J. Mod. Power Syst. Clean Energy (2018) 6(6):1332–1337
https://doi.org/10.1007/s40565-018-0409-1

Hybrid component and configuration model for combined-cycle units in unit commitment problem

Xin FANG[1], Linquan BAI[2], Fangxing LI[3], Bri-Mathias HODGE[1]

Abstract This letter proposes a novel hybrid component and configuration model for combined-cycle gas turbines (CCGTs) participating in independent system operator (ISO) markets. The proposed model overcomes the inaccuracy issues in the current configuration-based model while retaining its simple and flexible bidding framework of configuration-based models. The physical limitations—such as minimum online/offline time and ramping rates—are modeled for each component separately, and the cost is calculated with the bidding curves from the configuration modes. This hybrid mode can represent the current dominant bidding model in the unit commitment problem of ISOs while treating the individual components in CCGTs accurately. The commitment status of the individual components is mapped to the unique configuration mode of the CCGTs. The transitions from one configuration mode to another are also modeled. No additional binary variables are added, and numerical case studies demonstrate the effectiveness of this model for CCGT units in the unit commitment problem.

Keywords Combined-cycle gas turbines (CCGTs), Unit commitment, Component-based model, Configuration-based model

1 Introduction

Recently, the number of combined-cycle gas turbines (CCGTs) in power systems has been substantially increasing because of their high efficiency, operational flexibility, lower natural gas prices, and fast response to mitigate uncertainty with increasing penetration levels of variable renewable generation [1]. A CCGT unit is composed of multiple combustion turbines (CTs) and steam turbines (STs) that can operate in different modes corresponding to different combinations of these turbines. Some steam turbines use the exhaust gas of CTs to generate electricity, which leads to higher efficiency compared to the traditional thermal units.

However, it is challenging to model the operational flexibility of CCGTs in the UC problem because the scheduling of CCGT units needs to decide the on/off status and power output of each CT and ST unit at every time interval. In practice, independent system operators (ISOs) use three typical methods to model CCGTs [2–4]: the aggregated modeling approach, in which the whole CCGT unit is modeled as a pseudo-thermal unit, ignoring all different operating configurations; the configuration-based approach, in which each commitment combination of CTs and STs is a particular configuration; and the component-

CrossCheck date: 21 March 2018

Received: 14 December 2017 / Accepted: 21 March 2018 / Published online: 5 May 2018

✉ Fangxing LI
fli6@utk.edu

Xin FANG
allen.fangxin@gmail.com

Linquan BAI
linquan.bai@us.abb.com

Bri-Mathias HODGE
Bri.Mathias.Hodge@nrel.gov

[1] National Renewable Energy Laboratory, Golden, CO 80401, USA

[2] ABB Inc., Raleigh, NC 27606, USA

[3] Department of EECS, The University of Tennessee, Knoxville, TN 37996, USA

based approach, in which each individual CT and ST unit is modeled separately. The dependency among CTs and STs is represented by a group of MW-steam constraints for CTs and steam-MW constraints for STs.

Although the aggregated model is simple and computationally efficient, the commitment results cannot be directly interpreted to the status of each CT and ST, and the solutions from this method might be physically infeasible [5]. The configuration-based method is deployed by several ISOs—such as California Independent System Operator, the Electric Reliability Council of Texas, and Midcontinent System Operator [6]—because the bidding curve framework is convenient, and the commitment results directly correspond to the status of CTs and STs; however, the physical limitations of configuration modes—such as minimum online/offline time and ramping rates—are approximated from the parameters of the CT and ST components. In market operations, it is difficult for CCGTs to generate these parameters accurately, which leads to inaccurate results. Although several improvements are available for the configuration-based model—such as the edge-based model [7] and tight model [8]—the computational burden for actual ISO systems is still high. In the component-based method (CBM), the CTs and STs are modeled individually, and all physical constraints of CTs and STs are respected; however, it is not likely to provide bidding curves of STs because they generate electricity from the exhaust gas [9] which depends on the status of the CTs.

This paper proposes a hybrid component and configuration model for CCGTs in the ISOs' UC problem. The proposed model overcomes the above disadvantages of the current configuration-based and component-based models. In general, the advantage of the proposed hybrid method is modeling the day-ahead offer submission for CCGT units while respecting the physical constraints for each individual CT and ST component.

