

# Short-Term Scheduling of Combined Cycle Units

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**Abstract**—Combined cycle units represent the majority of new generating unit installations across the globe. Combined cycle units feature distinct advantages for power generation such as high efficiency, fast response, shorter installation time, abundance of gas, and environmental friendliness. The short-term scheduling of combined cycle units could represent a complicated optimization problem because combined cycle units could have multiple operating configurations based on the number and the status of combustion turbine and steam turbine. In this paper, we present a method for establishing the state space diagram of combined cycle units for applying dynamic programming and Lagrangian relaxation to the security constrained short-term scheduling problem. Although the proposed method is applied in this paper to analyze combined cycle units, it is suitable for other types of generating units with multiple configurations including fuel switching/blending units, constant/variable pressure units, and dual boiler units. The paper presents a few case studies to verify the advantages of combined cycle units in competitive electricity markets.

**Index Terms**—Combined cycle unit, emission, locational marginal prices, short-term scheduling, state transition diagram.

## I. INTRODUCTION

UNIT COMMITMENT (UC) in general refers to the strategic choice for determining the ON/OFF schedule of available generating units in power plants. The schedule will supply an economical solution for the short-term (24–168 h) load while satisfying the spatial constraints of generating units and the power network.

In the regulated power industry, UC refers to minimizing the cost of operating generation resources to satisfy the load demand. In the restructured power-system arena, UC is further developed and extended to resolve new problems posed by the unbundling of generation and transmission facilities. For instance, generating companies (GENCOs) use price-based unit commitment (PBUC) for maximizing their bidding strategy in power markets. In this case, individual GENCOs' objective is to optimize the scheduling of generation resources for maximizing the GENCO's profit rather than satisfying the load demand. In several electricity markets, the ISO plans the day-ahead schedule using security-constrained unit commitment (SCUC). Besides the prevailing constraints (such as load balance, system spinning reserve, ramp rate limits, and minimum up and down time limits) considered by traditional unit commitment algorithm, SCUC incorporates the ac network flow constraints in the unit commitment formulation for minimizing the network violation and the related costs for maintaining the transmission security in power systems [1], [2].

Manuscript received January 13, 2004.

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Digital Object Identifier 10.1109/TPWRS.2004.831706

TABLE I  
ERCOT GENERATING CAPACITY

UNIT TYPE	1995		2000		2005	
	Total MW	% Total	Total MW	% Total	Total MW	% Total
NUCLEAR	4800	8.9	4800	7.3	4800	6.6
HYDRO	436	0.8	470	0.7	470	0.7
ST-COAL	14259	26.4	15450	23.6	15950	21.9
ST-GAS	29082	53.9	30720	46.9	31331	43.1
GAS TURBINE	3036	5.6	3938	6.0	3512	4.8
COMBINED CYCLE	1974	3.7	9671	14.8	15962	22.0
OTHER	333	0.6	498	0.7	671	0.9

Over the last 20 years, a new trend in power generation has emerged as combined cycle gas turbines (CCGTs) have been installed in increasing numbers throughout the world. Synthesized from the traditional gas and steam turbine technology, CCGTs appear to have been at a sufficiently mature stage of development to take advantage of the worldwide shift toward a more market-driven economic climate. Also of importance has been the availability of large quantities of natural gas, coupled with widespread concerns with environmental effects of traditional turbine technologies [3].

It is noted that in 1995 approximately 80% of the generation capacity in ERCOT was based on conventional steam boiler type plants. Nuclear generation, with 8.9% of the total capacity, was a very distant second. By 2000, conventional steam boiler plants still constitute the largest block (70%) of the total capacity, but combined cycle plants were the next highest with almost 15% of the total installed capacity. Looking into the future, it is projected that by 2005 combined cycle plants will constitute 22% of the total installed capacity in ERCOT. Table I indicates that combined cycle plants are a significant part of the generation mix in ERCOT, the preponderance of generation capacity additions in the last five years has been combined cycle plants, and the trend is expected to continue for the next five years [4].

## II. COMBINED CYCLE UNITS

Traditional gas fired units generally expel the waste gas without any further utilization, which lead to a relatively low efficiency of energy conversion. Thermal cycles can be combined in theory irrespective of the type of fuel and working media they utilize. It was demonstrated that a combination of two or more thermal cycles within a single power plant could increase the efficiency of the plant [5]. In practice, combined cycle units, which represent a combination of gas and steam turbines within a power plant, have received much recognition for reasons which are summarized next.

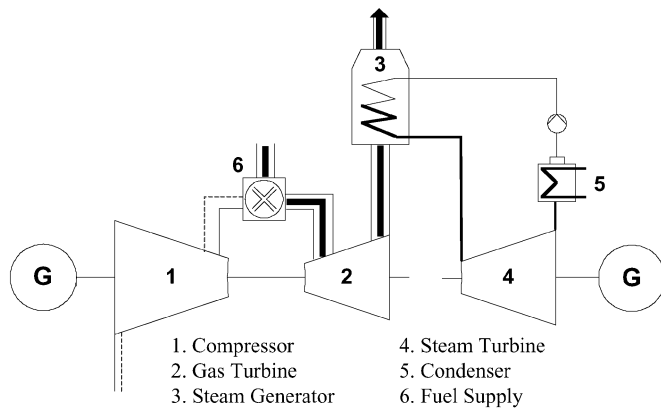


Fig. 1. Flow diagram of a combined cycle plant.

### A. High Efficiency

Fig. 1 depicts a simplified flow diagram of a combined gas turbine/steam turbine power plant with two cycles for generating electricity. In the first cycle, natural gas and compressed air from a combustion turbine compressor are mixed and burned in a combustion chamber. Air is a relatively nonproblematic and inexpensive medium that can be used in modern gas turbines at an elevated temperature of above 1000 °C. That provides the optimum prerequisites for the first cycle. The energy released during the combustion is used to turn a turbine. The turbine drives a generator to produce electricity. The heat captured from the exhaust gas, that would otherwise be wasted, is used in the heat-recovery steam generator (HRSG) that is sent to turn a steam turbine. The steam turbine drives an electric generator to produce additional electricity [6]. After the utilization of both cycles, the total energy conversion efficiency of combined cycle plants can reach 60%, which is a 20%–30% improvement over that of traditional thermal plants.

