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Including Combined-Cycle Power Plants in Generation System Reliability Studies

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***Abstract*—This paper presents a model to include combined-cycle power plants in generation system reliability studies. Combined-cycle power plants are energy and power limited sources, arising these bounds from the natural gas available to be burned. Natural gas availability depends on the natural gas supplies, the pipeline network constraints and the natural gas demand for non-electric purposes. Hence, the power and energy delivered by a combined-cycle power plant is a non-linear function of its time-dependent natural gas availability.**

This paper present a procedure to perform power generation reliability studies including combined-cycle power plants. The procedure is based on an original model of combined-cycle power plants. This model is based on the definition of a fictitious demand which represents the combined-cycle power plant not available capacity due to lack of gas in the natural gas network and/or unavailability of the plant.

***Index Terms*— Combined-cycle power plant, Natural gas, Power generation, Power system reliability.**

I. INTRODUCTION

THE structure of the power industry has undergone important changes in many countries during the last years. The general trend is to move towards a greater competition which means larger risks for private companies. These changes have been driven by political, economical and technical reasons. Among the technical reasons, the outstanding feature is the development of combined-cycle power plants. These plants are efficient power plants that use natural gas to generate electricity. They present higher efficiencies and require lower investment costs and shorter depreciation periods than the traditional thermal and nuclear power plants. Furthermore, they can easily adapt their production to fluctuations in customer demand and their environmental impact is low. Because of these advantages, the growth of generating power in Spain and several other countries is mainly based on the construction of combined-cycle power plants. The increase of electrical generation by this technology has promoted the merge of the electrical system and the natural gas system into a unique energy system [1]-[3]. Fig. 1 illustrates the joint operation of the electrical and the natural gas systems.

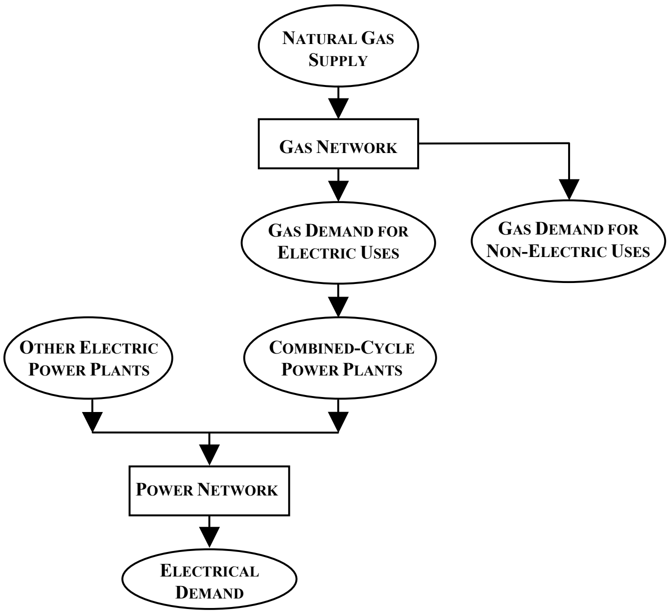

Fig. 1. Joint operation of the electric and natural gas systems.

Research on power system reliability has been intensive over the last decades [4]. The main approaches to derive generation system reliability indexes can be structured into analytical and simulation methods. This paper focuses on the evaluation of generation system reliability using analytical techniques. The most typical model of a power plant for generation system reliability studies is a two-state model (power plant available with a time-constant maximum capacity or not available with null generation). For time-dependent generation power plants (e.g. run-of-the-river hydro units), multi-state power plant models have been developed [4]. This multi-state description is not able to describe accurately the chronological nature of a time-dependent power generation unit.

The available capacity of a combined-cycle power plant at each time period is a function of the available gas supply at that time period. Therefore, combined-cycle power plant available capacity is a time-dependent function.

This paper proposes a model of a combined-cycle power plant that allows its introduction into the classic generation

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system reliability studies based on probabilistic simulation techniques, with an accurate description of the chronological nature of its time-dependent power generation. This model is based on the definition of a fictitious demand. This fictitious demand represents the not available capacity of the combined-cycle power plant because of the lack of available gas supply and/or the unavailability of the plant. It is noteworthy that the proposed method is able to deal with gas supply and electricity demand correlations. In fact, constraints in gas supply are more likely to arise when electricity demand is high (for instance, during the winter peak).

