Zeszyty Naukowe Wydziału Elektrotechniki i Automatyki Politechniki Gdańskiej Nr 62

XIX Konferencja Naukowa

AKTUALNE PROBLEMY W ELEKTROENERGETYCE APE'19

Jastrzębia Góra, 12-14 czerwca 2019

doi: 10.32016/1.62.13

COMPARISON OF THREE APPROACHES TO THE SECURITY CONSTRAINED UNIT COMMITMENT PROBLEM

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Summary: A two phase approach to obtain feasibility of the Security Constrained Unit Commitment schedules is analysed. In the first planning phase a computationally tractable variant of the security constrained UC problem is considered with a simplified representation of the network flows. Three computationally tractable variants of the UC problem formulations are investigated: (i) UC_NN model without network flow constraints, (ii) UC_NC model with network constraints reflected by enforcing *nodal constraints* at the bus level, and (iii) UC_DC model by enforcing network constraints on active power flows. These models are tested and compared with respect to efficiency, computational burden and complexity of the corrective actions performed by TSO in the operational phase to meet security and technical requirements of the system.

Keywords: security constrained unit commitment, economic dispatch, optimal power flow, active and reactive power.

1. INTRODUCTION

Controlling power flows in the power systems and management in the transmission and distributed networks must take into account many dimensions related to efficiency, security and physical feasibility of all processes, power flows and systems operations. The transmission system operator (TSO) operates real-time balancing by matching the generation resources with loads under severe operational and systems constraints. Important tasks performed during the planning phase include solving the security-constrained (SC) unit commitment (UC), the economic dispatch (ED), and the optimal power flow (OPF) optimization subproblems.

In the transmission network analysis, a simplified OPF may be focused on active power flows (OPF_DC version), but at a more detailed level the reactive power flow and voltage control issues are also of great importance (OPF_AC version).

The UC planning problem is a mixed-integer optimisation problem aiming at scheduling generating units at the least total operational cost, by meeting the required demand, systems constraints and security requirements.

Generally, we can distinguish the *centralized* and *decentralized* approaches to the unit commitment. The decentralized approach is based on allocation unit self-commitment to power producers. The decentralized approach to unit commitment will not be analyzed in this paper.

The centralized security-constrained unit commitment and economic dispatch is based on planning generation over a given time horizon by TSO through solving mixed-integer optimization problems with security constraints. The objectives is to provide feasibility of schedules under network and systems constraints and to manage deviations from planned schedules, due to various factors, including load forecast errors, unforeseen generation and transmission outages.

In this paper we investigate three computationally tractable variants of the UC problem formulations: (i) UC_NN model without network flow constraints, (ii) UC_NC model with network constraints reflected by enforcing *nodal constraints* at the bus level, and (iii) UC_DC model by enforcing network constraints on active power flow. These models are tested and compared with respect to efficiency, computational burden and complexity of the corrective actions performed by TSO in the operational phase to meet security and technical requirements of the system.

2. UNIT COMMITMENT PROBLEM

The security constrained UC problem provides scheduling generating units at the least cost, by balancing generation with loads, and satisfying systems and security constraints. The constraints that can be considered in the problem are the power station constraints, network flow constraints, reserve requirements, etc. The constraints of the power generation plants at bus level include the individual generator constraints, such as the start-up characteristics, ramping limits, number of consecutive up/down periods, as well as the other constraints related to the operational limitations of the power plants at the bus level. Other data of the UC problem may include projected demand, projected reserve requirements, inter-area power exchange, projected available capacity of controllable generating units, and must-run generation.

Since the OPF_AC constraints in the UC planning problems of practical size lead to complexity, nonlinearity and excessive computational burden, typically a two phase approach is used by TSOs to obtain feasibility. In the first planning phase a computationally tractable variant of the security constrained UC problem is considered with a simplified representation of the network flows. During operational second phase, a detailed security-constrained transmission network analysis is performed for each period. The aim of the second phase is to economically re-dispatch generation and adjust power flows, not only active, but also reactive power flows, by considering security and voltage control issues as well and energy losses. In this paper efficacy and efficiency of such two-phase approach is investigated for three variants of the UC problem formulations.