### B. Fast Response

The mid-1960s power blackouts in the U.K. and North America led to the installation of a large number of gas units for use in emergencies. The ability of gas units to start and ramp up very quickly was a crucial factor in selection. The additional interest in power generation allowed manufacturers to utilize new gas turbine technologies that were already applied to jet engines. These technologies included air-cooled blades and high temperature materials for enhancing the power output and efficiency of gas units. In today's power markets, where load demands are often uncertain and electricity prices are determined based on competition, combined cycle units can be quite instrumental in facing rapid fluctuations in the power and fuel markets [7]–[9].

### C. Environmentally Friendly

Carbon dioxide, a greenhouse gas, is an unavoidable product of the fossil fuel combustion for power generation. The carbon dioxide production of a gas-fired combined-cycle plant is much lower than that of other fossil-fueled turbine technologies because of a relatively high thermal efficiency of combined cycle technology and a high hydrogen-carbon ratio of methane (the primary constituent of natural gas). A typical combined cycle plant would produce about 0.8-lb CO<sub>2</sub> per kilowatt-hour output

as compared with that of a new coal-fired power plant which is about 2-lb CO<sub>2</sub> per kilowatt-hour [10].

Other types of environmentally hazardous exhaust gas for burning fuel are nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), and sulfur dioxide (SO<sub>2</sub>). Normally, in a gas-fired combined cycle plant, nitrogen oxide abatement can be accomplished by using “dry low-NO<sub>x</sub>” combustors and a selective catalytic reduction (SCR) system within HRSG. CO emissions are typically controlled by using an oxidation catalyst within HRSG. No special controls for particulates and sulfur oxides are used since only trace amounts are produced when operating on natural gas. Accordingly, NO<sub>x</sub>, CO, and SO<sub>2</sub> emission from a gas-fired combined cycle plant could be reduced to much less than that from other types of thermal plants.

### D. Flexibility

Combined cycle plants are extremely flexible as they can be operated by burning a variety of fuels ranging from clean natural gas and distillate oil fuels to ash-bearing crude oil and residual oil. Commercial-size combined cycle units have been operated with coal-derived gas fuels.

Combined-cycle equipment generally costs more than that of conventional steam plants due to the applied technology and the type of material used in the design of these plants. However, the installation cost of a combined-cycle plant is significantly lower, resulting from the shorter installation cycle [11]. Combined cycle units are very compact which require a smaller square footage. All major equipment, such as gas turbine generators, HRSGs, and steam turbine generators, is shipped to the field as assembled and tested components. Auxiliary equipment, such as condensers, can be shipped factory-tubed and hydro-tested. These arrangements greatly reduce the inventory of parts that must be managed in the field and minimize the installation cost and duration.

## III. SHORT-TERM SCHEDULING OF COMBINED CYCLE UNITS

Reference [12] presents an economic dispatch model for combined cycle cogeneration plants based on Lagrangian and Kuhn-Tucker approach. The model [12] includes typical plant-level and environmental constraints. Due to the multiple configurations of a combined cycle unit, individual cost functions are chosen to represent the characteristic of each configuration. Moreover, the model in [12] assumes that unit ON/OFF states for combined cycle units are already determined.

In contrast, we deal in our paper with the short-term scheduling of thermal and combined cycle units. Through the Lagrangian relaxation technique, we decompose the original problem into several subproblems in which the combined cycle unit subproblem is discussed thoroughly in our paper. In this paper, we solve the economic dispatch as well as the unit commitment of combined cycle units by determining the hourly ON/OFF states and configurations of combined cycle units. By applying the Lagrangian relaxation technique, the state transition for combined cycle units is calculated through the single-unit dynamic programming.

The calculation of optimal commitment and dispatch of combined cycle units is more cumbersome than that of traditional

thermal units. The same issue applies to other types of units with multiple configurations including fuel switching/blending units, constant/variable pressure units, over-fire units, and dual boiler units [13]. The paper [13] applies Lagrangian relaxation to schedule generating units and discusses the operating flexibility of such units which can be exploited to reduce production costs. Also, the utilization of average cost could affect the accuracy of final results.

Reference [14] considers combined cycle plants in the short term resource scheduling. The proposed algorithm in [14] is based on the assumption that the thermal subsystem of a combined cycle plant is modeled through input-output curves that are defined for all configurations and all steam load ranges. The paper [14] discusses the application of a single combined cycle plant dynamic programming algorithm to a plant's state space with restricted transitions.

In this paper, we discuss thoroughly the state transition rules inside a configuration and between configurations. Also, to facilitate the implementation of modeling techniques for combined cycle units, state transitions between configurations are divided into upward and downward transitions. Although the proposed method for creating a state-space diagram is applied to combined cycle units, the method is applicable to various types of units with multiple configurations.

This paper calculates the optimal generation scheduling based on the decomposition of large and complex SCUC problem (with network constraints) into a master problem (generating units) and a subproblem (network constraints). The paper applies Lagrangian relaxation to generating units (master problem) which is decomposed into a set of simple subproblems for individual units. The individual subproblems are solved using dynamic programming to get the optimal commitment at all periods based on state transition diagrams.

The results presented in this paper tabulate the superiority of combined cycle units in short term generation scheduling. In particular, this paper presents case studies addressing the following issues:

- high efficiency of combined cycle units;
- fast response of combined cycle units;
- emission friendliness of combined cycle units;
- impact on locational marginal price (LMP) of combined cycle units.

The paper is organized as follows. Section IV provides a brief discussion on a short-term generation scheduling problem. A detailed description for creating the state-transition diagram of a combined cycle unit is presented in Section V. Section VI provides case studies to demonstrate the advantages of combined cycle unit listed in Section II. Conclusions are drawn at the end of the paper.

