Wind Power Integration through Stochastic Unit Commitment with Topology Control Recourse

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***Abstract*— We introduce a two stage stochastic unit commitment formulation in which the second stage recourse actions include possible reconfiguration of the power grid topology through transmission line switching. We conduct numerical test on IEEE 118 system to demonstrate the benefits of such adaptive topology control. Our results show that such recourse capability in response to realized uncertainty of intermittent renewable resources can mitigate such adverse variability and significantly improve unit commitment efficiency.**

***Index Terms*—Renewables integration, stochastic unit commitment, topology control, transmission switching, wind generation.**

I. NOMENCLATURE

Indices and Sets:

i, j	Buses (nodes).
t	Time period.
s	Scenario.
g	Conventional generator.
w	Wind generator.
G	Set of generators.
GS	Set of slow generators.
GF	Set of fast generators.
N	Set of buses.
$N(i)$	Set of buses connected to bus i .
S	Set of scenarios.
T	Set of time periods, $T=\{1,2,...,24\}$.
GW	Set of wind generators.

Parameters:

B_{ij}	Susceptance of line ij .
$D_{i,t}$	Demand on bus i at time t .
π_s	The probability of scenario s .
h_g	Start-up cost of generator g .
k_g	No-load cost of generator g .
c_g	Production cost of generator g .
ρ_i	Penalty cost of load shedding at bus i .
R_g^U	Maximal ramping up rate of generator g .
R_g^D	Maximal ramping down rate of generator g .
ω_g^{On}	Minimal on-time of generator g .
ω_g^{Off}	Minimal off-time of generator g .
$P_g^{\max}$	Maximal production level of generator g .
$P_g^{\min}$	Minimal production level of generator g .
Γ_t	System reserve requirement at time t.
$F_{ij}^{\max}$	Maximal line flow capacity of line ij .
$W_{w,t,s}$	Production level of wind generator w at time t in scenario s .

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 .
$\theta_{i,t,s}$	Voltage angle of bus i at time t in scenario s .
$r_{ij,t,s}$	On-off status of line ij at time t in scenario s .
$L_{i,t,s}$	Load shedding on bus i at time t in scenario s .

II. INTRODUCTION

THE massive integration of wind resources into the generation mix of the electric power infrastructure poses new challenges to system operators due to the uncertainty and variability of these resources. Unlike conventional generators, wind generation output is uncontrollable and unpredictable until at most few hours before the delivery time and its output level exhibits wide variability. Due to the limitation of storage in current power systems, demand and supply of

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This work was supported by NSF Grant ECCS 1549572.

electricity must be matched instantaneously and the flows of power throughout the electricity networks are governed by Kirchhoff's laws and are prone to congestion. Thus, serving load reliably in the presence of the variability and uncertainty of wind resources imposes extreme ramping requirements on the conventional generation resources. Such requirement can be met by deploying increased amounts of reserves and through increased utilization of flexible generation resources. However, such a solution is expensive and could undermine the economic and environmental objectives of deploying renewable resources in the first place unless implemented judiciously. Efficient deployment of conventional and flexible resources require new methods that explicitly account for uncertainty in day-ahead unit commitment. Hence, such methodologies have become a prevalent direction of research over the last decade adopting methods such as stochastic two-stage optimization and robust optimization to unit commitment optimization.

Two-stage stochastic optimization approaches typically differentiate between slow ramping resources that must be committed before uncertain wind scenarios are realized and flexible resources that provide recourse capability in response to diverse realizations of uncertain wind output and load. Recourse actions in response to realized uncertainties serve as hedging mechanisms that can reduce the need for reserves provided by the early commitment of slow generators. Hence increasing the scope of available recourse actions is the key to improving the efficiency and reducing the cost of providing reliable service. The conventional means for such recourse actions are fast ramping generators that as mentioned are expensive, especially if deployed infrequently and for short durations. Alternative innovative approaches include storage devices that at this point are uneconomical and demand response that provides vast opportunities. In this paper, we focus on an alternative that received little attention as a means for recourse actions in response to wind uncertainty realization. Specifically we focus on active control of the network topology through on or off switching of transmission lines that will result in redirecting flows in the network. In a practical system, once a decision, including turning on or off generators and switching on or off lines, is made, the system operator should check the stability of the system. But this issue is not in the scope of this paper. Here, we will only focus on how to make such decisions. If the switching of lines may undermine the stability of the system, we could put a constraint in our model and solve it again.