The rest of this paper is organized as follows. Section 2 proposes the mapping formulation from component status to configuration modes. Section 3 presents the UC model, including CCGT units and traditional thermal units. Section 4 presents a case study comparing the proposed method to the component-based model. Finally, Section 5 presents conclusions.

2 Mapping of component status to configuration mode

The components status of a CCGT unit can be mapped to a unique configuration mode (CM) in the following manner:

$$CM_m = \prod V_1 V_2 \cdots V_s \cdots V_S \tag{1}$$

where S is the number of components in this CCGT unit; V_s ($s=1\sim S$) represents the status of the s-th component in the m-th configuration mode (CM_m). Here, assume that v_s is the binary variable (i.e., an unknown binary variable for the UC problem) representing the commitment status of the s-th component. Then, if in the m-th mode, the s-th component (CT or ST) is online, V_s is v_s; otherwise, V_s is 1-v_s if the s-th component is offline in the m-th mode. Because both v_s and 1-v_s are binary variables, CM_m in (1) can be bounded by these linear constraints:

$$\begin{cases} CM_m \le V_1 \\ CM_m \le V_2 \\ \vdots \\ CM_m \le V_S \\ CM_m \ge \sum\limits_{s=1}^{S} V_s - (S-1) \end{cases} \tag{2}$$

Here CM_m can be defined as a continuous variable because V_s is binary and, because of the constraints in (2), CM_m can be only 0 or 1. Therefore, adding CM_m does not increase the number of binary variables in the UC problem, and the total number of binary variables will be less than those in the configuration-based model.

For instance, if there are 2 CT units and 1 ST unit, there will be 8 commitment combinations in the configuration model which leads to 8 configuration model binary variables at every time interval. But with the proposed method, the number of binary variables is 3 for three units. Table 1 shows the relationship between the configuration modes and component status for two CTs and one ST. Due to operational constraints (e.g. the ST cannot run unless at least one CT is running) the configuration modes do not explore the full set of commitment combinations.

The relationship between the configuration modes and component commitments is formulated as, for example:

$$CM_1 = (1-v_1)(1-v_2)(1-v_3) \tag{3}$$

Table 1 Mapping between modes and commitment for two CTs and one ST

Configuration mode	CT1 (v_1)	CT2 (v_2)	ST (v_3)
CM_1	0	0	0
CM_2	1	0	0
CM_3	0	1	0
CM_4	1	1	0
CM_5	1	0	1
CM_6	0	1	1
CM_7	1	1	1

which means only when v_1, v_2 and v_3 are 0, CM_1 is active.

CM_2 to CM_7 can be formulated in a similar manner. Because v_1, v_2, v_3, $1-v_1$, $1-v_2$, and $1-v_3$ are binary variables of the components' status, CM_1 to CM_7 are bounded by the linear constraints in (2). For example, CM_1 is bounded by the following constraints:

$$CM_1 \le 1 - v_1 \tag{4}$$

$$CM_1 \le 1 - v_2 \tag{5}$$

$$CM_1 \le 1 - v_3 \tag{6}$$

$$CM_1 \ge 1 - v_1 + 1 - v_2 + 1 - v_3 - 2 \tag{7}$$

Additional constraints on the configuration mode are formulated because the mode can be transitioned to only a limited number of possible modes, as shown in Fig. 1. For example, Mode 1 can only reach {Mode 1, Mode 2, Mode 3, Mode 4} in the next time interval. Therefore, the following constraint can be added:

$$CM_{i,t-1,m} \le \sum_{n \in M_m} CM_{i,t,n} \tag{8}$$

where M_m is the possible next time interval configuration mode set of Mode m.

If there are 2 CT units and 1 ST unit, the total number of configurations is 8, but the mode with only the ST unit online is impossible. To eliminate the impossible modes (here CM_8) with only STs online, constraint (9) is added. The bilinear terms are linearized by (2) as follows:

$$CM_8 = (1 - v_1)(1 - v_2)v_3 = 0 \tag{9}$$

$$CM_8 \le 1 - v_1 \tag{10}$$

$$CM_8 \le 1 - v_2 \tag{11}$$

$$CM_8 \le v_3 \tag{12}$$

$$CM_8 \ge 1 - v_1 + 1 - v_2 + v_3 - 2 = v_3 - v_1 - v_2 \tag{13}$$

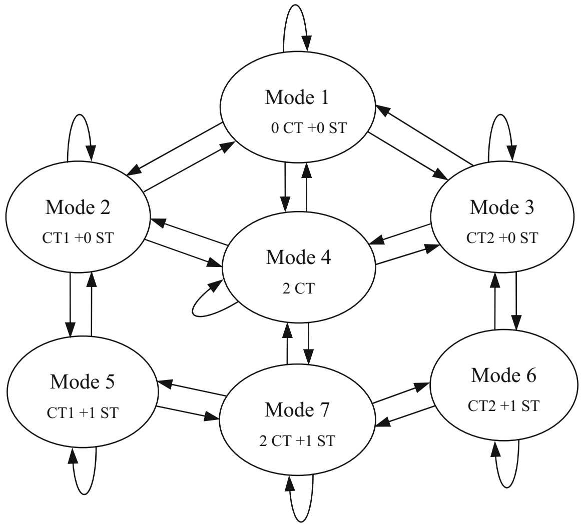

Fig. 1 State transition graph for two CTs and one ST

3 Unit commitment problem formulation

The general formulation of the UC problem including both traditional thermal and CCGT units is presented below.

3.1 Objective function

The objective of the UC problem includes the operational costs of traditional thermal and CCGT units represented by their generation cost and start-up and shutdown costs, as follows:

$$\min \sum_{t \in T} \sum_{i \in g} \left(SU_i \cdot u_{i,t} + SD_i \cdot w_{i,t} + cp_{i,t} \right) \tag{14}$$

In (14), the start-up and shutdown costs of a CCGT unit can be calculated as the summation of the costs of its components, as for a set of traditional thermal units, or calculated according to its configuration [8]. The production cost of the CCGT units at each time interval is equal to the total production costs of all configuration modes at each time interval:

$$cp_{i,t} = \sum_{m \in M} cp_{i,t,m} \tag{15}$$

The cost of each configuration mode $cp_{i,t,m}$ is formulated as:

$$cp_{i,t,m} \ge \alpha^n_{i,m} \cdot CM_{i,t,m} + \beta^n_{i,m} \cdot G_{i,t,m} \tag{16}$$

where $\alpha^n_{i,m}$ and $\beta^n_{i,m}$ are the coefficients of the bidding curve of the m^{th} configuration mode.

The generation amount of a CCGT unit is the sum of all the generation of its modes, as shown in (17), considering that only one mode at a time can generate:

$$G_{i,t} = \sum_{m \in M} G_{i,t,m} \tag{17}$$

Each mode also has its own generation output limits, as:

$$G^{\min}_{i,m} \cdot CM_{i,t,m} \le G_{i,t,m} \le G^{\max}_{i,m} \cdot CM_{i,t,m} \tag{18}$$

3.2 Constraints for the single unit

The constraints for traditional thermal units are like those in [9] and are presented as follows for the sake of completeness:

Table 2 Computational results

	Without trans. constraints		With trans. constraints	
	MIP Obj ($)	Time (s)	MIP Obj ($)	Time (s)
Hybrid	1804655	56.0 (tot.); 17.5 (so.)	1815632	72.8 (tot.); 36.5 (so.)
CBM	1807623	46.5 (tot.); 11.8 (so.)	1827627	71.9 (tot.); 34.8 (so.)

Note: tot. means total simulation time, so. means solver only time

Table 3 Mode results from hybrid model and CBM

CCGT unit	Model	Without trans.		With trans.	
		Time 1	Time 2	Time 1	Time 2
4001	Hybrid	2	5	2	5
	CBM	2	5	2	5
4002	Hybrid	2	5	2	5
	CBM	4	7	4	7
4003	Hybrid	2	5	2	5
	CBM	2	5	2	5
4004	Hybrid	2	5	2	5
	CBM	2	5	2	5
4005	Hybrid	2	5	2	5
	CBM	2	5	2	5
4006	Hybrid	2	5	2	5
	CBM	2	5	2	5
4007	Hybrid	2	5	2	5
	CBM	4	7	4	7
4008	Hybrid	2	5	2	5
	CBM	4	7	4	7
4009	Hybrid	2	5	2	5
	CBM	4	7	2	5
4010	Hybrid	2	5	2	5
	CBM	2	5	2	5
4011	Hybrid	2	5	2	5
	CBM	2	5	2	5
4012	Hybrid	2	5	2	5
	CBM	4	7	2	5