#### IV. SHORT-TERM GENERATION SCHEDULING

The objective function of the short-term generation scheduling problem is given as

$$\text{Min} \sum_{i=1}^{N_g} \sum_{t=1}^{N_t} [C_i(P(i,t))I(i,t) + S(i,t)] \quad (1)$$

subject to the following equality and inequality constraints:

system real power balance

$$\sum_{i=1}^{N_g} P(i,t)I(i,t) = P_D(t) \quad t = 1, \dots, N_t \quad (2)$$

system spinning reserve requirements

$$\sum_{i=1}^{N_g} r_s(i,t)I(i,t) \geq R_s(t) \quad t = 1, \dots, N_t \quad (3)$$

line-flow limits

$$-\text{LineCapacity}(\text{km}) \leq \text{PF}(\text{km}, t) \leq \text{LineCapacity}(\text{km})$$

$$\text{km} \in \{\text{all lines in the system}\}$$

$$t = 1, \dots, N_t \quad (4)$$

bus-voltage limits

$$V^{\text{Min}}(i) \leq V(i,t) \leq V^{\text{Max}}(i) \quad i = 1, \dots, N_{\text{bus}}$$

$$t = 1, \dots, N_t \quad (5)$$

where

- $N_g$  number of units;
- $N_t$  number of time periods;
- $P(i,t)$  dispatch of unit  $i$  at time  $t$ ;
- $C_i(\cdot)$  cost function of unit  $i$ ;
- $I(i,t)$  commitment state of unit  $i$  at time  $t$ ;
- $\tau_i$  time constant that characterizes unit  $i$  cooling speed;
- $P_D(t)$  total system real power load demand at time  $t$ ;
- $r_s(i,t)$  contribution of unit  $i$  to spinning reserve at time  $t$ ;

where

$$r_s(i,t) = \min\{10 \times \text{MSR}(i), P_{g_{\text{max}}}(i) - P(i,t)\}$$

and

- $\text{MSR}(i)$  maximum sustained ramp rate of unit  $i$  (MW/min);
- $P_{g_{\text{max}}}(i)$  maximum generation of unit  $i$ ;
- $R_s(t)$  system spinning reserve requirement at time  $t$ ;
- $S(i,t)$  start-up cost of unit  $i$  at time  $t$ ;

where

$$S(i,t) = I(i,t)[1 - I(i,t-1)]$$

$$\times \left[ \alpha_i + \beta_i \left( 1 - \exp \frac{-X^{\text{off}}(i,t)}{\tau_i} \right) \right]$$

and

- $\alpha_i$  integrated cost of start-up cost and equipment maintenance unit  $i$ ;
- $\beta_i$  starting-up cost of unit  $i$  from cold conditions;
- $X^{\text{off}}(i,t)$  duration for which unit  $i$  has been OFF at time  $t$ ;
- $\text{PF}(\text{km}, t)$  line flow between buses  $k$  and  $m$  at time  $t$ ;
- $\text{LineCapacity}(\text{km})$  capacity of the line between buses  $k$  and  $m$ ;
- $N_{\text{bus}}$  number of buses in the system;
- $V(i,t)$  voltage at bus  $i$  and time  $t$ ;
- $V^{\text{Min}}(i)$  lower limit of voltage at bus  $i$ ;
- $V^{\text{Max}}(i)$  upper limit of voltage at bus  $i$ .

The objective function (1) is a cost-based optimization. However, the proposed approach would similarly apply to the priced-based optimization approach.  $MSR(i)$  is the maximum sustained ramp rate which is used for supplying spinning reserve when a unit is ramped up aggressively and for a short period (about 10 min). Ramp up and down figures are not necessarily the same while each would be less than or equal to  $MSR(i)$ .

We consider SCUC in this study for LMP calculations. The formulation of SCUC includes traditional thermal unit constraints (e.g., ramping, min up/down time, generating capacity limit) as well system-wide constraints such as fuel, network, and crew constraints [1]. The traditional generation scheduling constraints are not listed in this section so that we can analyze the solution steps more clearly.

We consider network constraints including line flow and bus voltage limits into the SCUC formulation. To solve the SCUC problem, we apply the Bender's decomposition technique to decompose the problem into a master problem for solving the generating scheduling problem and a subproblem for minimizing the network violations. If network violations occur, the corresponding Bender's cuts are created and sent back to the master problem for inclusion in the next iteration of master problem. The detailed discussion on Bender's decomposition is presented in [1] which is beyond the scope of this paper.

According to the Lagrangian relaxation approach, the coupling constraints of the generation scheduling problem are relaxed and added to the objective function using Lagrangian multipliers. The Lagrangian function is written as

$$L = \sum_{t=1}^{N_t} \left\{ \begin{array}{l} \sum_{i=1}^{N_g} [C_i(P(i,t))I(i,t) + S(i,t)] \\ + \lambda(t)[P_D(t) - \sum_{i=1}^{N_g} P(i,t)I(i,t)] \\ + \mu_s(t)[R_s(t) - \sum_{i=1}^{N_g} r_s(i,t)I(i,t)] \end{array} \right\} \quad (6)$$

where

- $\lambda(t)$  Lagrangian multiplier for the load balance constraint at time  $t$ ;
- $\mu_s(t)$  Lagrangian multiplier for the spinning reserve constraint at time  $t$ .

Based on (6), the Lagrangian function is decomposed into a set of independent subproblems according to different unit types which are each associated with its own local constraints [15]. Since combined cycle units have a more complicated state-transition diagram, we emphasize the formulation of the subproblem of combined cycle units in (7) after ignoring constant terms

$$L_{cc} = \sum_{t=1}^{N_t} \left\{ \begin{array}{l} \sum_{i=1}^{N_{cc}} [C_i(P(i,t)I(i,t) + S(i,t))] \\ - \lambda(t) \sum_{i=1}^{N_{cc}} P(i,t)I(i,t) \\ - \mu_s(t) \sum_{i=1}^{N_{cc}} r_s(i,t)I(i,t) \end{array} \right\} \quad (7)$$

where

- $L_{cc}$  Lagrangian function of combined cycle units;
- $N_{cc}$  number of combined cycle units.

In the combined cycle unit subproblem, each configuration is considered as a pseudo unit with constraints that are similar to those of thermal units. However, because configurations of a combined cycle unit are mutually exclusive, we consider them

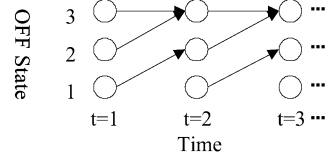


Fig. 2. State transition diagram for OFF state.

simultaneously for commitment, given the Lagrangian multipliers. Details of this approach will be discussed in the next section.