Various models have been studied for unit commitment of systems with wind generation. One of the simple approaches, as described in [1], is to model requirements for excess generation in a deterministic formulation of unit commitment where explicit constraints on reserves and import limit are imposed. When renewable supply and load fluctuations or when transmission lines and generation outages occur, there should be excess generation capacity, i.e., reserves, that can be called on. In contrast to the deterministic formulation, another way to model this problem is to adopt stochastic programming models where the uncertainty of wind generation is modeled as weighted scenarios and reserve requirements are modeled endogenously [2]-[4]. Stochastic models require substantial information about wind generation uncertainty. Scenario reduction techniques have been proposed to reduce computational complexity and improve tractability. Approaches to optimize the operation cost include Lagrangian relaxation [4] augmented Lagrangian methods [3] and progressive hedging methods [2]. There is also extensive literature on chance-constrained formulations [5] and robust optimization models [6] of the day-ahead scheduling problems for power systems with variable renewable resources. In this paper, we focus only on the stochastic programming formulation.

Transmission lines are traditionally considered as static uncontrollable assets in the operations of power systems. However, recent studies [7]-[9] show that, in practice, system operators can and do change the topology of the grid to improve voltage profiles, increase transfer capacity, and even improve system reliability. Through actively controlling the topology of power systems, more flexibility can be achieved. The idea of topology control has been studied by researchers since 1980's: to relieve abnormal conditions in a system with scheduled outages or unscheduled events [10],[11]; and to reduce system loss [12],[13]. The switching of transmission lines utilizes existing assets required by normal operating conditions. It incurs no additional cost other than possible wear of the breakers which is typically small comparing to the potential benefits. Recent studies show that topology control can significantly reduce the cost of optimal power flow (OPF) [8],[14]. The core idea is to co-optimize the topology with the generation dispatch. A mixed-integer programming (MIP) problem is solved to provide system operators choices of altering dispatches as well as system topologies. Ruiz et al. proposed fast heuristics for OPF with topology control instead of solving MIP directly [15],[16]. Preliminary studies [17],[18] of topology control in a deterministic unit commitment setting show that with topology control, the operating cost can be reduced significantly.

To mitigate the variability and reduce operation cost without affecting system reliability in day-ahead scheduling, we propose to incorporate topology control into the formulation of stochastic unit commitment (SUC). The objective of this paper is to demonstrate that topology control as a recourse action may provide benefits by mitigating the variability of wind generation and reduce the system operation cost. The remainder of the paper is organized as follows. In section III, we formulate the two-stage stochastic unit commitment model with topology control recourse. In section IV, results of numerical tests conducted on IEEE 118 system are presented and analyzed. And section V concludes the paper.

III. MODEL DESCRIPTION

In this paper, the set of conventional generation resources (G) was partitioned into a set of slow generators (GS) and a set of fast generators (GF). Fast generators can be synchronized to or disconnected from the power network within a shorter period of time than slow generators. We formulate the problem as a mixed-integer two-stage stochastic program. The uncertainty of wind generation is modeled as a discrete set of scenarios with known probabilities. The first stage of the problem represents day-ahead decisions and the second stage represents the real-time recourse in response to the revealed system conditions. In the model, the commitments of slow generators are first-stage decisions that are made before the realization of wind generation. Other decisions including fast generator commitments, production of all generators and the switching of transmission lines are second-stage decisions. The commitment of fast units and the dispatch of generators' production are co-optimized with topology control actions in the recourse. The stochastic unit commitment with topology control recourse (TCSUC) can be formulated as follows:

$$\begin{aligned}\min\sum_{t\in T}\Bigg(&\sum_{s\in S}\pi_s\Bigg(\sum_{g\in GF}\left(h_g\sigma_{g,t,s}+k_g u_{g,t,s}+c_g P_{g,t,s}\right)+\sum_{g\in GS}c_g P_{g,t,s}\\&+\sum_{i\in N}\rho_i L_{i,t,s}\Bigg)+\sum_{g\in GS}\left(h_g\sigma_{g,t}+k_g u_{g,t}\right)\Bigg)\end{aligned}\tag{1}$$

$$\begin{aligned}s.t.\ &\sum_{j\in N(i)}F_{ij,t,s}-\sum_{k\in N(i)}F_{ki,t,s}+\sum_{\substack{g\in G\\ g\text{ on bus }i}}P_{g,t,s}+\sum_{\substack{w\in W\\ w\text{ on bus }i}}W_{w,t,s}\\&-D_{i,t}+L_{i,t,s}=0,\forall i\in N,t\in T,s\in S\end{aligned}\tag{2}$$

$$\begin{aligned}&-\mathrm{M}_{ij}\left(1-r_{ij,t,s}\right)\le F_{ij,t,s}-B_{ij}\left(\theta_{i,t,s}-\theta_{j,t,s}\right)\le\mathrm{M}_{ij}\left(1-r_{ij,t,s}\right),\\&\forall i,j\in N,t\in T,s\in S\end{aligned}\tag{3}$$

$$-r_{ij,t,s}F_{ij}^{\max}\le F_{ij,t,s}\le r_{ij,t,s}F_{ij}^{\max},\forall i,j\in N,t\in T,s\in S\tag{4}$$

$$P_g^{\min}u_{g,t}\le P_{g,t,s}\le P_g^{\max}u_{g,t},\forall g\in GS,t\in T,s\in S\tag{5}$$

$$P_g^{\min}u_{g,t,s}\le P_{g,t,s}\le P_g^{\max}u_{g,t,s},\forall g\in GF,t\in T,s\in S\tag{6}$$

$$\begin{aligned}&P_{g,t,s}-P_{g,t-1,s}\le R_g^U+\sigma_{g,t,s}\left(P_g^{\max}-R_g^U\right),\\&\forall g\in G,t\in T,t\ge 2,s\in S\end{aligned}\tag{7}$$

$$\begin{aligned}&P_{g,t-1,s}-P_{g,t,s}\le R_g^D+\left(P_g^{\max}-R_g^D\right)\left(u_{g,t-1,s}-u_{g,t,s}\right),\\&\forall g\in G,t\in T,t\ge 2,s\in S\end{aligned}\tag{8}$$

$$\sigma_{g,t}\ge u_{g,t}-u_{g,t-1},\forall g\in GS,t\in T,t\ge 2\tag{9}$$

$$\sigma_{g,t,s}\ge u_{g,t,s}-u_{g,t-1,s},\forall g\in GF,t\in T,t\ge 2,s\in S\tag{10}$$

$$\sum_{\tau=t}^{\min\left(t+\omega_g^{On},24\right)}\sigma_{g,\tau}\le u_{g,t},\forall g\in GS,t\in T\tag{11}$$

$$\sum_{\tau=t}^{\min\left(t+\omega_g^{On},24\right)}\sigma_{g,\tau,s}\le u_{g,t,s},\forall g\in GF,t\in T,s\in S\tag{12}$$

$$\sum_{\tau=t+1}^{\min\left(t+\omega_g^{Off},24\right)}\sigma_{g,\tau}+u_{g,t}\le 1,\forall g\in GS,t\in T,t<24\tag{13}$$

$$\sum_{\tau=t+1}^{\min\left(t+\omega_g^{Off},24\right)}\sigma_{g,\tau,s}+u_{g,t,s}\le 1,\forall g\in GF,t\in T,t<24,s\in S\tag{14}$$

