-effective transmission technologies on wind power accommodation in the presence of transmission congestions. The predicted wind speed of the wind farms will be converted to the wind power based on the standard power output curve of wind turbine generators, which is depicted in (54) and (55) [41].

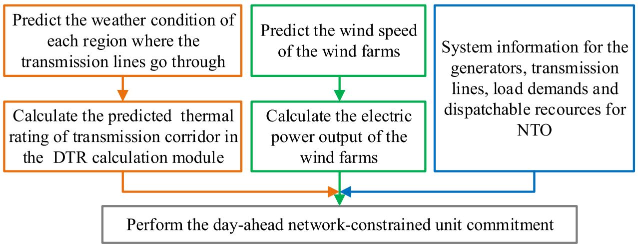

FIGURE 3. **Solution method for the proposed NCUC model.**

$$P_{WT}(v) = \begin{cases} 0 & 0 \leq v \leq v_{ci}, \ v \geq v_{co} \\ \left(a_1 + a_2 v + a_3 v^2\right) P_r & v_{ci} \leq v \leq v_r \\ P_r & v_r \leq v \leq v_{co} \end{cases} \tag{54}$$

$$\begin{cases} a_1 = \dfrac{1}{\left(v_{ci} - v_r\right)^2}\left[v_{ci}\left(v_{ci} + v_r\right) - 4 v_{ci} v_r \left(\dfrac{v_{ci} + v_r}{2 v_r}\right)^3\right] \\ a_2 = \dfrac{1}{\left(v_{ci} - v_r\right)^2}\left[4\left(v_{ci} + v_r\right)\left(\dfrac{v_{ci} + v_r}{2 v_r}\right)^3 - \left(3 v_{ci} + v_r\right)\right] \\ a_3 = \dfrac{1}{\left(v_{ci} - v_r\right)^2}\left[2 - 4\left(\dfrac{v_{ci} + v_r}{2 v_r}\right)^3\right] \end{cases} \tag{55}$$

For the implementation of NTO, similar to the existing studies on the transmission system's topological control technology, some predetermined transmission lines are considered to be switchable and some of the substations are deemed to have the bus splitting capability.

Finally, the TRIR information of the lines, system data and the output of the wind farms are entered into the NCUC model to perform the day-ahead power system scheduling.

VI. CASE STUDIES

The proposed NTO and DTR incorporated NCUC model is tested on a modified IEEE RTS-79 system [42] to demonstrate its performance. The daily load curve of the weekday in 51th week of RTS-79 system is applied here as system load pattern and the maximum load level is modified to be 2950 MW. The ramp rate, minimum up and down time of generating units are obtained from [43]. The generation cost information is from [44]. The shut-down cost is considered to be zero in this study. Similar to some existing studies with respect to the topology control technology, some modifications are made to the standard test system to introduce some transmission congestions, the ratings of line 25, 26 and 27 are decreased to 175 MW. The rating of line 21 is decreased to 220 MW [45]. The transmission capacities of other transmission lines are decreased to 0.9 p.u. of their original values. The optimization model is formulated by YALMIP under MATLAB 2016a environment and is solved by Gurobi optimizer 8.1.0 [46].

A. DESIGN OF CASE STUDIES

For DTR, the transmission system is divided into six weather regions to take the multiregional characteristic of weather conditions into account, which is shown in Fig. 4. Based on the meteorological data from North Dakoda Agriculture Weather Network [47], the hourly temperature data and wind speed information of six cities in North Dakota of the U.S. including Fargo, Grand Forks, Jamestown, Dickinson, Williston and Bottineau are used as day-ahead predicted environmental information for six weather regions to quantify the influence from DTR and NTO technologies on power system scheduling. Twenty percent dynamic TRIR of each overhead line is applied during the scheduling intervals to guarantee the safety margin for the secure operation of power system while capturing the typical influence of DTR. All the OHLs are considered to be standard 795 kcmil 26/7 overhead bare Drake ACSR conductors. The thermal rating calculation process and parameters are in accordance with IEEE Standard 738 [37]. The maximum allowable temperature for the surface of conductor is assumed to be 100 °C and the DTR technology is considered to be integrated in all OHLs.