Once the commitment of a combined cycle unit is scheduled, we treat its unit configurations as a set of pseudo units with associated commitments and incorporate them into economic dispatch. According to the dispatch solution, we update the Lagrangian multipliers. The multipliers are sent back to each subproblem to re-schedule the units. This process is built into the existing SCUC algorithm, which includes other types of units. Such iterations will continue as discussed below until the final solution is achieved.

## V. STATE SPACE OF COMBINED CYCLE UNITS

Typically, a combined cycle plant consists of several combustion turbines (CTs), and a HRSG/steam turbing (ST) set. Based on different combinations of CTs and STs, a combined cycle unit can operate at multiple configurations according to its operating limits. So the state space for a combined cycle unit must be set up according to the operation rules for individual configurations as well as those governing the relationship between the configurations. First, we define the operating rules for individual configurations.

The number of nodes in the state space of each configuration is equal to the minimum operation time of the configuration. The OFF state of a combined cycle unit is Configuration 0 and the minimum OFF time of the unit is the minimum operation time of Configuration 0. In Fig. 2, if the minimum OFF time of a combined cycle unit is 3 h, the number of states for the Configuration 0 will be three [16].

Accordingly, state transitions for a configuration are as follows:

$$X(i, t+1) = \begin{cases} X(i, t) + 1, & X(i, t) + 1 < T_{\min} \\ T_{\min}, & X(i, t) + 1 \geq T_{\min} \end{cases} \quad (8)$$

where

- $X(i, t)$  duration of time that unit  $i$  has been in a given configuration at time  $t$  (positive value);
- $T_{\min}$  minimum time for unit  $i$  to stay in a configuration (positive value).

Second, we define the transition rules between configurations. The following rules are established accordingly.

- The outward transition from a configuration will be from its top node.
- The inward transition to a configuration will be to its bottom node.
- Since the ST operation relies on the exhaust gas emitted by CT, we choose the "first CT, then ST" rule for turning a unit ON. So a combined cycle unit with two CTs and one ST is represented by those configurations listed in Table II.

TABLE II  
CONFIGURATIONS OF (TWO CTs, ONE ST)

Configuration Number	Components
1	1CT + 0ST
2	2CT + 0ST
3	1CT + 1ST
4	2CT + 1ST

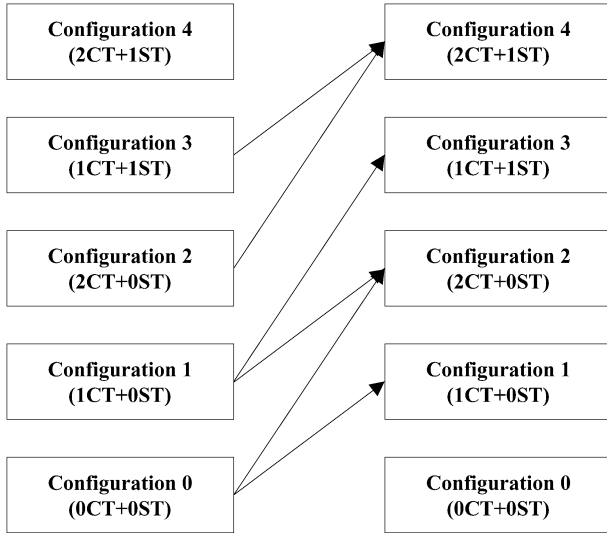


Fig. 3. Upward state-transition diagram.

We consider Configuration 0 at the bottom of the state-space diagram for a combined cycle unit. Figs. 3 and 4 are the upward and downward state transitions for a combined cycle unit with configurations listed in Table II. We should point out that an outward transition could be either upward or downward. The outward transition represents the departure from the top state of a configuration; an inward transition must arrive at the bottom state of the configuration.

The conditions for establishing the state transition between configurations are discussed as follows.

- Ignore a state transition between the same configurations, which follows the representation in Fig. 2.
- Multiple CTs can be turned ON/OFF simultaneously, but a CT and a ST cannot be turned ON/OFF simultaneously.
- The transition cost between two configurations is associated with the changes in the number of CTs and STs.

The state transitions represent additional sets of rules in practical cases. Accordingly, we may form new state-transition rules between configurations and create a new state transition diagram in each practical situation. As stated before, we consider a combined cycle configuration as a pseudo thermal unit with its own cost curve and minimum/maximum power output capacities. By relaxing coupling constraints and adjoining them to the cost function, we calculate the optimal generation ( $P^*(i, t)$ ) for any configuration and time by minimizing a single variable cost function, as follows:

$$P^*(i, t) = \arg \min_{P(i, t)} L_{cc}(i, t) \quad (9)$$

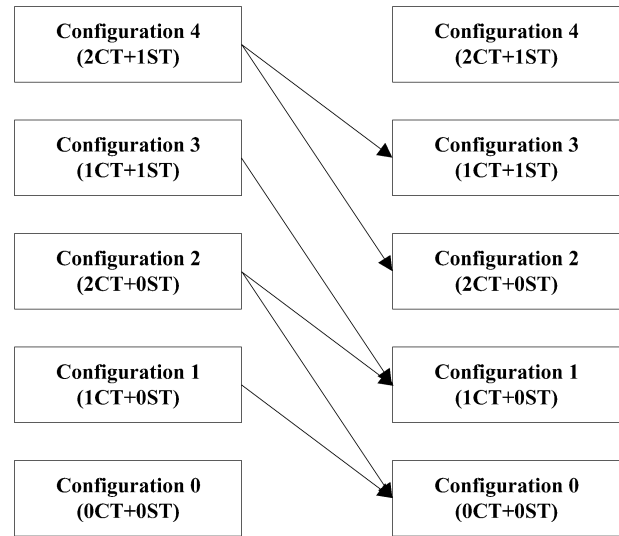


Fig. 4. Downward state-transition diagram.

with:

$$L_{cc}(i, t) = [C_i(P(i, t))I(i, t) + S(i, t)] \\ - \lambda(t)P(i, t)I(i, t) \\ - \mu_s(t)r_s(i, t)I(i, t).$$

Dynamic programming is applied to find the least-cost path for the entire time horizon once the least cost generation of individual configurations are calculated. Dynamic programming results will show the optimal configurations of combined cycle units at each hour for calculating the optimal generation dispatch. It is conceivable that when temporal constraints such as ramping are present, dynamic programming would result in sub-optimal solutions [17].