$$\sum_{ij}\left(1-r_{ij,t,s}\right)\le J,\forall i,j\in N,t\in T,s\in S\tag{15}$$

$$u_{g,t}\in\{0,1\},s_{g,t}\in[0,1],\forall g\in GS,t\in T\tag{16}$$

$$\begin{aligned}&r_{ij,t,s},u_{g,t,s}\in\{0,1\},\sigma_{g,t,s}\in[0,1],\forall g\in GF,i,j\in N,\\&\quad t\in T,s\in S\end{aligned}\tag{17}$$

The objective (1) is to minimize total expected cost. The first constraint (2) is the energy balance constraint. Decision variable $r_{ij,t,s}$ denotes the on-off status of transmission lines ij which is made after the realization of wind generation. When $r_{ij,t,s}=1$, line ij is on at time t in scenario s. Otherwise, it is off. Constraint (3) represents the modified linear approximation of Kirchhoff's current law. The parameter M_{ij} in this constraint has to be greater or equal to $\left|B_{ij}\right|\max\left(\left|\theta_i-\theta_j\right|\right)$, so that if a line is off, the voltage angles of the two buses are no longer related. We want M_{ij} to be as small as possible to generate efficient cuts. In normal operating states of power systems, the voltage angle difference between connected buses is below 5°. Using the topology information of the system, we can estimate $\max\left(\left|\theta_i-\theta_j\right|\right)$ and a sufficiently small value of M_{ij}. Constraint (4) states that if a line is off, the line flow is zero. If a line is not switched off, the flow on it should be within the flow limit. Constraints (5) and (6) limit the amount of power that can be supplied by a slow generator and a fast generator in both on and off state. Constraints (7) and (8) are ramping constraints that limit the up/down ramp rate of generators. Constraints (9) and (10) are on/off transition constraints that link the commitment decisions of generators and the start-up variable. In our model, we assume the initial states of all generators are off. Constraints (11)-(14) are minimum up/down time constraints. Constraint (15) limits the number of lines that can be switched off at each time in each scenario. The commitments of generators are binary variables while the start-up indicators can be relaxed as continuous variables. The relaxation is valid because the coefficients of start-up indicators in the objective are positive, and we want to minimize the cost. With constraints (9) and (10), the relaxed variables can only be 0 or 1.

The optimization problem described above is a MIP. Even with scenario reduction, a certain number of scenarios are required to represent the uncertainty of wind generation accurately. Thus, the MIP has a large number of decision variables. Taking the IEEE 118 system with 10 wind generation scenarios as an example, the model contains about 50,000 integer variables and over 80,000 continuous variables. Moreover, the solution to the linear relaxation of this problem is not informative on binary switching decisions. For an interconnected practical power system with thousands of buses, the scale of the problem will be even larger, which makes the problem difficult to solve.

IV. TEST RESULTS AND ANALYSIS

A. Test System and Data Description

We conduct numerical tests on an IEEE 118 system. There are 118 buses, 186 transmission lines, 4 slow generators, and 15 fast generators in the test system. The data of the system and the costs of the generators are the same as those in [19]. In our test, wind speed and wind power data of three wind farms in Wyoming are obtained from NREL Western Wind Resources Dataset [20]. In the dataset, each turbine icon represents a site consisting of ten 3MW wind turbines. For each wind farm, we randomly picked one site and used it to represent the location. The wind generation is simulated using the method presented in [4]. We generate 1000 scenarios of 24 hours wind power output using Monte Carlo simulation. The scenario reduction is implemented based on the algorithm in [20]. The 10 selected scenarios for one of the wind farms are shown in Fig. 1.