2.1 No-Network UC formulation (UC_NN)

A MILP formulation of the deterministic UC problem was proposed in [1,5]. Its simplified notation is presented below:

$$\min \sum_{t=1}^{T} C_p^t + C_r^t + C_s^t \tag{1a}$$

subject to: Load balance constr. (1b)

Generator power output constr. (1c)

Power reserves constr. (1d)

Min/max up-/downtime constr. (1e)

Logical constr. (1f)

$u_i^t \in \{0,1\}$ (1g)

where T-number of time periods in optimisation horizon, C_p^t – total production cost at time *t*, C_r^t- total reserve cost at time *t*, C_s^t- total startup cost at time *t*, u_i^t – on/off state of unit *i* at time *t*.

Let us draw attention to constraint (1b). In the UC_NN formulation it takes the form of balancing the total energy output and total demand:

$$\sum_{i \in N_G} u_i^t \, P_{G,i}^t = \sum_{i \in N} P_{D,i}^t \tag{2}$$

where N_G -set of PV buses, N – set of all buses in the system, $P_{G,i}^t$ – active power output of generator i at time t, $P_{D,i}^t$ – active power load at bus *i* at time *t*.

As the network flows are not modelled in this formulation, the solution does not necessarily meet the system's transmission constraints. The impact is examined further in the paper.

2.2 Nodal-Constrained UC formulation (UC_NC)

TSO may deal with security requirements through reliability must run (RMR) generation that provides a variety of functions, including satisfying certain network constraints, local and system reliability, mitigation of local market power, ancillary services, etc. To maintain quality and reliability standards, the TSO may use output data from security-constrained network OPF flow analysis to determine the required minimum and maximum generation at bus level, given system demand and outage of system elements. Therefore, a practical approach to handling congestion management during solving the UC problems can be based on enforcing *nodal constraints* at the bus level, either by imposing limits on input/output flow in the generation nodes, or at interconnectors (to provide the net transfer capability (NTC) between zones).

In TSOs' practice, some restrictions of (1) may be used to ensure feasibility of the UC results. These restrictions are formulated by adding new *nodal constraints* (NC) imposed on generation in certain nodes. The candidate generator nodes may be identified by additional network analyses – in this paper we use the OPF_AC problem [1] solved with Interior-Point Method. If, at time period *t*, there is no possible to attain a feasible network solution (by considering economic OPF_AC redispatch with active and reactive flows and losses), the UC model may be modified by limiting the scope of feasible generation. If the upper limit of a generator *i* was violated at time *t*, the minimum active power $P_{t,i}^{min}$ in the UC problem can be set to a higher value (reliability must-run RMR generation). By analogy, if a lower limit is violated, $P_{t,i}^{max}$ is set to a lower value. With added constraints, we obtain a restricted UC_NC problem, which can be re-solved. This procedure may be repeated with aim to obtain a security constrained UC solution, which is OPF_AC feasible for all time periods.

2.3 DC-Network UC formulation (UC_DC)

Better formulations of the UC problem are possible by enforcing network flow constraints rather than generation constraints. To better address transmission limits and balancing of each node of the system, the DC Power Flow equations are introduced as constraints in the UC_DC model. This operation allows us to ensure active power network feasibility of the solution, but it makes the UC optimisation problem harder to solve than for the UC_NN and UC_NC variants.

