Long term maintenance optimization of CCGT plants

E. Lobato, P. Sánchez-Martín, E. Sáiz-Marín
Institute of Research and Tecnology (IIT)
Comillas University, Madrid, Spain
Enrique.lobato@iit.upcomillas.es

***Abstract*—The rising share of renewable energies within the generation mix has reduced the load factor of actual CCGT power plants. In this way, a more flexible operation of this technology with an increased number of annual start-up cycles is needed. Since CCGT design assumed a base load operation at nominal power with a few number of annual start cycles, plant owners have to face higher maintenance costs, reliability reduction and lower market incomes. This paper presents a mixed-integer optimization model that schedules the long term maintenance planning based on the daily operation of a CCGT plant in order to maximize its global profit. The model is illustrated with an actual CCGT plant operating in the Spanish power system.**

Keywords-component; maintenance planning;unit-commitment; optimization models

I. NOMENCLATURE

A. Sets

d	Day
mt	Maintenance type: "minor", "hgpi" or "major"
g	Generator
ht	Hour type: "valley", "plateau" and "peak"
$daux$	Auxiliary copy of day d set

B. Parameters

$MDAYS_{g,mt}$	Duration of maintenance type mt of g
$EOH^{\max}_{g,mt}$	Maximum number of equivalent operating hours (EOH) of generator g before maintenance type mt
$EOH^{ini}_{g,mt}$	Initial number of equivalent operating hours of generator g after maintenance type mt
$NUMH_{d,ht}$	Number of hours of type ht within each day d
$MCOST_{g,mt}$	Cost of maintenance type mt of generator g
$KSTART_g$	Start up factor in EOH computation of generator g
$KHOURS_g$	Operating hours factor in EOH computation of generator g
M	Upper bound of constraints (let's say 10^6)

C. Binary variables

$\delta on_{g,d,ht}$	Binary variable [0,1] of operation of generator g in type of hour ht within day d
$\delta start_{g,d}$	Binary variable [0,1] that indicates if generator g is started in day d
$\delta mant_{g,d,mt}$	Binary variable [0,1] that indicates if generator g starts maintenance of type mt within day d

D. Positive variables

$eoh_{g,d,mt}$	Accumulated EOH of generator g at the end of day d since the last maintenance of type mt
$\Delta eoh_{g,d}$	Increased EOH of generator g at the end of day d
FO	Objective function (start up cost+operational cost+maintenance cost-market income)

II. INTRODUCTION

Renewable energy has experienced an extensive growth throughout the world due to technological advances and favorable policy incentives. The diversification of technologies in the generation mix has reduced the load factor of actual combined cycle gas turbines (CCGT) power plants. TABLE I compares the evolution of installed power and energy supplied of the generation mix of Spain in 2006 and 2010 [1]. Even though the relative installed power of CCGT increased representing 14.6% in 2006 to 25.5% in 2010, the relative energy supplied decreased from 23.3% to 23.1% of the total demand.

TABLE I EVOLUTION OF THE GENERATION MIX IN SPAIN

	INSTALLED(2010)		INSTALLED(2006)		ENERGY (2010)		ENERGY (2006)	
	MW	%	MW	%	GWh	%	GWh	%
Hydro	17561	17.7%	17499	22.2%	38653	13.8%	25330	9.3%
Nuclear	7777	7.9%	7716	9.8%	61990	22.1%	60126	22.1%
Coal-fired	11380	11.5%	11424	14.5%	22097	7.9%	66006	24.2%
Fuel/gas	2860	2.9%	6647	8.4%	1825	0.7%	5905	2.2%
CCGT	25235	25.5%	15504	19.6%	64604	23.1%	63506	23.3%
Wind	20057	20.3%	11521	14.6%	43355	15.5%	22881	8.4%
PV	4140	4.2%	153	0.2%	6719	2.4%	102	0.0%
Other	10033	10.1%	8444	10.7%	40828	14.6%	28651	10.5%
Total	99043	100.0%	78908	100.0%	280071	100.0%	272507	100.0%

CCGT design assumed a base load operation over 6000 operating hours and less than 20 annual start-up cycles. However, the raising share of renewable energies within the generation mix requires a more flexible operation of CCGT plants incurring in more start-ups (sometimes over 50 annual cycles) and partial load operation. Fig 1 displays the operating hours of the 51 CCGT plants within the Spanish power system during year 2010, with a mean value of 4528 (representing a mean load factor of 51%). It should be noted that several plants

The authors gratefully acknowledge the contribution of J. Chofre, O. Cardenas, F. Anthonioz, M. Alvarez, F de los Rios and F. Martín from Eon Generación S. L

978-1-4577-0547-2/12/$31.00 ©2012 IEEE

operate less than 2000 operating hours representing a load factor under 23%.