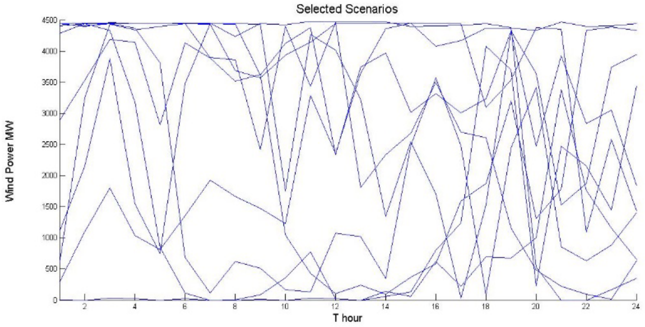


Fig. 1 Selected Wind Generation Scenarios for One of the Wind Farms

In the test, TCSUC is implemented in Java. The problem is solved using CPLEX through concert technology with Java. The test is conducted on a laptop with an Intel Core i7 2.6 GHz CPU and 12 GB RAM. When the gap tolerance is set to be 5%, and the default setting of CPLEX is adopted, the program does not terminate after 8 hours. This indicates that this MIP cannot be solved directly within a reasonable time. One of the approaches that can help reduce the solution time is to provide CPLEX a good warm-start.

B. Method for Finding Warm-Start

The objective function of TCSUC is the sum of operation cost over 24 hours. Assuming a switching solution can reduce the cost of the 24-hour unit commitment problem, it should reduce the operation cost for some 1-hour sub-problem. To obtain a start solution for switching decision, we can solve the optimal power flow problem with topology control for 1 scenario's 1 single time period with the heaviest net load. Here, net load is the actual demand minus the wind generation. To obtain warm-start for unit commitment decisions, we can solve the stochastic unit commitment without transmission switching. Normally, the system is more congested when the netload is heavier. In this case, the switching of transmission lines can relieve congestions and increase the output of cheaper generation. Combining the warm-start for unit commitment decisions and the warm-start for line switching decisions will yield the warm-start for the problem.

C. Results of TCSUC and Analysis

We conducted 9 numerical tests, in which different numbers of lines are allowed to be switched off, in order to explore whether topology control recourse will benefit the day-ahead operations of power systems with wind generation. For brevity, we name the cases "TCSUC-x", where "x" stands for the maximum number of lines that can be switched off. For example, TCSUC-5 means a stochastic unit commitment problem with topology control recourse and at most 5 lines can be switched off in each scenario at each time. TCSUC-∞ represents the case where there is no limit on the number of lines that can be switched. An SUC is also implemented whose objective value serves as a reference value. The warm-start of switching solutions obtained by solving optimal power flow with topology control are listed in Table I.

Table I Start Switching Solutions

Case	**Start switching solution**
TCSUC-1	132
TCSUC-2	132,136
TCSUC-3	132,136,153
TCSUC-4	132,136,153,162
TCSUC-5	132,136,151,153,163
TCSUC-6	132,136,148,153,161,162
TCSUC-7	63,132,136,148,153,161,162
TCSUC-10	126, 132, 136, 146, 151, 153, 157, 165
TCSUC-∞	1, 10, 14, 25, 28, 31, 57, 63, 66, 77, 79, 86, 96, 103, 110, 111, 132, 136, 146, 151, 153, 161, 165, 184

Costs for ten cases are compared to demonstrate that topology control recourse can mitigate the variability of wind generation and reduce the operation cost. The time limit of CPLEX was 30 minutes. Note that this time limit is for a laptop. When we use a more powerful computer, the time limit can be reduced. The maximum optimality gap was configured to be 5%. If a solution within the given optimality gap cannot be found within 30 minutes, a feasible solution with the best objective value is regarded as the solution. The cost of the 10 cases is depicted in Fig. 2. Cost reductions are defined as the percentage difference of costs with and without topology control recourse. The results for ten cases are shown in Fig. 3.