An analytical procedure to assess generation system reliability including combined-cycle power plants is presented. A case study is analyzed. The results of the case study, using the proposed method, are compared to those obtained using analytical techniques based on state enumeration [4].

II. COMBINED-CYCLE POWER GENERATION

A combined-cycle power plant is composed of one or more combined-cycle units. The power generated by a combined-cycle unit is a non-linear function of the natural gas supply to the unit [5]. Mathematically:

$$P(t) = \mu(g(t)) \times LHV \times g(t) \tag{1}$$

where P is the electrical power generated by the unit (MW), μ is the combined-cycle unit efficiency, g is the natural gas supply to the combined-cycle unit (m^3/s), LHV is the Lower Heating Value for natural gas ($MW/(m^3/s)$) and t is the time function.

The electric power P(t) which can be produced at time period t by a combined-cycle unit is bounded by the maximum capacity P^{max} of the unit and the available natural gas supply g(t), which depends on the natural gas system constraints. Table I shows the power generated by a combined-cycle unit for different values of natural gas supply g(t) to the unit.

TABLE I
COMBINED-CYCLE UNIT POWER GENERATION

	Combined-Cycle Unit Available	Combined-Cycle Unit Unavailable
$g(t) = 0$	0	0
$0 < g(t) < g^{max}$	P(t)	0
$g(t) \geq g^{max}$	P^{max}	0

As shown in Table I, if available natural gas supply g(t) to the combined-cycle unit is lower than the unit maximum capacity natural gas supply g^{max}, the bounding limit is the available gas supply g(t) and the generated power is computed by using (1). On the other hand, if available natural gas supply g(t) is greater than the unit maximum capacity natural gas supply g^{max}, then the generated power is the maximum power of the unit P^{max}.

Fig. 2 shows the power generation of a combined-cycle unit as a non-linear function of the available gas supply to the unit.

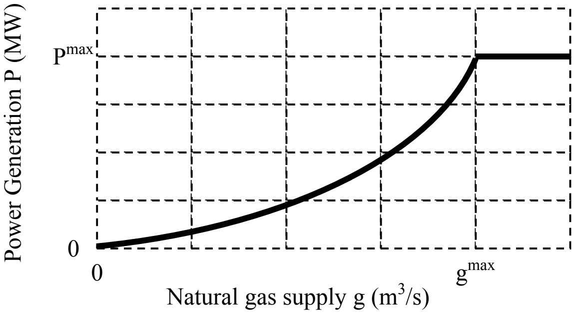

Fig. 2. Power generation of a combined-cycle unit.

It can be seen in Fig. 2 that maximum efficiency of a combined-cycle unit is achieved for maximum capacity generation. The combined-cycle unit efficiency decreases as the natural gas supply is reduced.

III. MODEL DESCRIPTION

In this section, the proposed model to include combined-cycle power plants into generation system reliability studies based on probabilistic simulation is presented.

A. Fictitious Demand: Deterministic Definition

Let us consider a combined-cycle unit whose forced outage rate is zero. The available capacity of this unit P(t) is modeled as: i) a conventional thermal unit with a constant maximum capacity P^{max} (equal to the maximum capacity of the unit), and ii) a fictitious load $L^F(t)$. This load represents the not available capacity of the combined-cycle unit because of lack of natural gas. Hence, the fictitious load $L^F(t)$ is computed as:

$$L^F(t) = P^{max} - P(g(t)) \tag{2}$$

where P^{max} is the maximum capacity of the combined-cycle unit and P(g(t)) is the unit available capacity at time period t which is computed using (1).

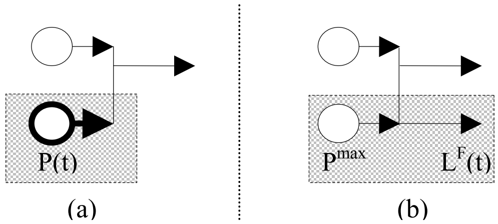

Fig. 3. Combined-cycle unit available capacity model.