Mathematically, in the UC_DC formulation, instead of the overall power balance constraint (2), a set of additional constraints on active power injection in each node is added to problem (1) as

$$P_i^{inj} = 0 \, , \forall i \in N \tag{3}$$

where P_i^{inj} is the overall active power injection in bus *i.* It is comprised of generation and load attached to *i,* as well as of in-/outcoming power transferred via adjacent lines to *i*. Mathematical formulation of P_i^{inj} can be found in [2] and will not be cited here. Obviously, it is possible to assure that flows are within lines' acceptable power limits.

3. TESTING METHODOLOGY

This paper focuses on comparison of the results of the two-phase approach for three variants of the UC problem – UC_NN, UC_NC and UC_DC. To perform tests, the following methodology was applied:

1. In Phase 1 solve a given variant of the UC problem over horizon of 12 consecutive time periods, each time period stands for one hour of system's operation. To assure that any further corrective action do not violate period-to-period constraints, ramping constraint in this step is restricted to 1/3 of its real value.
2. In Phase 2, for each time period, perform a corrective redispatching action, by trying to rebalance both real and reactive flows, to make the dispatch feasible[1]. This rebalancing step is performed by solving a restricted

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[1] In feasible solution the flows on transmission lines, voltage levels, generation levels etc. are within their technically acceptable limits and active/reactive power is balanced.

OPF_AC problem for each period, with generation on all buses varying by max. ± 1/3 ramp, as compared to the UC results, and respecting the original generation cost functions.
3. Compute all performance measures of the result.

In this study we use seven different performance measures for comparison:

- f_{val}^{UC}: UC step value of cost function [\$],
- f_{val}^{Corr}: Cost function value including costs of corrective actions [\$],
- t_{tot}: The overall solving time of the UC problem – (model setup time + optimiser solve time) [sec],
- t_{conv}: Number of feasible redispatching actions in Step 2 (max. 12),
- $\overline{t_{OPF}}$: Mean OPF_AC solving time, calculated as $\overline{t_{OPF}} = \frac{1}{t_{conv}}\left(\sum_{i \in CONV} t_{OPF}^{i}\right)$, where $CONV$ is the set of convergent OPF_AC redispatching cases,
- $max\{r\}$: Maximum value of bus' active power redispatch to compensate losses [MW],
- $\overline{\lambda_{crit}}$: Mean value of maximum loading parameter calculated as $\overline{\lambda_{crit}} = \frac{1}{t_{conv}^{NN}}\left(\sum_{i \in CONV\_NN} \lambda_{crit}^{i}\right)$.

Parameter λ_{crit} is the maximum loadability as computed by *Continuation Power Flow* algorithm [3,4], and t_{conv}^{NN} – the number of the OPF_AC convergent time periods ($CONV\_NN$) for the UC_NN variant.

4. RESULTS AND DISCUSSION

We performed the tests for 3 systems: 14-bus IEEE 14, 57-bus IEEE 57, 118-bus IEEE 118. It was assumed that each test system is equipped with 1 time-varying, deterministic, 100 MW wind generator and that the loading varies between periods by no more than 15% between two consecutive time periods.

The problem was coded using [2,3] and solved with MOSEK 8.0 MILP/MIQP solver on a 2-core, 4-thread Intel Pentium CORE i5-4210U CPU. Results obtained with [4] for the UC_NN model are shown in Table 1. As none of time periods were OPF-convergent for IEEE 57 test system, measures $\overline{t_{OPF}}$, $max\{r\}$ and $\overline{\lambda_{crit}}$ could not have been calculated.

Table 1: UC_NN model results

	UC_NN model						
	f_{val}^{Corr}	f_{val}^{UC}	t_{tot}	t_{conv}	$\overline{t_{OPF}}$	$max\{r\}$	$\overline{\lambda_{crit}}$
IEEE 14	4,75 E+04	4,40 E+04	1,59	8	0,22	9,25	0,16
IEEE 57	2,70 E+05	2,58 E+05	1,59	0	-	-	-
IEEE 118	9,00 E+05	8,81 E+05	4,61	9	0,30	36,40	0,25

As it can be observed from obtained results, the larger a system is, the more computationally demanding optimisation process is, both for the UC and OPF. Measure $\overline{\lambda_{crit}}$ is not related to the topology. Therefore, it cannot be compared between different test systems.