$$u_{i,t} + w_{i,t} \leq 1 \tag{19}$$

$$v_{i,t} - v_{i,t-1} \leq u_{i,t} - w_{i,t} \tag{20}$$

$$\sum_{\tau=t-T_{i,\min,\mathrm{up}}+1}^{t} u_{i,t} \leq v_{i,t} \tag{21}$$

$$\sum_{\tau=t-T_{i,\min,\mathrm{dn}}+1}^{t} w_{i,t} \leq 1 - v_{i,t} \tag{22}$$

$$G_{i,t}^{\min} v_{i,t} \leq G_{i,t} \leq G_{i,m}^{\max} v_{i,t} \tag{23}$$

$$G_{i,t} - G_{i,t-1} \leq R_i^U v_{i,t-1} + R_i^{SU} u_{i,t} \tag{24}$$

$$G_{i,t-1} - G_{i,t} \leq R_i^D v_{i,t} + R_i^{SD} w_{i,t} \tag{25}$$

$$G_{i,t} + SR_{i,t} \leq G_{i,t}^{\max} v_{i,t} \tag{26}$$

$$SR_{i,t} \leq SR_{i,t}^{\max} \cdot v_{i,t} \tag{27}$$

$$v_{i,t}, u_{i,t}, w_{i,t} \in \{0, 1\} \tag{28}$$

where $v_{i,t}$, $u_{i,t}$ and $w_{i,t}$ are binary variables for the on/off, start-up and shutdown status; $G_{i,t}$, $G_{i,t}^{\min}$ and $G_{i,t}^{\max}$ are the actual, minimum, and maximum power output of unit i at time t; R_i^U, R_i^D, R_i^{SU} and R_i^{SD} are the ramping-up, ramping-down, start-up ramping, and shutdown ramping capabilities; $SR_{i,t}$ and $SR_{i,t}^{\max}$ are spinning reserve capacity and the spinning reserve limit, respectively. Note that the configuration mode variables are applied only to CCGT units.

3.3 System energy balance, reserve constraints, and transmission constraints

Typically, system constraints include the system power and load balance, system reserve and transmission line limits:

$$\sum_{i \in g} G_{i,t} - \sum_{b \in SB} D_{b,t} = 0 \tag{29}$$

$$\sum_{i \in g} SR_{i,t} \geq SR_t \tag{30}$$

$$-L_l \leq \sum_{i \in Lg} GSF_{l-i} \cdot G_{i,t} - \sum_{b \in Lb} GSF_{l-b} \cdot D_{b,t} \leq L_l \tag{31}$$

where GSF_{l-i} is the generation shift factor of bus i to line l; g is the generator set; Lg is the generator set for line l; and Lb is the demand set for line l.

4 Case studies

Because the CBM is currently the most accurate model of CCGTs in the UC problem, the CBM from [9] is employed as a benchmark to validate the effectiveness and efficiency of the proposed hybrid model. This section compares the proposed model's performance on a modified IEEE 118-bus system. The test system has 54 traditional thermal units and 12 CCGT units (4001 to 4012), and the system data can be found in [7]–[9]. The models are solved by GUROBI 7.0.1 on a laptop with 2.40 GHz computer processing units and 12 GB RAM. The results of the two models are listed in Table 2.

Table 2 shows that the total cost of the hybrid model is very close to that of the CBM in both cases, “with” and “without” transmission constraints. The computational time of the hybrid model is less than 5% longer than the CBM for the case considering transmission constraints. This table shows that the total operation cost of the proposed hybrid model is within 0.6% of that of the CBM, which means that the proposed hybrid model accurately reflects the true cost of the system. Although the computational time of the hybrid model is slightly more than the CBM, the proposed model can be used to bid CCGT in ISO markets.

The CCGT schedules based on the two methods are very close, as shown in Table 3. The differences in the commitment status between the hybrid model and the CBM are because of the bidding curve approximation. Note, in Table 3, that only the results at time intervals 1 and 2 are listed, and the schedules are the same (Mode 7) for the rest of the time periods.

In the proposed method, the CCGT status changes from Mode 2 to Mode 5 between the first two intervals; whereas in the CBM, the status for several CCGT units changes from Mode 4 to Mode 7. The cost of Mode 4 is higher than that of Mode 2 under the same load level, but Mode 7 is cheaper than Mode 5. Therefore, the commitment cost results from the proposed method and CBM are close.