Fig. 3(a) represents (shadowed) a combined-cycle unit as an element of a generation system. On the other hand, Fig. 3(b) shows the proposed model: the combined-cycle unit is replaced by a conventional thermal unit with constant capacity P^{max}, and a fictitious load $L^F(t)$. It should be noted that the available capacity is the same in both cases, as it is stated in (2).

B. *Extension to a Probabilistic Definition*

The main advantage of this model is that it allows the combined-cycle unit to be considered as a conventional thermal unit in the probabilistic simulation procedure. The combined-cycle unit is included in the probabilistic simulation procedure as a thermal unit with a constant capacity P^{max} and zero forced outage rate, while the fictitious demand is added, by time period, to the electric demand, taking into account the combined-cycle unit forced outage rate. In this sense, the concept of fictitious demand is extended to consider the probabilistic nature of the combined-cycle unit capacity. This extension supposes that the fictitious demand models the unavailable capacity due to both a bounding limit on the natural gas available and the forced outage rate of the combined-cycle unit.

Hence, the fictitious demand of a combined-cycle unit is a discrete random variable:

$$L^F(t) = \begin{cases} P^{max} & \text{with probability } q \\ P^{max} - P(t) & \text{with probability } p = 1 - q \end{cases} \qquad (3)$$

where q is the forced outage rate of the unit and P(t) is the unit available capacity in time period t which depends on the natural gas available in that time period.

B. *Combined-Cycle Power Plants*

Besides the bounds arising from the natural gas network operation, the natural gas available for a combined-cycle unit depends on the number of units included in the same power plant, or, in general, the number of units connected to the same node of the natural gas network. Hence, the computation of the fictitious demand must take into account that different units of the same node of the gas network share the available natural gas. It is necessary to define a natural gas dispatching rule among the units included in the same power plant. In this paper, it is considered the available natural gas is used to supply a chosen unit, and only if the maximum capacity is achieved, the remaining natural gas is used to supply the other units following the same criteria. The fictitious demand is then evaluated by taking into account the possible states (on/off) of the units included in the combined-cycle power plant, the probability associated to each state and the available capacities previously computed.

A combined-cycle power plant with two different units is used to illustrate the fictitious demand evaluation. In this example, the available natural gas g is: $\max\{g_1^{max}, g_2^{max}\} \leq g \leq g_1^{max} + g_2^{max}$, where g_i^{max} is the natural gas necessary to reach the maximum capacity of combined-cycle unit i. Table II represents for each possible state the available capacity of each unit, the fictitious load and the probability.

C. *Modified Load Curve (MLC)*

Once the fictitious demand is evaluated for every time period, it is convoluted by time period to the electric demand to get the modified load curve. Fig. 4 shows the modified load curve for the time period analyzed in Table II. Note that this procedure preserves electricity demand and gas supply capacity correlations.

TABLE II
COMBINED-CYCLE POWER PLANT FICTITIOUS DEMAND

State		P(t)		$L^F(t)$	Prob.
Un.1	Un.2	Un.1	Un. 2		
0	0	0	0	$P_1^{max} + P_2^{max}$	$q_1 \times q_2$
1	0	P_1^{max}	0	P_2^{max}	$p_1 \times q_2$
0	1	0	P_2^{max}	P_1^{max}	$q_1 \times p_2$
1	1	P_1^{max}	$P_2(g-g_1^{max})$	$P_2^{max} - P_2(g-g_1^{max})$	$p_1 \times p_2$