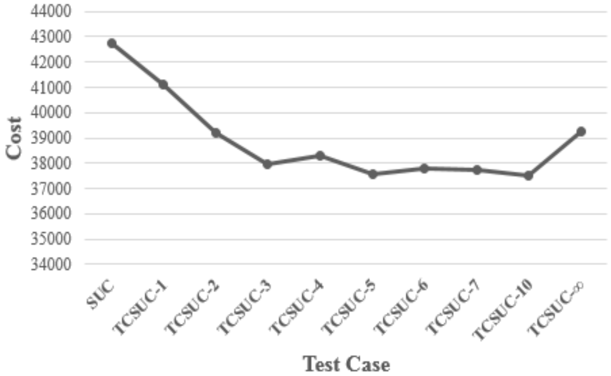


Fig. 2 Cost for Different Test Cases

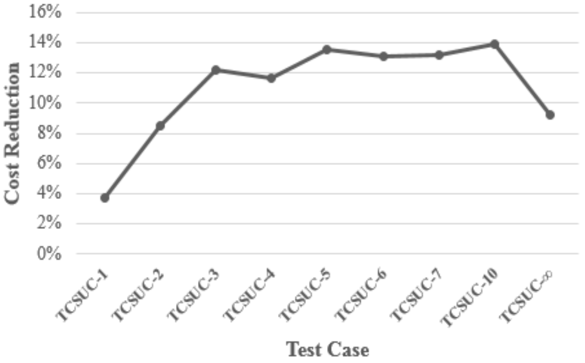


Fig. 3 Cost Reduction for Different Test Cases

From the results, we can see that the total cost can be reduced significantly with topology control recourse. Moreover, to achieve the cost reduction, we do not need to switch many lines. When at most 3 lines are allowed to be switched off, the cost reduction is above 12%. Switching off more lines may not benefit the system much more if we set a limit on the time for solving the problem. For instance, when at most 4 lines can be switched, the best solution CPLEX can find within 30 minutes is not better than the solution of TCSUC-3. The highest cost reduction is achieved in TCSUC-10. We note that the cost reduction in TCSUC-∞ where there is no constraint on the number of lines that can be switched is lower than the cost reduction in TCSUC-3 to TCSUC-10. An explanation for this anomalous result is that when starting from the given solution, relaxation induced neighborhood search (RINS) or solution polishing may be invoked to improve the given warm-start solution. In TCSUC-∞, the solution to an optimal transmission switching (OTS) problem is more targeted on that load profile. It is sensitive to the change of loads and the uncertainty of wind generation in the system. Switching off some line in one load profile may increase the cost in other load profiles. Thus in TCSUC, the warm-up solution cannot be generalized well to other scenarios. However, the solution to OTS with a constraint on the number of lines to switch tends to find lines that are in common with the switching solutions to other load profiles. They can be generalized to other scenarios effectively. Starting from the warm-start, it is easier to find a better solution for the cases with cardinality constraints for switching decisions. This can be seen from the termination gap: within the same time, the termination gap for TCSUC-10 is 3.66% while the termination gap for TCSUC-∞ is 7.88%.

With topology control recourse, the system could achieve lower cost as compared to generic stochastic unit commitment. The objective of SUC has four components: production cost for generators, start-up cost for generators, no-load costs for generators and the penalty cost for load shedding in the system. The cost reduction could be broken down into four parts based on the structure of the objective of SUC. First, given the commitment of generators, in each hour, the scheduling of production can be regarded as an OPF with transmission switching. The production of generators with low production costs could increase while the production of generators with high production costs could decrease given they are all on, which leads to lower production cost for the whole system. Second, with transmission switching, the number of on-off status changes of generators could be lowered, which reduces the startup cost. Third, if the production of some generators with high no-load cost is low, the production of that generator can be shifted to other generators that are on to reduce no-load cost. Fourth, the average load shedding in each hour is lower. All four parts are observed in the test results.