At the unit commitment subproblem, we could take into account the ramping by extending the state space through the discretization of generation capacity range in each configuration. However, we currently do not consider ramping in transitions between configurations. Instead, we consider the ramping between configurations and inside a configuration as part of economic dispatch once the commitment of combined cycle unit is determined to make sure that the final results satisfy all types of constraints.

The proposed state space diagram for combined cycle units is also suitable to model other types of units and their special cases. For instance, given a traditional thermal unit, we can define the ON state as Configuration 1 and the OFF state as Configuration 0. Also, for a pumped-storage hydro unit, we can define generation state as Configuration 1, idle state as Configuration 0, and pumping state as configuration  $-1$ . Then we can apply the method discussed above to form the state space diagram for each unit in dynamic programming.

## VI. CASE STUDIES

In this section, we use the SCUC approach proposed in Section V to analyze the attributes of combined cycle units listed in the Section II. An 8-Bus system with six thermal units is chosen for the case study. Fig. 5 is the diagram of the test system, and parameters of thermal units are listed in Table III. Bus load distribution factors and branch data are presented in Tables IV and

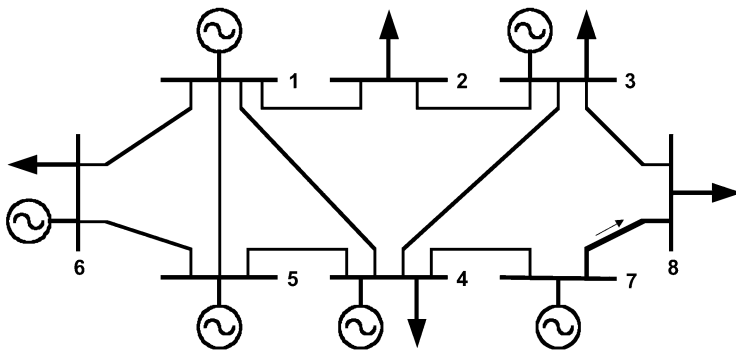


Fig. 5. Network diagram of the 8-bus system.

TABLE III  
PARAMETERS OF THERMAL UNITS (CASE 1)

Unit	Pmin (MW)	Pmax (MW)	af (Mbtu/MW <sup>2</sup> h)	bf (Mbtu/MWh)	cf (Mbtu/h)	St (Mbtu)
1	5	30	0.01059	38.7770	238.7551	50
2	5	30	0.01059	38.7770	238.7551	50
3	10	60	0.00664	30.4000	197.0575	100
4	10	60	0.00895	18.3538	181.2980	100
5	20	100	0.00578	13.2800	176.7752	280
6	25	120	0.00473	10.7154	143.0288	350
MSR (MW/Min)	Ramp Up (MW/Min)	Ramp Dn (MW/Min)	Min ON (Hour)	Min OFF (Hour)	IniT (Hour)	Bus No
0.8	0.5	0.5	2	2	-2	1
0.8	0.5	0.5	2	2	-2	3
1.9	1.0	1.0	6	5	-6	4
1.9	1.0	1.0	6	6	8	5
2.5	1.5	1.5	8	8	10	6
2.5	1.5	1.5	8	8	10	7

V, respectively. We disregard branch flow constraints in Cases 1–3, as discussed next.

In Table III, the quadratic cost function coefficients are given. The last column represents the start-up cost. All the cost terms are given as a per-unit function of fuel cost. So in order to calculate the actual cost, we multiply the cost function by fuel cost which is assumed to be 1 \$/MBtu in this study. This figure includes the fuel efficiency (coal or gas) for generating each MBtu. The “IniT” column represents the initial condition for operating the unit in which the negative number shows the number of hours when the unit has been OFF. Table III shows that units 4, 5, 6 are base units, while the other three units (especially units 1 and 2) are expensive and used for supplying peak loads.

*Case 1: High Efficiency of Combined Cycle Units*

The 24-h system load/reserve requirements are listed in Table VI in which the peak load is 344.11 MW at hour 11. By committing the six thermal units we supply the system load and satisfy reserve requirements.

Since units 4, 5, and 6 are always committed, we resort to the commitment schedule for units 1, 2, and 3 in Table VII in which the daily generation cost is \$122 885.5. Unit 3 is cheaper than units 1 and 2, so it is the first one to be turned ON and the last one to be turned OFF as the system cycles between its daily minimum and maximum loading.

TABLE IV  
BUS-LOAD DISTRIBUTION FACTORS OF THE 8-BUS SYSTEM

Bus No	1	2	3	4	5	6	7	8
Bus Load	0.00	0.14	0.11	0.25	0.00	0.25	0.00	0.25

TABLE V  
BRANCH DATA OF THE 8-BUS SYSTEM

Br No	From Bus	To Bus	R (p.u.)	X (p.u.)	Limit (MW)
1	1	2	0.00	0.0300	50
2	1	4	0.00	0.0300	30
3	1	5	0.00	0.0065	50
4	2	3	0.00	0.0110	25
5	3	4	0.00	0.0300	45
6	4	5	0.00	0.0300	40
7	5	6	0.00	0.0200	35
8	6	1	0.00	0.0250	35
9	7	4	0.00	0.0150	70
10	7	8	0.00	0.0220	77
11	8	3	0.00	0.0180	30

TABLE VI  
HOURLY LOAD AND RESERVE (CASE 1)

Hour	Load (MW)	Reserve (MW)	Hour	Load (MW)	Reserve (MW)
1	216.80	10.84	13	320.00	16.00
2	213.36	10.67	14	316.56	15.83
3	206.47	10.32	15	309.69	15.48
4	199.56	9.98	16	302.80	15.14
5	203.00	10.15	17	309.69	15.48
6	223.67	11.18	18	316.56	15.83
7	247.76	12.39	19	330.33	16.52
8	292.48	14.62	20	337.20	16.86
9	326.89	16.34	21	330.33	16.52
10	340.64	17.03	22	309.69	15.48
11	<b>344.11</b>	<b>17.21</b>	23	275.28	13.76
12	340.64	17.03	24	240.88	12.04