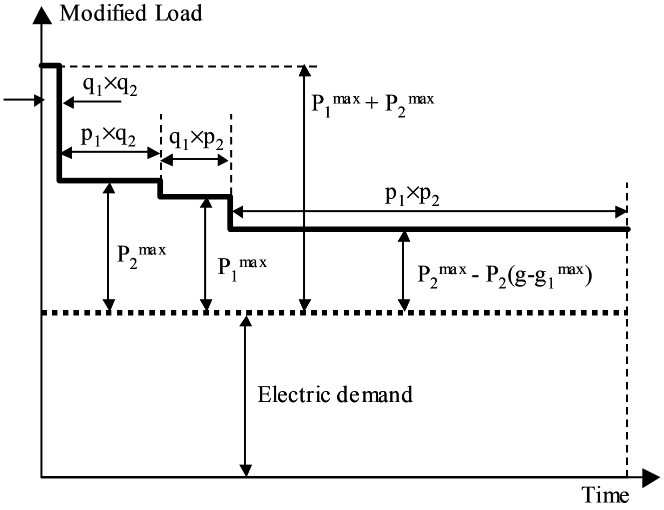

Fig. 4. Modified load curve of time period t.

Note that the aforementioned convolution can handle the correlation between the natural gas demand for electric and non-electric purposes.

D. *Modified Load Duration Curve (MLDC)*

Finally, the modified load duration curve is then evaluated by ordering the modified load curve from higher to lower load values. This MLDC is used to achieve the generation reliability indexes (LOLE and EUE) by using probabilistic simulation [6]. Fig. 5 represents both the MLC and the MLDC for a three time period case example.

TABLE III
POWER UNITS

	Unit	P^{max} (MW)	Forced Outage Rate
Thermal	1	200	0.2
	2	500	0.1
	3	450	0.15
Combined-Cycle	I-A	400	0.1
	I-B	400	0.1
	II-A	350	0.2
	II-B	350	0.2

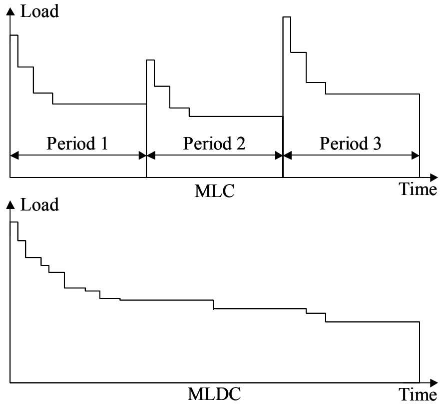

Fig. 5. MLC and MLDC.

IV. PROPOSED SOLUTION PROCEDURE

The proposed procedure to find out the generation reliability indexes (LOLE and EUE) of a thermal power system including combined-cycle power plants is stated below.

Step 1:
Compute by time period the fictitious load for each combined-cycle power plant or those combined-cycle units supplied from the same node of the natural gas network (section III.C).

Step 2:
Convolute by time period the fictitious load and the electric demand to get the Modified Load Curve (section III.D).

Step 3:
Derive the Modified Load Duration Curve from the Modified Load Curve by ordering from higher to lower load values (section III.E).

Step 4:
Apply traditional probabilistic simulation techniques to compute the LOLE and EUE indexes. Combined-cycle units will be load on the MLDC as units with a constant maximum capacity P^{max} and whose forced outage rate is zero. It should be noted that the units merit order used in the probabilistic simulation procedure is irrelevant because it does not change the considered reliability indexes (LOLE and EUE) [7].

V. CASE STUDY

To validate the proposed method, a case study is analyzed. The results of the proposed method are checked using a state enumeration technique [4]. This is possible because the case study is a small-size one.

The generation system of the case study includes 3 traditional thermal units (1, 2 and 3) and 2 combined-cycle power plants (I and II). Each combined-cycle power plant consists of 2 units (A and B). Three time periods (t_1, t_2 and t_3) are considered.

The case study data are summarized in Tables III and IV.

A general 4th order function that relates combined-cycle unit natural gas supply g and unit generation P (that fits the data in a least-squares sense) is developed. The following function is used:

$$P = C_4 e^4 + C_3 e^3 + C_2 e^2 + C_1 e + C_0 \tag{4}$$

The values of the coefficients C_4, C_3, C_2, C_1 and C_0 depend on the unit size, and can be obtained using a combined-cycle unit relative efficiency - relative power curve [5]. The coefficients for a 400 MW combined-cycle unit and for a 350 MW combined-cycle unit are shown in Table V.