Similar tests were performed for the UC_DC case, for the same loading, network topology and generation constraints as in the UC_NN case. The results are shown in Table 2.

Table 2: UC_DC model results

	UC_DC model						
	f_{val}^{Corr}	f_{val}^{UC}	t_{tot}	t_{conv}	$\overline{t_{OPF}}$	$max\{r\}$	$\overline{\lambda_{crit}}$
IEEE 14	4,77 E+04	4,47 E+04	1,99	12	0,19	6,09	0,16
IEEE 57	2,68 E+05	2,65 E+05	2,14	12	0,21	33,80	-
IEEE 118	8,99 E+05	8,81 E+05	6,11	12	0,27	36,48	0,23

As we can see from Table 2, UC_DC results follow the same pattern as the one described for the UC_NN case – increase of system's size implies increase of computational burden.

To make the UC_NN results technically feasible, given real and reactive power flows, new constraints on generation were added to create the restrictive UC_NC model. The number of these constraints is given by $N_{con} = [N_{con}^{14}, N_{con}^{57}, N_{con}^{118}] = [14, 19, 5]$, where N_{con}^{i} is the number of constraints added to *i*-bus system. Table 3 shows the results.

Table 3: Restrictive UC_NC model results

	Restrictive UC_NC model						
	f_{val}^{Corr}	f_{val}^{UC}	t_{tot}	t_{conv}	$\overline{t_{OPF}}$	$max\{r\}$	$\overline{\lambda_{crit}}$
IEEE 14	5,17 E+04	5,37 E+04	1,54	12	0,17	25,85	0,23
IEEE 57	2,70 E+05	2,70 E+05	1,89	12	0,25	47,00	-
IEEE 118	8,99 E+05	8,82 E+05	5,65	12	0,30	36,52	0,23

Results also show that computational burden increases with increase of the size of the system. In our tests, measure $max\{r\}$ did not follow any particular pattern related to system size. Thus, it is unlikely that such pattern exists.

Corrective actions can be seen as TSO's interventions necessary to actually meet technical requirements of the system, given nonlinear reactive flows. Therefore, it is worth looking at their associated cost. As can be seen from Tables 1-3, generally these are more costly than dispatch obtained for the UC problem itself. However, in our tests two exceptions were noticed: for the UC_NC case, where for IEEE 14 $f_{val}^{Corr} < f_{val}^{UC}$ and for IEEE 57, where $f_{val}^{Corr} = f_{val}^{UC}$.

Our main motivation for this study was to investigate differences in system's behaviour under control via using different UC models, considering especially satisfaction of all technical constraints. This is important from TSO's perspective, as obtaining efficient network-feasible results in the shortest time are needed. As we can see from the results, total cost of the UC dispatch is the lowest for UC_NN models and highest for the restrictive UC_NC variant. Similar pattern was observed for the corrective actions cost. However, it is important to remember that in the UC_NN case only some of time periods were OPF-convergent and thus considering only the cost of corrective redispatch might be of little meaning.

In our tests, the best cost results obtained from the UC_NC model were equal to the results of the UC_DC model. This was observed for f_{val}^{Corr} at IEEE 118 system, while in other experiments UC_DC model yielded lower cost results. Despite this fact, UC_DC model is the most computationally demanding for all studied models in terms of t_{tot}. However, this model has a real advantage – ratio of convergence. As we see from Tab. 1 and Tab. 2, the number of the OPF-convergent periods t_{conv} is significantly higher in the UC_DC case than in the UC_NN one. This is also understandable as the UC_DC computation phase takes into consideration active power flow constraints.