5 Conclusion

This paper proposed a hybrid component and configuration model for CCGT units in the UC process. The mapping between component status and configuration mode does not increase the number of binary variables in the UC formulation and only increases the total computation time slightly when compared to the component-based model, which is generally considered the most accurate traditional model for CCGTs in UC. Thus, the proposed hybrid model can more accurately represent the CCGT bidding and modeling issues encountered by ISOs in electricity markets, while still allowing an efficient UC modeling and computation.

Acknowledgements This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with Alliance for Sustainable Energy, LLC, the Manager and Operator of the National Renewable Energy Laboratory. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office.

References

[1] Energy Perspectives 1949–2011. http://www.eia.gov/totalenergy/data/annual/perspectives.cfm
[2] Hui H, Yu CN, Gao F et al (2011) Combined cycle resource scheduling in ERCOT nodal market. In: Proceedings of 2011 IEEE power and energy society general meeting, San Diego, USA, 24–29 July 2011, pp 1–8
[3] Lopez JA, Gómez RN, Moya IG (2011) Commitment of combined cycle plants using a dual optimization-dynamic programming approach. IEEE Trans Power Syst 26(2):728–737
[4] Lu B, Shahidehpour M (2004) Short-term scheduling of combined cycle units. IEEE Trans Power Syst 19(3):1616–1625
[5] Blevins B (2007) Combined-cycle unit modeling in the nodal design. ERCOT. Taylor, TX, USA. http://www.ercot.com/content/meetings/tptf/keydocs/2007/0611/18a1_IDA00Combined_Cycle_Whitepaper_v.91.doc
[6] Papavasiliou A, He Y, Svoboda A (2015) Self-commitment of combined cycle units under electricity price uncertainty. IEEE Trans Power Syst 30(4):1690–1701
[7] Fan L, Guan Y (2016) An edge-based formulation for combined-cycle units. IEEE Trans Power Syst 31(3):1809–1819
[8] Morales-Espana G, Correa-Posada CM, Ramos A (2016) Tight and compact MIP formulation of configuration-based combined-cycle units. IEEE Trans Power Syst 31(2):1350–1359
[9] Liu C, Shahidehpour M, Li Z et al (2009) Component and mode models for the short-term scheduling of combined-cycle units. IEEE Trans Power Syst 24(2):976–990

Xin FANG received his B.S. degree from Huazhong University of Science and Technology (China) in 2009, M.S. degree from China Electric Power Research Institute in 2012, and Ph.D. degree from the University of Tennessee, Knoxville, USA in 2016. He is currently with the National Renewable Energy Laboratory (NREL). His research interests include electricity market, power system planning and optimization, renewable energy integration, and demand response.

Linquan BAI received his B.S. degree and M.S. degree in electrical engineering from Tianjin University, Tianjin, China, in 2010 and 2013 respectively and his Ph.D. degree in electrical engineering from the University of Tennessee, Knoxville, USA in 2017. He is currently a Consulting R&D Engineer with ABB Inc., NC, USA. His research interests include electricity markets, power system operation and optimization, and integrated energy systems.

Fangxing LI is also known as Fran LI. He received the B.S.E.E. and M.S.E.E. degrees from Southeast University (China) in 1994 and 1997, respectively, and the Ph.D. degree from Virginia Tech in 2001. He is currently the James McConnell Professor in electrical engineering and the Campus Director of the CURENT research center at the University of Tennessee, Knoxville (UTK), USA. Prior to joining UTK, he worked at ABB Consulting as a Senior Engineer and then as a Principal Engineer from 2001 to 2005. His current research interests include renewable energy integration, demand response, power markets, distributed generation, measurement-based technology and power system computing.

Bri-Mathias HODGE received the B.S. degree in chemical engineering from Carnegie Mellon University in 2004, the M.S. degree from the Process Design and Systems Engineering Laboratory of Abo Akademi, Turku, Finland, in 2005, and the Ph.D. degree in chemical engineering from Purdue University in 2010. He is currently the Manager of the Power System Design and Studies Group at the National Renewable Energy Laboratory (NREL), Golden, CO. His current research interests include energy systems modeling, simulation, optimization, and wind power forecasting.