TABLE VII  
COMMITMENT OF UNITS 1, 2, AND 3 (CASE 1)

Unit	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	0	1	1	1	1
2	0	0	0	0	0	0	0	0	1	1	1	1
3	0	0	0	0	0	0	0	1	1	1	1	1
Unit	Hour											
	13	14	15	16	17	18	19	20	21	22	23	24
1	0	0	0	0	0	0	1	1	1	0	0	0
2	0	0	0	0	0	0	1	1	1	0	0	0
3	1	1	1	1	1	1	1	1	1	1	1	0

Here, the expensive thermal units 1 and 2 are turned ON at peak hours, as extra generating capacity is required. To study the

TABLE VIII  
DATA OF COMBINED CYCLE UNITS

Unit	CT Num	ST Num	Config Num	CT Mbtu	ST Mbtu	Ini Config	IniT (Hour)
401&402	2	1	5	20	10	0	3

TABLE IX  
PARAMETERS OF COMBINED CYCLE UNITS

Unit	Config #	CT	ST	Pmin (MW)	Pmax (MW)	Tmin (Hour)
401&402	0	0	0	0.0	0.0	3
	1	1	0	2.0	10.0	2
	2	2	0	4.0	20.0	2
	3	1	1	2.5	15.0	2
	4	2	1	5.0	30.0	2
Unit	Config #	CT	ST	af (Mbtu/MW <sup>2</sup> h)	bf (Mbtu/MWh)	cf (Mbtu/h)
401&402	0	0	0	0.00000	0.0000	0.0000
	1	1	0	0.01099	20.5510	87.9083
	2	2	0	0.00549	20.5510	175.8166
	3	1	1	0.00938	17.4921	98.0760
	4	2	1	0.00789	15.9367	108.9102

TABLE X  
COMMITMENT OF UNITS 401, 402 AND 3 (CASE 1)

Unit	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
401&402	0	0	0	0	0	2	2	4	4	4	4	4
3	0	0	0	0	0	0	1	1	1	1	1	1
Unit	Hour											
	13	14	15	16	17	18	19	20	21	22	23	24
401&402	4	4	4	4	4	4	4	4	4	4	4	4
3	0	0	0	0	0	1	1	1	1	1	1	0

efficiency of combined cycle units, we replace units 1 and 2 with two combined cycle units (401 and 402) with same capacities as those of units 1 and 2. The data for combined cycle units are given in Tables VIII and IX, respectively. In Table VIII, "IniT" represents the number of hours that unit has been at the "Ini-Config" state as discussed by (8). In other words, "IniT" would be listed as a positive number for the OFF state in Table VIII. Table X shows the commitment of combined cycle units 401 and 402 and thermal unit 3 for the same level of system load and reserve. Once units 1 and 2 are replaced by combined cycle units, the daily generation cost in Table X will be reduced by 8.65% to \$112 259.21.

When both CT and ST are in operation, a combined cycle unit will demonstrate a high efficiency and low cost per unit of power generation. So, combined cycle units will be turned ON more often (between hours 6 and 24) as compared with expensive thermal units 1 and 2. Furthermore, thermal unit 3 will no longer be scheduled at certain hours (between 13 and 17) because it is

TABLE XI  
24-H SYSTEM LOAD AND RESERVE (CASE 2)

Hour	Load (MW)	Reserve (MW)	Hour	Load (MW)	Reserve (MW)
1	184.28	9.21	13	262.00	13.10
2	181.36	9.07	14	259.08	12.95
3	175.50	8.77	15	253.24	12.66
4	169.63	8.48	16	257.38	12.87
5	172.55	8.63	17	263.24	13.16
6	190.12	9.50	18	269.08	13.46
7	210.60	10.53	19	280.78	14.04
8	248.61	12.43	20	286.62	14.33
9	257.86	12.89	21	280.78	14.04
10	289.54	14.48	22	263.24	13.16
11	<b>292.49</b>	<b>14.63</b>	23	233.99	11.70
12	289.54	14.48	24	204.75	10.23

TABLE XII  
COMMITMENT OF THERMAL UNIT 3 (CASE 2)

Unit	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
3	0	0	0	0	0	0	1	1	1	1	1	1
Unit	Hour											
	13	14	15	16	17	18	19	20	21	22	23	24
3	0	0	0	0	0	1	1	1	1	1	1	0

more expensive than Configuration 4 (i.e., 2CT + 1ST). The changes in commitment as compared with those in Table VII are highlighted in Table X.

Table X confirms that the Configuration 4 is the most efficient configuration for utilizing the exhaust gas from combustion turbines. However, according to Fig. 3 a unit must transit first from the OFF state (Configuration 0) to Configuration 2 (i.e., 2CT + 0ST) before reaching Configuration 4. This transition is based on the minimum ON time (2 h) of Configuration 2 at hours 6 and 7 as listed in Table X. The change in the commitment of unit 3 at hour 7 is due to its minimum ON time (6 h) before it is turned OFF between hours 13 and 17.

#### Case 2: Fast Response of Combined Cycle Units

The 24-h load and reserve requirements of Case 2 are given in Table XI in which the maximum load of 344.11 MW in Table VI is reduced to 292.49 MW. The lower load will not require units 1 and 2 to be committed. Also the reduced system load will not require unit 4 to be always committed (it is only ON between hours 8 and 22). So we can focus our attention on the comparison between unit 3 and combined cycle units when we replace unit 3 in this case.

The commitment schedule of unit 3 in Case 2 is given in Table XII. In this case, the peak load according to Table XI has lasted for 6 h (hours 10–12 and 19–21); however the unit remains ON for 12 h (hours 7–12 and 18–23). The extra ON hours correspond to the minimum ON time of unit 3 which is 6 h. The additional dispatch of unit 3 during off-peak hours would prevent the dispatch of economical units. The daily generation cost is \$90 892.78.

TABLE XIII  
COMMITMENTS OF COMBINED CYCLE UNITS 401 AND 402 (CASE 2)

Unit	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
401&402	0	0	0	0	0	0	1	1	3	3	4	4
Unit	Hour											
	13	14	15	16	17	18	19	20	21	22	23	24
401&402	4	4	4	4	4	4	4	4	4	4	4	3

We replace unit 3 with the two combined cycle units in Case 1. The minimum time of each configuration is shown in Table IX which is lower than the ON/OFF time of thermal units. Table XIII shows the flexibility of the combined cycle units when compared with thermal unit 3. Here, a combined cycle can switch quickly between its various configurations according to different system conditions to exhibit a faster response and lower generation cost.