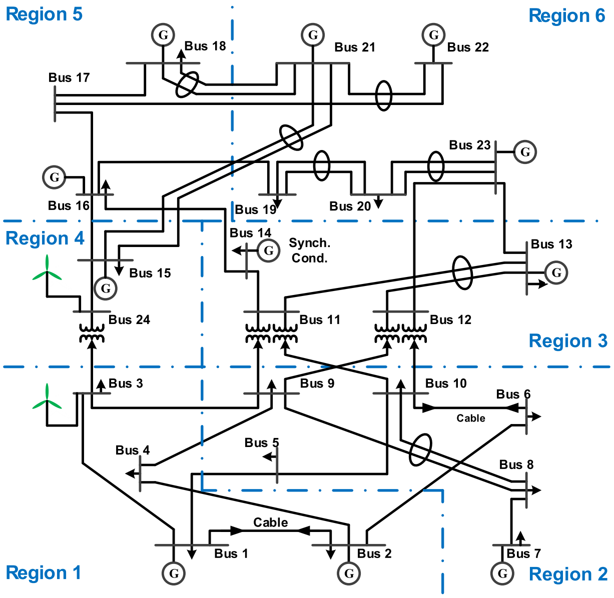

FIGURE 4. Weather regions of the power system.

As for the implementation of NTO, similar to the existing studies [48], some lines are considered to be switchable including line 2, 4, 6, 8, 9, 10, 32, 34 and 36. In addition, substation 9, 10 and 16 are considered to have the bus splitting capability.

Two wind farms which have 450 MW rated installed capacity respectively are integrated at buses 3 and 24 of the power system. The cost of wind curtailment is set as 58.8 \$/MWh [49]. The load curtailment cost is considered to be 800 \$/MWh which is much higher than the generating cost. It should be mentioned that the load curtailment variables are auxiliary variables in this study. Here the load should all be satisfied in the day-ahead scheduling. Therefore, in the case studies only the generation cost and wind curtailment cost are analyzed. The predicted wind speeds for two wind farms are depicted in Fig. 5. The rated power of wind turbine generator (WTG) is considered to be 5 MW. The cut-in, rated, and cut-out wind speeds of WTGs are set as 3 m/s, 11 m/s and 25 m/s in this study, respectively.

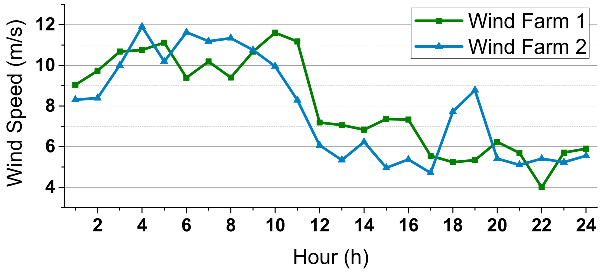

FIGURE 5. Sequential wind speed information for the wind farms.

B. SCENARIOS ANALYSIS FOR TYPICAL DAYS

To fully incorporate NTO and DTR in NCUC modeling and quantify their operational benefits in power system scheduling, 4 scenarios are tested in the case studies, including: a) Basic NCUC, b) NCUC with NTO enforced, c) NCUC with DTR enforced, and d) NCUC with NTO and DTR enforced simultaneously.

As the meteorological and geographical conditions, such as temperatures, wind speeds and solar altitudes, may vary in different seasons, the information of four typical days in four seasons is applied for scenario analysis to fully consider the influence of seasonal meteorological condition on DTR. The parameters of 1st, 91st ,181st and 271st day in 2007 are applied for four typical days including winter, spring, summer and autumn respectively as day-ahead predicted meteorological data. The summarized geographical data and ranges of the meteorological data of multiple cities applied in the scenario analysis for typical days are shown in Table 2 [47]. The locations of the cities are shown in Fig. 6 [50]. The maximum load levels for four typical days are considered to be 100%, 85%, 90% and 95% of the maximum system load so as to cover the load level variation characteristics between different seasons comprehensively.

TABLE 2. Applied geographical and meteorological data for different regions.

Region	City	Latitude	Temperature Range (°C)	Wind Speed Range (m/s)
1	Fargo	46.897°N	[-14.08, 28.84]	[1.411, 15.725]
2	Grand Forks	47.836°N	[-16.40, 27.36]	[1.033, 14.968]
3	Jamestown	46.906°N	[-14.30, 28.01]	[1.411, 13.494]
4	Dickinson	46.895°N	[-14.75, 30.94]	[1.640, 14.466]
5	Williston	48.133°N	[-13.97, 27.44]	[2.404, 17.808]
6	Bottineau	48.821°N	[-24.05, 24.51]	[1.633, 16.755]

The simulation results of total costs for the above-described four scenarios under multiple typical days are shown in Fig. 7.

FIGURE 6. Locations of the cities [50].