TABLE IV
NATURAL GAS SUPPLY AND ELECTRIC DEMAND

Time Period	Natural Gas Supply to Plant I (m^3/s)	Natural Gas Supply to Plant II (m^3/s)	Electric Demand (MW)
t_1	30	20	2000
t_2	35	27	2500
t_3	28	22	2200

Because of the least-square approximation, very small natural gas supplies produce a very small negative value of power generation in (4). In this case, the small negative values are set to 0.

The maximum natural gas supply g^{max} for a combined-cycle unit can be obtained by using (1) for full-load situation. Maximum efficiency of a combined-cycle unit occurs at full-load situation, and is set to 0.57 [5]. Lower Heating Value (LHV) of natural gas is assumed to be 35.07 MW/(m^3/s) [8].

TABLE V
COEFFICIENTS OF APPROXIMATION POWER-GAS SUPPLY

	C_4	C_3	C_2	C_1	C_0
400 MW unit	0.0022	-0.1210	2.3947	3.0017	-0.8209
350 MW unit	0.0033	-0.1574	2.7348	2.9727	-0.5929

Therefore, (1) for full-load situation is:

$$P^{max} = 0.57 \times 35.07 \times g^{max} \tag{5}$$

From (5):
- If P^{max} = 400 MW, g^{max} = 20.0101 m^3/s
- If P^{max} = 350 MW, g^{max} = 17.5088 m^3/s

Using the above data, the proposed solution procedure is developed next.

Step 1: Fictitious load computation by time period for each combined-cycle power plant

A combined-cycle power plant with two units presents four different on-off states. Assuming that the forced outage rates of the units of each combined-cycle power plant are independent, the probabilities of these states are shown in Table VI.

TABLE VI
COMBINED-CYCLE POWER PLANT STATES AND PROBABILITIES

State	Unit A	Unit B	Probability Plant I	Probability Plant II
0	OFF	OFF	0.01	0.04
1	ON	OFF	0.09	0.16
2	OFF	ON	0.09	0.16
3	ON	ON	0.81	0.64

E.g., for combined-cycle power plant I, the probability of state 3 is (1 - 0.1) × (1 - 0.1) = 0.81, as the forced outage rate of units A and B is 0.1 (Table III).

The fictitious load value $L^F(t)$ for a combined-cycle unit depends on its available capacity P(t), as shown in (3). Table VII presents the values of available capacity and fictitious load of each unit of combined-cycle power plant I in time period t_1.

TABLE VII
COMBINED-CYCLE POWER PLANT I
POWER GENERATION AND FICTITIOUS LOAD IN TIME PERIOD t_1

State	Unit A	Unit B	P_A (MW)	P_B (MW)	L^F_A (MW)	L^F_B (MW)	$L^F_A+L^F_B$ (MW)	Prob.
0	OFF	OFF	0	0	400	400	800	0.01
1	ON	OFF	400	0	0	400	400	0.09
2	OFF	ON	0	400	400	0	400	0.09
3	ON	ON	400	169.4	0	230.6	230.6	0.81

Let us analyze state 3 of combined-cycle power plant I at time period t_1 (Table VII). Available natural gas supply is 30 m^3/s (Table IV). As g^{max} of unit A (20.0101 m^3/s) is less than 30 m^3/s, available natural gas exists for both units. Unit A natural gas supply is 20.0101 m^3/s and, therefore, unit B natural gas supply is 30 - 20.0101 = 9.9899 m^3/s. As a consequence, unit A power generation is P^{max} (400 MW), and, using (4), unit B power generation is 169.4 MW. From (2), unit A fictitious load if $P = P^{max}$ is 0 MW. On the other hand, unit B fictitious load is 400 - 169.4 = 230.6 MW. Therefore, fictitious load of power plant I at time period t_1 for state 3 is 0 + 230.6 MW = 230.6 MW. State 3 probability is 0.81 (Table VI). Note that because the two units of the power plant are identical, states 1 and 2 in Table VII produce the same power plant fictitious demand and can be described together.

Fictitious load computation is repeated for each combined-cycle power plant and for each time period. Table VIII shows, for each time period, the fictitious load values and the associated probabilities for plant I and plant II.