In Table XIII, units switch from OFF state (Configuration 0) to Configuration 1 (i.e., 1CT + 0ST) at hour 7 and after 2 h switch to Configuration 3 (i.e., 1CT + 1ST). As load increases, the combined cycle units will switch to Configuration 4 (i.e., 2CT + 1ST). Since the minimum time for each operating configuration is small, combined cycle units are able to switch over rapidly. Accordingly, the daily dispatch cost will be reduced by 2.14% to \$88 949.25 for using combined cycle units. Since combined cycle units have a higher efficiency (especially in Configuration 4), they can compete with the thermal unit 4 by remaining ON between hours 13 and 17.

Tables XII and XIII show that once the unit 3 is turned OFF at hour 13, it must stay OFF for at least 5 h. During this period, if the dispatch of unit 3 is deemed necessary, the system operator must take some critical measures such as load shedding, or turning ON the more expensive units, to keep the system in a balanced condition. In contrast, a shorter minimum configuration time of combined cycle units could render excessive load shedding requirements unnecessary.

*Case 3: Environmentally Friendliness of Combined Cycle Units*

The natural gas used in a gas turbine has a high hydrogen to carbon ratio in methane and the emission level is quite smaller than that from conventional plants. With mounting concerns about global environmental issues in many regions of the world, a combined cycle can be a serious candidate for the future electricity generation. Here, we demonstrate the corresponding benefits of combined cycle units. The system emission constraint in the short-term scheduling problem is formulated by

$$\sum_{t=1}^{N_t} \sum_{i=1}^{N_g} [C_{ei}(P(i,t))I(i,t) + S_e(i,t)] \leq \text{EMS} \quad (10)$$

where

- $C_{ei}(P)$  emission function of unit  $i$ ;
- $S_e(i,t)$  start-up emission of unit  $i$  at time  $t$ ;
- EMS system emission cap.

In (10), we assume that the emission is a function of thermal power dispatch. While starting a unit up, the emission level could be higher than that of power dispatch.

TABLE XIV  
EMISSION COEFFICIENTS OF THERMAL UNITS (CASE 3)

Generating Unit	1	2	3	4	5	6
Emission Coefficient (lbs/MBtu)	0.2	0.2	0.1	0.4	0.1	0.1

TABLE XV  
COMMITMENT OF THERMAL UNITS 1 AND 2 (CASE 3)

Unit	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
4	0	0	0	0	0	0	0	1	1	1	1	1
Unit	Hour											
	13	14	15	16	17	18	19	20	21	22	23	24
4	1	1	1	1	1	1	1	1	1	1	0	0

TABLE XVI  
COMMITMENT OF UNITS 401 AND 402 (CASE 3)

Unit	Hour											
	1	2	3	4	5	6	7	8	9	10	11	12
401&402	0	0	0	0	0	1	1	3	3	4	4	4
Unit	Hour											
	13	14	15	16	17	18	19	20	21	22	23	24
401&402	4	4	4	4	4	4	4	4	4	4	3	3

For this test, thermal unit data and system load/reserve requirements are given in Tables III and XI, respectively. The system emission cap is 13 000 lb. The correlation coefficients between emission and heat consumed for power generation of thermal units are found in Table XIV. Accordingly, unit 4 will emit more pollution than the other five units at a given level of power dispatch. Table XV shows the commitment of thermal unit 4 after we enforce the system emission constraint. Because of the enforced emission cap, the expensive unit 3 (which is also the cleanest) is dispatched more often while the relatively cheap unit 4 is utilized less frequently to meet the emission cap.

We now replace unit 4 with two identical combined cycle units with the same capacity and parameters given in Tables VIII and IX. Emission correlation coefficients for all configurations of combined cycle units are 0.1 (lb/MBtu). Combined cycle units are cheaper than unit 3, and have the same emission coefficient as that of unit 3, so combined cycle units will have a dispatch priority. Table XVI represents the commitment of units 401 & 402 in which the units are in operation more often than the thermal unit 4 (hours 6, 7, 23, and 24) in Table XV. The commitment changes are highlighted in Tables XV and XVI.

Table XVII indicates that the thermal unit 3 will be less attractive than combined cycle units, and its daily dispatch will be reduced from 216.86 to 122.49 MWh. At the same time, generation from units 401 and 402 is increased from 560.61 to 669.00 MWh while satisfying the system emission cap. So combined cycle units reduce the daily generation cost to \$90 407.39. Accordingly, the total cost is 1.65% lower than that without combined cycle units (\$91 923.60).

*Case 4: LMP for Combined Cycle Units*

TABLE XVII  
DAILY POWER GENERATION (CASE 3)

Unit No	Daily Generation (MWh)	
	No Combined Cycle	With Combined Cycle
3	216.86	122.49
4	560.61	---
401&402	---	669.00

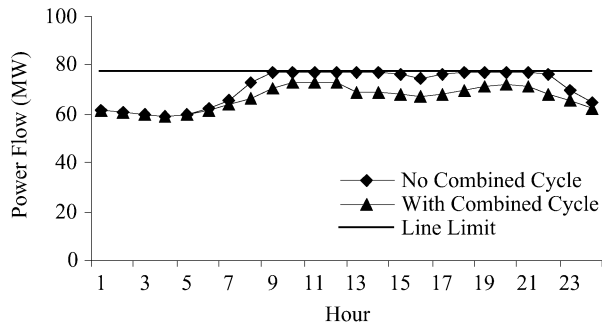


Fig. 6. Power flow on Branch 10.

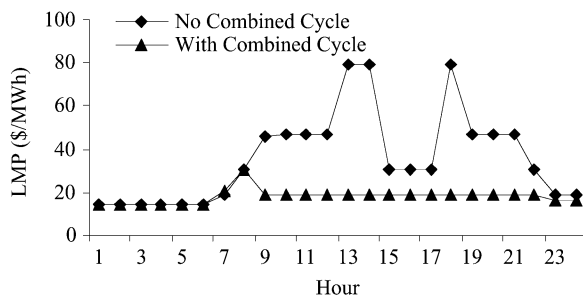


Fig. 7. LMP at Bus 8.