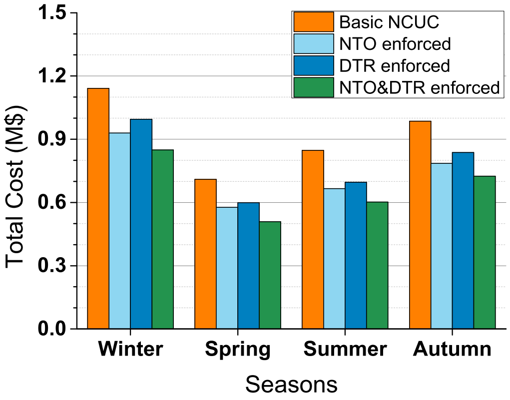

FIGURE 7. Simulation result under four typical days.

It can be seen that the DTR can help reduce the total operation cost of the system dramatically under the specified meteorological conditions of four seasons. In addition, NTO is also a promising technology to enhance the system performance and contribute to the economical operation of power grid. Meanwhile, the coordinated operation of NTO and DTR can leverage the potential transmission capacity effectively and help the power system to obtain the most operational benefits in four typical days of multiple seasons.

The operational information of winter typical day is used here to further analyze the system performance in detail. The total dispatch cost and the wind curtailment cost under four scenarios of winter typical day are listed in Table 3. The dispatch cost includes start-up cost, shut-down cost, no-load cost and generation cost of generating units. The dispatch cost saving rates under NTO, DTR and NTO & DTR scenarios comparing to the basic NCUC scenario are 16.58%, 10.01% and 19.92%, respectively. The wind curtailment saving rates in the abovementioned 3 scenarios comparing to the basic NCUC scenario are 34.19%, 36.31% and 72.71%, respectively. It can be concluded that the enforcement of NTO and DTR can all improve the performance of power system scheduling and enhance the utilization efficiency of wind power in the presence of transmission congestions, which contributes to the reduction of total operating cost.

TABLE 3. Simulation result of dispatch cost and wind curtailment cost information.

Deployed technology	Dispatch cost (M$)	Dispatch cost saving	Wind Curt. cost (K$)	Wind Curt. saving
Basic NCUC	1.019	N/A	122.33	N/A
NTO	0.850	16.58 %	80.50	34.19 %
DTR	0.917	10.01 %	77.90	36.31 %
NTO & DTR	0.816	19.92 %	33.38	72.71 %

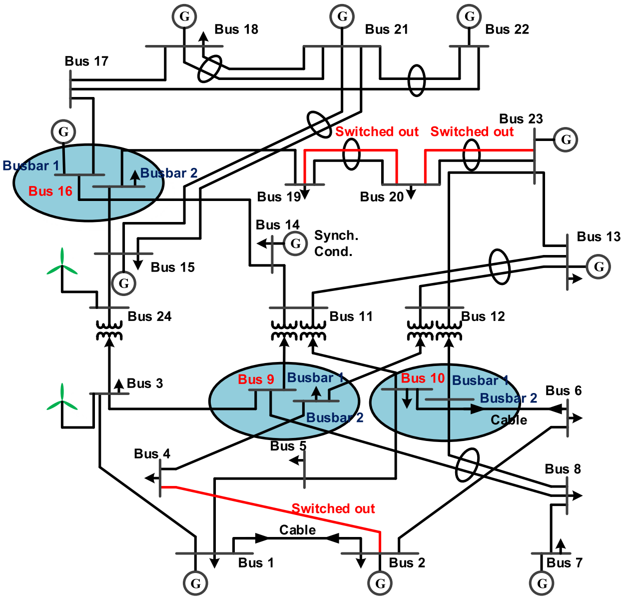

FIGURE 8. System topology diagram in winter typical day under the NTO scenario.

Some operating state and information of electric power system under a winter typical day is utilized to illustrate the operational mechanism of NTO and DTR. A system topology diagram of the 7th hour in winter typical day under the NTO scenario is depicted in Fig. 8. It can be seen that the busbars of substations which have bus splitting capability are split into two busbars under this system state. Meanwhile, the Line 4, Line 34 and Line 36 are switched out under this system state. The states of all switchable lines for 24 hours of winter typical day under NTO scenario are shown in TABLE 4. By the transmission topology reconfiguration including bus-splitting technology and transmission switching technology, the power flow distribution can be changed and transmission congestions can be mitigated, which help improve the utilization efficiency of the transmission infrastructures and lead to operational benefits. The TRIR of line 38 in region 6 under the DTR scenario during a sampled winter week is shown in Fig. 9. It can be concluded that the thermal rating can be dynamically improved during favorable weather conditions, which help enhance the transmission capacities of the power system.