TABLE VIII
COMBINED-CYCLE POWER PLANT FICTITIOUS LOAD

	State	$L^F(t_1)$ (MW)	$L^F(t_2)$ (MW)	$L^F(t_3)$ (MW)	Prob.
Plant I	0	800	800	800	0.01
	1-2	400	400	400	0.18
	3	230.6	114.9	275.6	0.81
Plant II	0	700	700	700	0.04
	1-2	350	350	350	0.32
	3	329.7	184.7	294.5	0.64

Step 2: Modified Load Curve Computation

The system fictitious load is computed by adding the fictitious loads of power plants I and II for each time period (Table VIII). Table IX shows the system fictitious load values and the associated probabilities.

TABLE IX
SYSTEM FICTITIOUS LOAD AND PROBABILITIES

State Plant I	State Plant II	$L^F(t_1)$ (MW)	$L^F(t_2)$ (MW)	$L^F(t_3)$ (MW)	Prob.
0	0	1500	1500	1500	0.0004
0	1-2	1150	1150	1150	0.0032
0	3	1129.7	984.7	1094.5	0.0064
1-2	0	1100	1100	1100	0.0072
1-2	1-2	750	750	750	0.0576
1-2	3	729.7	584.7	694.5	0.1152
3	0	930.6	814.9	975.6	0.0324
3	1-2	580.6	464.9	625.6	0.2592
3	3	560.3	299.6	570.1	0.5184

Let us analyze state 3 of both plants at time period t_1. From Table VIII, fictitious load of plant I is 230.6 MW and fictitious load of plant II is 329.7 MW, with probabilities of 0.81 and 0.64 respectively. Therefore, system fictitious load (Table IX) is 560.3 MW (230.6 + 329.7) and the associated probability is 0.5184 (0.81 × 0.64).

To derive the modified load curve (Table X), the system fictitious load in each time period (Table IX) is added to the electric demand in each time period. Note that the probability of the electric demand for each time period is 1 (Table IV).

TABLE X
MODIFIED LOAD CURVE (MLC)

State Plant I	State Plant II	MLC(t_1) (MW)	MLC(t_2) (MW)	MLC(t_3) (MW)	Prob.
0	0	3500	4000	3700	0.0004
0	1-2	3150	3650	3350	0.0032
0	3	3129.7	3484.7	3294.5	0.0064
1-2	0	3100	3600	3300	0.0072
1-2	1-2	2750	3250	2950	0.0576
1-2	3	2729.7	3084.7	2894.5	0.1152
3	0	2930.6	3314.9	3175.6	0.0324
3	1-2	2580.6	2964.9	2825.6	0.2592
3	3	2560.3	2799.6	2770.1	0.5184

Step 3: Modified Load Duration Curve

Table XI presents the Modified Load Duration Curve.

TABLE XI
MODIFIED LOAD DURATION CURVE (MLDC)

MLDC (MW)	Prob.	MLDC (MW)	Prob.	MLDC (MW)	Prob.
4000	1.0000	3294.5	0.9797	2930.6	0.7980
3700	0.9999	3250	0.9776	2894.5	0.7872
3650	0.9997	3175.6	0.9584	2825.6	0.7488
3600	0.9987	3150	0.9476	2799.6	0.6624
3500	0.9963	3129.7	0.9465	2770.1	0.4896
3484.7	0.9961	3100	0.9444	2750	0.3168
3350	0.9940	3084.7	0.9420	2729.7	0.2976
3314.9	0.9930	2964.9	0.9036	2580.6	0.2592
3300	0.9821	2950	0.8172	2560.3	0.1728

Step 4: Reliability index computation

The reliability indexes LOLE and EUE are calculated using probabilistic simulation techniques. If each time period is considered to be one hour, the obtained reliability indexes are:

· LOLE = 2.5241 hours/number of hours
· EUE = 943.26 MWh

An state enumeration technique is used to test the method.

Table XII presents, for each time period, the system available capacity $P_S(t)$ according to the combined-cycle power plant states. It is assumed that the three thermal units are available.