In today's restructured power systems, generating companies intend to locate their new units near heavy load centers which are usually located around big cities. At these locations the land is very scarce for installing large units and the emission caps prevents generating companies from utilizing more pollutant units such as coal. The alternative is to install the large coal units at a distance from the load center and transmit the electricity via high voltage lines. During peak hours, line flows could reach their upper limits and cause congestion in the power system. Once congestions occur, the power from cheaper units may not be fully utilized which will increase the LMP at various buses.

As indicated earlier, combined cycle units could be installed near load centers and remedy the perceived congestion problems due to their compact size, low pollution, and superb ramping capabilities. The lack of congestion in such systems would reduce LMPs and the dispatch cost. Here we use an example to demonstrate the impact of combined cycle units on LMPs.

The data for thermal units, system load, combined cycle units, and unit commitments are the same as those in Case 1. We execute the constrained economic dispatch and calculate line flows and LMPs for thermal units in Case 1 and exhibit the results in Figs. 6 and 7. Next we replace thermal units 1 and 2 at buses 1 and 3 with two combined cycle units and calculate the flows and LMPs as depicted in Figs. 6 and 7.

Because bus 7 has the largest generator and bus 8 has the largest load, the flow from bus 7 to 8 on branch 10 will be significant and will cause congestion at peak load hours. Accordingly, more expensive generation will be dispatched which will increase the LMP at bus 8. However, once we replace expensive thermal units 1 and 2 with combined cycle units, the generators located at buses 3 and 7 will provide cheaper power to the load at bus 8, which will relieve the congestion burden of branch 10. Figs. 6 and 7 indicate that branch 10 is not blocked and the LMP at bus 8 is decreased dramatically after the installation of combined cycle units.

## VII. CONCLUSION

Combined cycle units are very popular in today's power system due to their distinct advantages such as high efficiency, fast response, and environment friendliness. To the extent that new combined cycle plants substitute for existing coal plants, they can substantially reduce the installation time and the average kilowatt-hour CO<sub>2</sub> production. Since combined cycle units have multiple operating configurations, the scheduling of such units is a difficult task. In this paper we presented a method for creating the state space diagram of combined cycle unit for short-term scheduling applications. Although the method for creating the state space diagram is initially designed for combined cycle units, it is also suitable for other types of units with multiple configurations. In the paper, we considered various test cases including the impact of combined cycle units on LMP and discussed the impact of combined cycle units on minimizing the cost of supplying the load in a competitive electricity market. The results of case studies verify the advantages of combined cycle units presented in the introduction.

## REFERENCES

- [1] M. Shahidehpour, H. Yamin, and Z. Li, *Market Operations in Electric Power Systems: Forecasting, Scheduling, and Risk Management*. New York: Wiley, 2002.
- [2] K. H. Abdul-Rahman, S. M. Shahidehpour, M. Aganagic, and S. Mokhtari, "A practical power systems resource scheduling with OPF constraints," *IEEE Trans. Power Syst.*, vol. 11, pp. 254-259, Feb. 1996.
- [3] W. J. Watson, "The 'success' of the combined cycle gas turbine," in *Proc. 1996 IEE Opportunities and Advances in International Power Generation Conf.*, vol. 419, 1996.
- [4] R. Boyer, "Now that you have a combined-cycle plant in your backyard," in *Proc. 2001 IEEE PES Winter Meeting*, vol. 2, pp. 649-651.
- [5] R. Kehlhofer, *Combined-Cycle Gas & Steam Turbine Power Plants*. Lilburn, GA: Fairmont, 1991.
- [6] Combined Cycle Power Plants [Online]. Available: <http://www.pseg.com/companies/power/cycle.html>
- [7] J. M. Arroyo and A. J. Conejo, "Optimal response of a power generator to energy, AGC and reserve pool based markets," *IEEE Trans. Power Syst.*, vol. 17, pp. 404-410, May 2002.
- [8] C. Wang and S. M. Shahidehpour, "Effects of ramp-rate limits on unit commitment and economic dispatch," *IEEE Trans. Power Syst.*, vol. 8, pp. 1341-1350, Aug. 1993.
- [9] Z. Li and S. M. Shahidehpour, "Generation scheduling with thermal stress constraints," *IEEE Trans. Power Syst.*, vol. 18, pp. 1402-1409, Nov. 2003.
- [10] New Resource Characterization for the Fifth Power Plan: Natural Gas Combined-Cycle Gas Turbine Power Plants [Online]. Available: [http://www.westgov.org/wieb/electric/Transmission%20Protocol/SSG-WI/pnw\\_5pp\\_02.pdf](http://www.westgov.org/wieb/electric/Transmission%20Protocol/SSG-WI/pnw_5pp_02.pdf)
- [11] D. Chase, "Combined-cycle development, evolution, and future," *GE Power Systems, GER.4206*, Apr. 2001.

- [12] R. M. Rifaat, "Economic dispatch of combined cycle cogeneration plants with environmental constraint," in *Proc. 1998 IEEE Energy Management and Power Delivery Conf.*, vol. 1, pp. 149–153.
- [13] A. I. Cohen and G. Ostrowski, "Scheduling units with multiple operating modes in unit commitment," *IEEE Trans. Power Syst.*, vol. 11, pp. 497–503, Feb. 1996.
- [14] M. R. Bjelogric, "Inclusion of combined cycle plants into optimal resource scheduling," in *Proc. 2000 IEEE PES Summer Meeting*, pp. 189–195.
- [15] A. Wood and B. Wollenberg, *Power Generation, Operation, and Control*. New York: Wiley, 1996.
- [16] C. Wang and M. Shahidehpour, "Ramp-rate limits in unit commitment and economic dispatch incorporating rotor fatigue effect," *IEEE Trans. Power Syst.*, vol. 9, pp. 1539–1545, Aug. 1994.
- [17] S.-Y. Lai and R. Baldick, "Unit commitment with ramp multipliers," *IEEE Trans. Power Syst.*, vol. 14, pp. 58–64, Feb. 1999.

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