The hourly dispatch cost information and hourly electric power produced by oil-fueled generating unit are shown in Fig. 10 and Fig. 11, respectively. It can be concluded that the operational performance of power system is increased

TABLE 4. Switching states of switchable lines in NTO implemented scenrio.

Switchable Lines	Switching States for 24 Hours			
	1-6 h	7-12 h	13-18 h	19-24 h
2	111111	111110	011001	111111
4	100011	001001	101000	110000
6	111111	111111	111111	110100
8	111111	110111	111111	111111
9	111000	100111	000110	001111
10	111111	101000	100111	000111
32	110011	100100	000010	111000
34	001010	011100	100011	000010
36	111110	001001	010100	110001

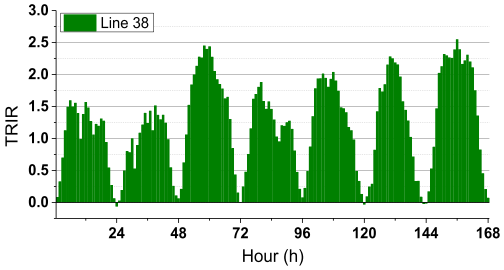

FIGURE 9. TRIR of line 38 in region 6 during a sampled winter week.

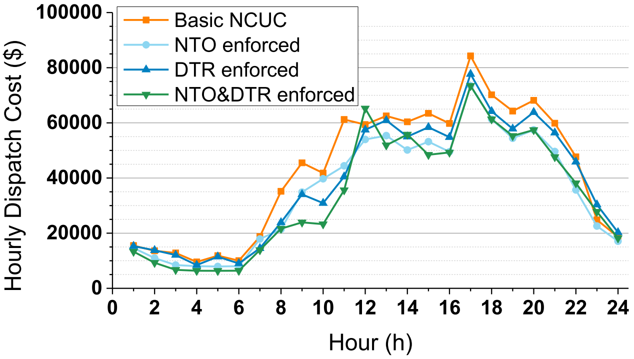

FIGURE 10. Hourly dispatch cost information under winter typical day.

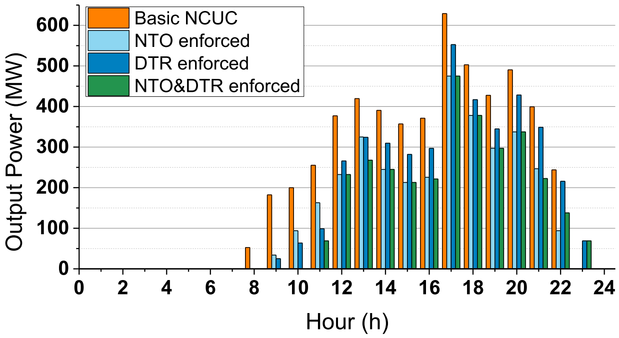

FIGURE 11. Hourly electric power produced by oil-fueled generating unit.

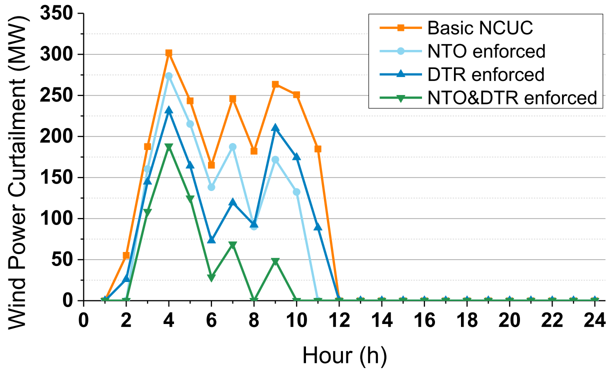

FIGURE 12. Sequential wind power curtailment information.

dramatically after the implementation of NTO and DTR. In Fig. 10, except for very few scheduling intervals, the NTO and DTR can contribute to the reduction of dispatch cost during most time intervals effectively. In 12th hour, the hourly dispatch cost in both technologies enforced scenario is increased. It is because the NTO and DTR improve the utilization efficiency of wind power. When there is a big drop on wind speed, more generating units are started up in this hour, which increases the start-up costs. However, the simultaneous enforcement of NTO and DTR can lead to best operational benefit, which is shown in abovementioned Table 3. In the presence of transmission congestions, the generation cost will be increased and more power will be generated from generators which have more generation cost, such as oil-fueled generators. In this study, the enforcement of NTO enable the switchable lines and the substations which have bus splitting capability to become schedulable resources for the system operator, which increases the flexibility of transmission system. Meantime, the deployment of DTR boost the transmission capacity of transmission lines. Both technologies are effective congestion mitigation measures. They can enlarge the feasible solution space for NCUC problem and help the power system to be dispatched in a more economical manner.