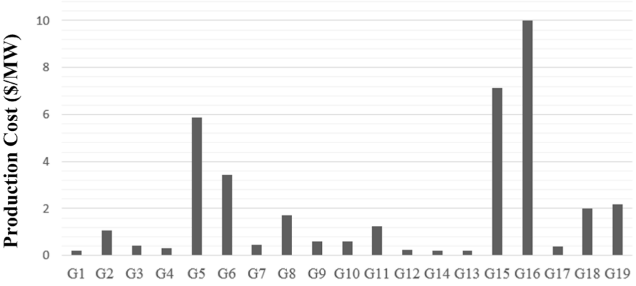


Fig. 4 Production Cost of Generators

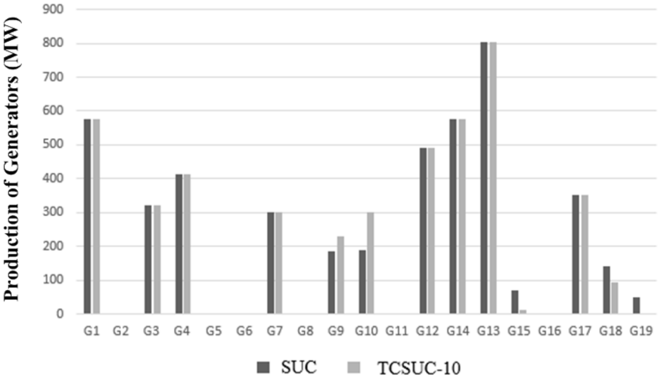
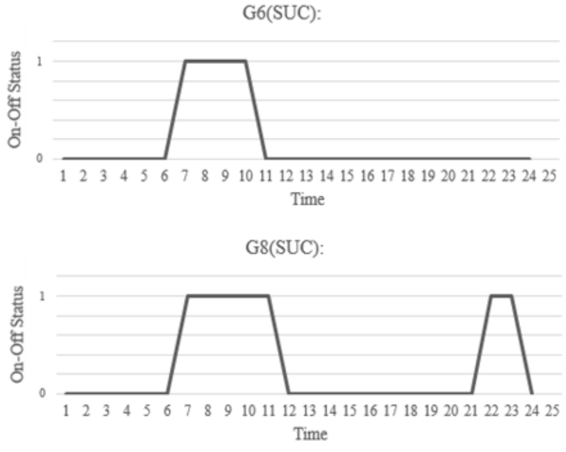


Fig. 5 Production of Generators in SUC and TCSUC-10

The production costs of fast generators are shown in Fig. 4. In TCSUC-10, the production of fast generators in scenario 1 hour 18 with and without topology control recourse is shown in Fig. 5. From Fig. 4 and Fig. 5, when there is topology control recourse, some of the production of generator 15, generator 18 and generator 19 with higher production costs is shifted to generator 9 and generator 10 with lower production costs.

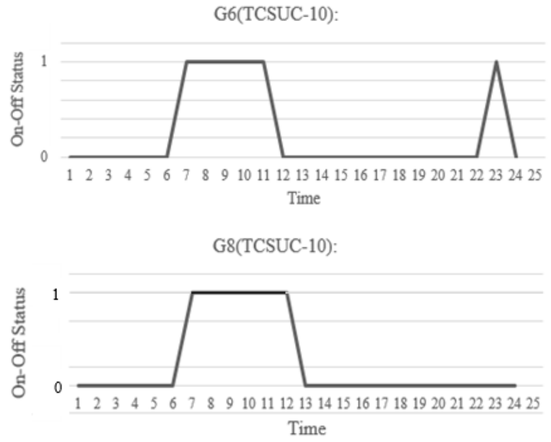
Fig. 6 shows the commitment decisions of generator 6 and generator 8 in SUC. Fig. 7 shows the commitment decisions of generator 6 and generation 8 in TCSUC-10. In SUC where there is no switching, generator 8 with higher start-up cost will be turned on twice. In TCSUC-10, the number of on-off status changes of generator 8 reduces to 1 while the number of on-off status changes of generator 6 with lower start-up cost will increase to 2. The numbers of on-off status changes of other generators in this scenario are the same. Thus, the start-up cost in this scenario is reduced.