As shown in our study, the limitations of the UC_NN model can be overcome by adding nodal constraints to form the UC_NC model. This can be done through analysis of OPF results returned by the Interior-Point Solver. From its output it is possible to identify tendencies in system's behaviour and to restrict the space of generation by adding new constraints. Unfortunately, as this operation is nontrivial, it often results in significant increase of the cost function value – as can be seen from Tables 2 and 3.

We investigated also the impact of the optimal dispatch model on voltage stability level. To make it comparable between the models, we looked at mean value of λ_{crit} , taken for only those time periods, for which OPF was convergent for the UC_NN model. By cross-checking Tables 1,2,3 we can say that, in terms of $\overline{\lambda_{crit}}$, the UC_NC model showed better performance than the UC_DC model. However, no clear tendency was outlined when all three models were taken into account.

In terms of $max\{r\}$ undoubtedly the best results were obtained for the UC_DC model. This is understandable as its output lays much closer to feasible network solution. What is more, similar pattern is also visible for $\overline{t_{OPF}}$ measure. Its lowest values were obtained for the UC_DC model for all systems but IEEE 14 and highest for the UC_NN model. However, the observed differences for 14-bus system between UC_NC and UC_DC models are slight and could be caused by other factors.

5. CONCLUSIONS

This study focused on power system's behaviour while active power is dispatched by solving three different variants of the Unit Commitment problem. In our test cases, the deterministic, time-varying wind generation at nodes of the network was also considered.

For the sake of comparison, 7 different performance measures were used. Three of them referred solely to computational issues, whereas the remaining correspond to the operational or convergence problems. The tests were performed on 3 different test systems.

Obtained results showed that operational cost and UC computational burden increase with the increase of power system's size but did not reveal any relation between size of the problem and maximum redispatch. Our test cases showed strong relation between the formulation used and computational burden and also with complexity of corrective actions that were need to be performed by TSO to meet security and technical requirements of the system.

From our observations it can be seen that even though the UC_DC model is the most computationally demanding, its performance, both at convergence and cost value measures, compensates for this effect. It can be concluded that the UC_DC variant of the model appears to meet the TSO's needs in the best way. Similar convergence ratio can be acquired by restricting generation space of the UC_NN model, however this is a nontrivial job that can significantly worsen f_{val}^{UC}, f_{val}^{Corr} and $max\ \{r\}$ indices.

Future work in this field may be focused on extending the research to cope directly with the UC_AC cases, on inclusion of uncertainty and market competition [6] into the study models.

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PORÓWNANIE WARIANTÓW MODELI DOBORU JEDNOSTEK I EKONOMICZNEGO ROZDZIAŁU OBCIĄŻEŃ

W pracy jest analizowane podejście dwufazowe do problemu doboru jednostek i ekonomicznego rozdziału obciążeń w systemie elektroenergetycznym. W pierwszej fazie planistycznej jest rozważany uproszczony wariant problemu doboru jednostek i ekonomicznego rozdziału obciążeń z uproszczonym modelem ograniczeń sieciowych rozpływu mocy. Badane są trzy realistyczne obliczeniowo warianty modelu doboru jednostek i ekonomicznego rozdziału obciążeń: (i) model UC_NN bez ograniczeń sieciowych, (ii) restrykcyjny model UC_NC z ograniczeniami sieciowymi w postaci ograniczeń przepływu na poziomie szyn i łączy, and (iii) model UC_DC uwzględniający model rozpływu mocy czynnej w sieci. Modele te są testowane symulacyjnie i porównywane pod względem obliczeniowym, efektywnościowym oraz złożoności i jakości akcji dostosowawczych Operatora Sieci Przesyłowej w drugiej fazie operacyjnych działań pozwalających na uzyskanie stanów sieci spełniających wymagania bezpieczeństwa i ograniczenia techniczne.

Słowa kluczowe: dobór jednostek i ekonomiczny rozdział obciążeń, optymalny rozpływ mocy czynnej i biernej.