TABLE XII
POWER SYSTEM AVAILABLE CAPACITY

Plant I	Plant II	$P_S(t_1)$ (MW)	$P_S(t_2)$ (MW)	$P_S(t_3)$ (MW)	Prob.
0	0	1150	1150	1150	0.0004
0	1-2	1500	1500	1500	0.0032
0	3	1520.3	1665.3	1555.5	0.0064
1-2	0	1550	1550	1550	0.0072
1-2	1-2	1900	1900	1900	0.0576
1-2	3	1920.3	2065.3	1955.5	0.1152
3	0	1719.4	1835.1	1674.4	0.0324
3	1-2	2069.4	2185.1	2024.4	0.2592
3	3	2089.7	2350.4	2079.9	0.5184

Time period t_1: Electric load for time period t_1 is 2000 MW. Loss of load occurs for each system state except for (3,1-2) and (3,3). Therefore, LOLP is: $1 - [0.8 \times 0.9 \times 0.85 \times (0.5184 + 0.2592)] = 0.5241$. It should be noted that if any thermal unit fails, loss of load exists.

Time period t_2: Electric load for time period t_2 is 2500 MW. All the states present loss of load, so LOLP is 1.

Time period t_3: Electric load for time period t_3 is 2200 MW. All the states present loss of load, so LOLP is 1.

The LOLE value is the addition of all the LOLP values:

LOLE = 0.5241 + 1 + 1 = 2.5241 hours/number of hours

which is the value previously obtained.

VI. CONCLUSION

This paper presents a model to properly include combined-cycle power plants into generation power system reliability studies using probabilistic simulation techniques. The maximum power that can be generated by a combined-cycle power plant is not a constant amount. It depends on the gas available on the natural gas system, that it is generally correlated with electricity demand.

In the proposed reliability study, a combined-cycle power plant is modeled as: i) a time-constant capacity thermal plant, and ii) a time-dependent "fictitious demand". This fictitious demand models the not available capacity of the combined-cycle power plant due to lack of gas supply and/or unavailability of the combined-cycle power plant. The electric load demand and the fictitious demand of each combined-cycle power plant are convolved by time period, considering the combined-cycle power plant forced outage rates, to perform a modified load curve. Finally, the modified load duration curve is computed and used to achieve the reliability indexes by using probabilistic simulation techniques. It should be noted that this method is able to implicitly handle the correlation between natural gas and electric load demands.

A small-size case study is presented to illustrate the method and the results are validated by applying an state enumeration method.

REFERENCES

[1] S. Takriti, C. Supatgiat, and L. S.-Y. Wu, "Coordinating Fuel Inventory and Electric Power Generation Under Uncertainty," *IEEE Transactions on Power Systems*, vol. 17, pp. 13-18, February 2002.

[2] M. S. Morais and J. W. Marangon Lima, "Natural Gas Network Pricing and Its Influence on Electricity and Gas Markets," presented at the 2003 IEEE Bologna Power Tech Conference, Bologna, Italy, June 23-26, 2003, Paper BPT03-396.

[3] J. Munoz, N. Jimenez-Redondo, J. Perez-Ruiz, and J. Barquin, "Natural Gas Network Modeling for Power Systems Reliability Studies," presented at the 2003 IEEE Bologna Power Tech Conference, Bologna, Italy, June 23-26, 2003, Paper BPT03-339.

[4] R. Billinton and R.N. Allan, *Reliability Evaluation of Power Systems*. 2nd Ed. New York: Plenum Press, 1996.

[5] R.H. Kehlhofer, J. Warner, H. Nielsen, and R. Bachmann, *Combined-Cycle Gas&Steam Turbine Power Plants*. 2nd Ed. Tulsa, Oklahoma: PennWell Publishing Company, 1999, pp. 204-217.

[6] A.J. Wood and B.F. Wollenberg, *Power Generation, Operation, and Control*. 2nd Ed. New York: John Wiley & Sons, 1996, pp. 264-327.

[7] A.J. Conejo, M.C. Caramanis, and J.A. Bloom. "An Efficient Algorithm for Optimal Reservoir Utilization in Probabilistic Production Costing". *IEEE Transactions on Power Systems*, vol. 5, pp. 439-447, May 1990.

[8] *Natural Gas Characteristics and Combustion*, BC Gas, Vancouver, 2001.