The application of NTO and DTR can also enhance the wind power accommodation capacity of electric power system when there is limited transmission capacity and congestions in the transmission system, which contributes to the system performance enhancement. The sequential wind power curtailment information in four scenarios under winter typical day is depicted in Fig. 12. As there are transmission congestions in the network and there is limited transmission capacity for the wind farms to deliver the generated power especially when the output of wind farms is close to or equal to their rated installed capacity, there are considerable wind power curtailment under Basic NCUC scenario. It can be observed that, when NTO and DTR are implemented, the wind power accommodation capacity of power grid is improved significantly, which helps reduce the waste of wind power.

The partial system topology figures and operational information for the 7th hour of winter typical day extracted from the day-ahead scheduling plan under Basic NCUC, NTO, and NTO & DTR scenarios are shown in Fig. 13 so as to illustrate the enhancement of wind power accommodation capacity. Line 1-3, 3-9 and 15-24 are three important transmission corridor for the large scale wind power to be delivered to other load point in the system. In Basic NCUC scenario, the fixed transmission topology leads to the underutilization of some transmission lines. The utilization efficiency of line 1-3 and 15-24 are only 66.4% and 96.5% respectively. Under this scenario, 246.1MW wind power are curtailed. When the NTO technology is implemented, the flexibility of transmission system is increased and the power flow distribution is changed, which contributes to the improved utilization efficiency of existing transmission corridor. The power flows of line 1-3 and 15-24 are increased. Therefore, the wind power curtailment is decreased to 187.3 MW under this scenario. When both DTR and NTO are enforced in the scheduling model, the maximum transmission capacity of the lines in this hour is increased due to the favorable weather conditions. So more wind power can be transferred to other load points of the system and be accommodated there by fully utilizing the limited transmission capacities. The wind power curtailment under this scenario is only 68.8 MW. The utilization efficiency of wind power and transmission system is further improved due to the simultaneous implementation of both NTO and DTR technologies.

From the above analysis, it can be concluded that the DTR and NTO can help to improve the utilization efficiency of wind power when there is limited transmission capacity and enhance the system operational performance in a cost-effective way. The research result provides novel solving strategies for the power system to break the bottleneck of wind power accommodation when the upgrade of transmission infrastructures cannot keep pace with the construction of large scale wind power bases. This will contribute to the establishment of a high proportion renewable energy power system and help boost the technical revolution for the renewable energy utilization.

C. COMPARATIVE STUDIES ON OTS AND NTO

There are some existing studies which explore the impact of OTS on the day-ahead scheduling of power system. As one of the contributions for this paper is to incorporate the comprehensive topological control technology of NTO including both transmission switching and bus splitting in the NCUC model, a comparative study is conducted in this part to compare the system performances under OTS and NTO operation strategies.

The total costs for OTS and NTO topology control strategy of the winter typical day under STR and DTR circumstance are shown in Fig. 14. It can be concluded that the total cost of system under NTO dispatch strategy is lower than the cost in OTS dispatch strategy. The coordination of DTR with both OTS and NTO can enhance the system performance comparing to the STR scenario.

The detailed dispatch cost and wind curtailment cost information under the OTS and NTO dispatch strategies in both STR and DTR scenarios are shown in TABLE 5. It can be concluded that coordination of DTR and two topology control strategies can reduce the system dispatch cost and the wind power curtailment cost effectively. However, the NTO can leverage more potential transmission capacity of the transmission system and have a better enhancement performance.