The no-load costs of fast generators for all scenarios in SUC and TCSUC-10 are calculated and compared. The results are shown in Fig. 8. From the results, we can see that with topology control recourse, the no-load cost in all scenarios can be reduced.


G6(SUC):

G8(SUC):

Fig. 6 On-off Status Changes of Generator 6 and Generator 8 in SUC


G6(TCSUC-10):

G8(TCSUC-10):

Fig. 7 On-Off Status Changes of Generator 6 and Generator 8 in TCSUC-10

We plot the average total system load shedding defined as the expected load shedding for the whole system in each hour in SUC and TCSUC-10 in Fig. 9. From the results, we can see that except for hour 8, the average total load shedding in TCSUD-10 is higher than that in SUC. Hence, the penalty cost for load shedding in SUC will be higher than that in TCSUC-10 given that we use uniform penalty cost for different buses.

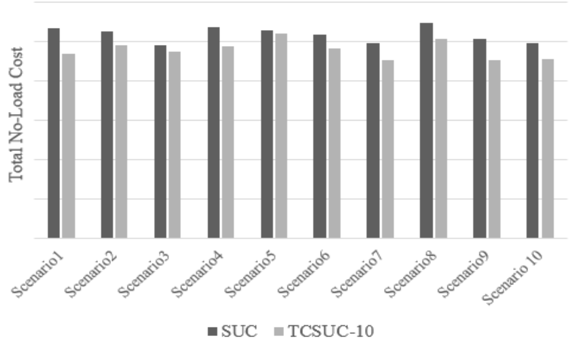


Fig. 8 No-Load Cost for All Scenarios in SUC and TCSUC-10

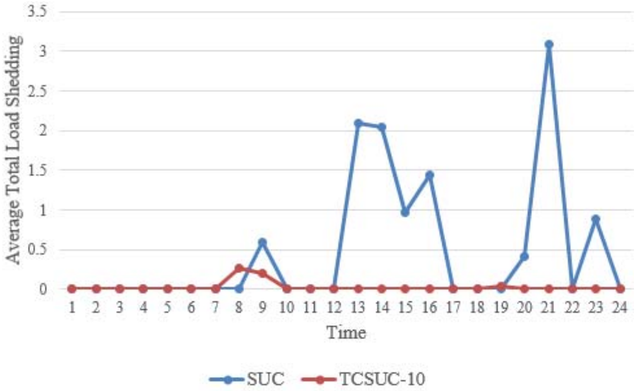


Fig. 9 Average Total Load Shedding in SUC and TCSUC-10

In TCSUC, wind generation scenarios are selected to represent the uncertainty. The purpose of reducing the number of scenarios is to reduce the complexity and make the problem easier to solve. In order to evaluate the performance of the switching policy generated using the reduced scenario set, we test the model on a larger set of scenarios. In the evaluation, the switching decisions of lines are restricted on the union of the switching solution to TCSUC-10 in each scenario and each time period, which means only lines that have been switched off in TCSUC-10 are allowed to be switched in the evaluation process. The commitment of slow generators is fixed as the solution to TCSUC-10. Since the switching solution is constrained on a set, the result of the evaluation process provides a lower bound for the cost reduction when there is no restriction on switching decisions. 1000 wind generation scenarios are generated using Monte Carlo simulation. In all 1000 tests, when there is topology control recourse, the total cost is less than when there is no transmission switching. The average total cost is reduced by 12.9% with topology control recourse with respect to stochastic unit commitment without topology control. This result shows that topology control in the recourse could help reduce the cost of the system with wind generation.

V. CONCLUSION

We have developed a two-stage stochastic programming model with topology control recourse for power systems with wind generation. We proposed a method to find a warm-start for the problem which helps reduce the solution time significantly. Numerical test results shown for the IEEE 118 system demonstrate that with topology control recourse, the operation cost will be reduced. Moreover, to achieve a significant cost reduction, only a small fraction of lines need be switched off. For future research directions, we will study efficient algorithms that solve the problem for commercial-scale systems.

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