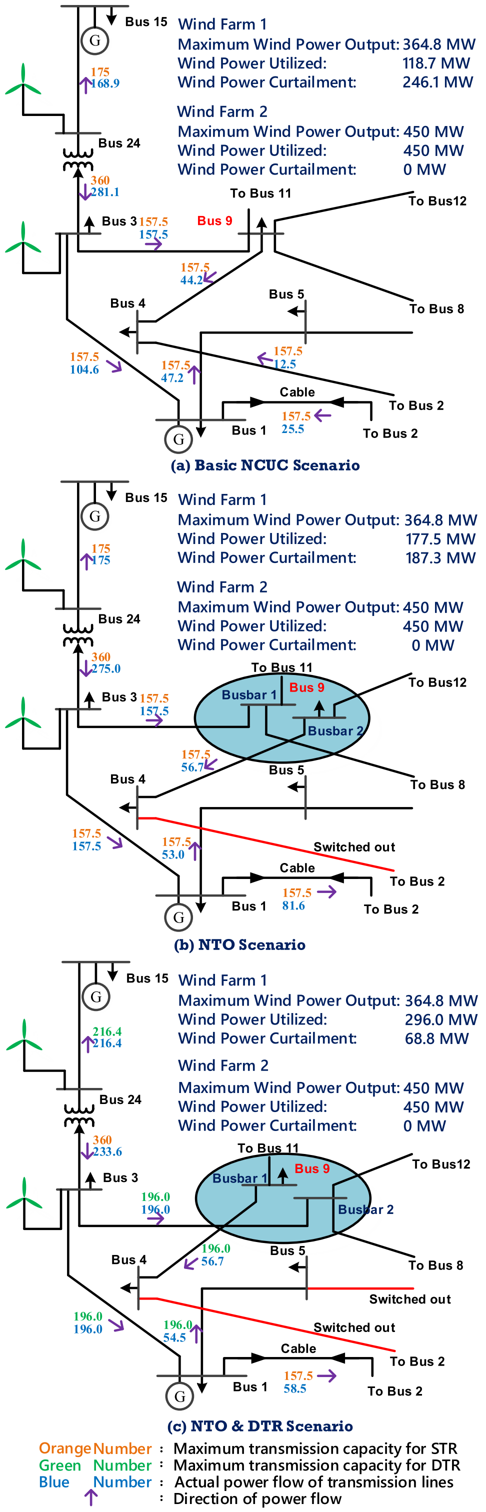

FIGURE 13. Partial system topology and operating information.

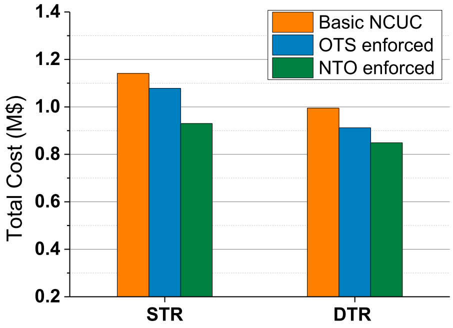

FIGURE 14. Total cost comparison for OTS and NTO topology control strategy.

TABLE 5. Performance comparison For OTS and NTO topology control strategy.

Scenarios		Dispatch Cost (M$)	Dispatch Cost Saving	Wind Curt. Cost (K$)	Wind Curt. Saving
S	Basic NCUC	1.019	N/A	122.33	N/A
T	OTS enforced	0.991	2.74 %	87.13	28.77 %
R	NTO enforced	0.850	16.58 %	80.50	34.19 %
D	Basic NCUC	0.917	10.01 %	77.90	36.31 %
T	OTS enforced	0.874	14.22 %	37.86	69.05 %
R	NTO enforced	0.816	19.92 %	33.38	72.71 %

Therefore, besides the transmission switching resources, it is also beneficial to enable some substations to have the bus-splitting capability. So the system operator can enhance the power system performance with comprehensive NTO technologies by means of the line switching and substation reconfiguration actions.

VII. CONCLUSION

The emerging transmission system technologies under a smart grid environment boost the technical revolution of power grid and can contribute to the efficient utilization of existing transmission infrastructures. This paper incorporates two promising, cost-effective technologies including DTR and NTO in the NCUC model to investigate their synergistic effect on the power system scheduling and renewable energy accommodation. Numerical results prove that NTO is able to further utilize the potential transmission capacity by network topology reconfiguration while DTR can increase the thermal rating of OHLs when there are suitable weather conditions. The implementation of these two technologies can contribute to the flexible operation of power system and can enlarge the solution domain of NCUC problem. This will bring considerable operational benefits to power system by means of the reduction of total dispatch cost and wind power spillage cost. In addition, comparative studies are conducted to compare the performance of OTS and NTO topology control technology. It is verified that the NTO can reduce the total operational cost and wind power curtailment more effectively comparing to OTS.

It is believed that the research results of this work can help the utility operator to dispatch the power system in a more economical manner by utilizing the existing infrastructures more efficiently. Meanwhile, it also provides novel solving strategies for the integration of large scale wind farms in the face of transmission congestions.

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