A higher number of start-up cycles decrease substantially CCGT profits. Plant owners have to face higher maintenance costs, reliability reduction and lower market incomes coming from a partial load operation and more frequent maintenance stops of the CCGT plant. In order to avoid the increase in maintenance cost, the alternative consists on keeping the CCGT plant connected in valley hours even though the market price may be lower than the operating cost. Advanced optimization tools are required in order to schedule the maintenance stops of the plants in the long term and to decide whether to stop or keep the unit connected in the short term depending on the level of market prices and daily spread (difference between the maximum and minimum hourly price within each day).

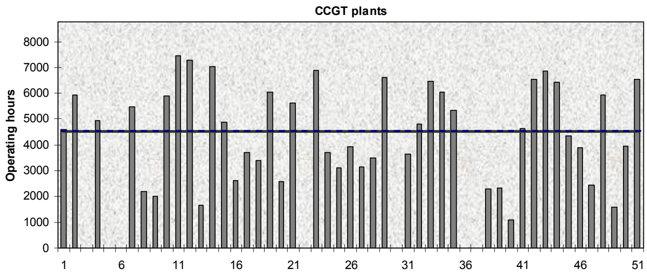

Fig 1: Operating hours of the CCGT plants of the Spanish power system during 2010

This paper presents a mixed-integer mathematical formulation in order to schedule the long term maintenance and daily operation of a CCGT plant. The formulation presented is included within an optimization model that maximizes the profit of the unit keeping the gas consumption according to the gas contracts subscribed by the generating agent. The planning horizon includes 3 years. The model is illustrated with an actual CCGT plant operating in the Spanish power system.

The paper has been organized as follows. Section III includes a brief bibliography review of optimization of maintenance scheduling. Section IV overviews the maintenance problem. The mathematical formulation of the maintenance is included in Section V. Section VI illustrates the maintenance optimization using an actual CCGT plant operating in the Spanish power system. Finally, conclusions are drawn in Section VII.

III. Bibliography Review

Due to its resolution complexity, one of the first optimal maintenance scheduling technique was based on Benders´ decomposition techniques [2]. A more sophisticated way to enhance the reliability indicators consists of using expert system outputs to assess on the design of a maintenance plan [3]. Multicriteria analysis techniques allow including not only reliability indicators but also economic aspects such as the goal programming technique uses at [4]. More recent researches are focused on selective maintenance to determine the optimal subset of desirable maintenance actions to perform when maintenance resources are constrained [5] [6].

More novel approaches include operation modeling to the maintenance plan design process to gain accuracy, credibility and assesibility. To cope with the dimensional increment of the model, lagrangian relaxation technique has been used [7] and also metaheuristics such as genetic algorithm [8]. Including operational constraints allows to deal with transmission outages [9] and preventive maintenance decisions [10] [11].

The maintenance model of this paper combines reliability and economic measures into a single objective function to design a high dimension long term optimal maintenance plan. This model details generator operation performance to gain accuracy on preventive maintenance decisions. This fine grained modeling allows to evaluate the economic impact of maintenance actions balancing the economic incomes from the hourly market price. This type of model takes into account technical constraint such as ramp rates, start-up and shut-down times among others.

IV. Maintenance of CCGT plants

The mathematical formulation of CCGT plants presented in this paper corresponds to Ansaldo/Siemens (AS) technology CCGT plants. Future research will include the modeling of General Electric technology CCGT plants.

Maintenance planning of AS CCGT plants is defined according to the equivalent operating hours (EOH), computed as a function of the number of start-ups of the plant and the number of operating hours. Maintenance working can be classified into three types: (a) minor, (b) hot gas path inspection (hgpi) and (c) major. Minor inspections are executed before accumulating $EOH^{\max}_{g,\text{"minor"}}$ EOH; hgpi inspections are performed before accumulating $EOH^{\max}_{g,\text{"major"}}$ EOH; finally, major inspections are carried out before accumulating $EOH^{\max}_{g,\text{"major"}}$ EOH. The duration of the three types of inspections are $MDAYS_{g,\text{"minor"}}$, $MDAYS_{g,\text{"hgpi"}}$ and $MDAYS_{g,\text{"major"}}$ days respectively.

V. Mathematical formulation

This section reviews the mathematical formulation of the long term maintenance modeling of Ansaldo/Siemens CCGT power plants that has been included within the optimization problem. For clarification purposes, variables are represented with upper case letters, while variables remain in lower case letters. Due to the paper length limitations only constraints related with the maintenance modeling are presented. Constraints not shown in this paper include among others monthly gas limitations consumption, maximum and minimum operating limits, reliability modeling of generating units.

A. *Objective function*

The cost of the maintenance of the generator is included within the objective function as an additional term to be added to other costs of generator (start up cost and operational cost):

$$FO = \min\left(... + \sum_{g,d,mt} MCOST_{g,mt} \cdot \delta mant_{g,d,mt} + ... \right) \quad (1)$$

B. Constraints

In order to include the maintenance modeling of CCGT plants within the optimization problem the following constraints are needed:

- Start up modeling between consecutive type of hours in the same day.

$$\delta start_{g,d} \geq \delta on_{g,d,ht} - \delta on_{g,d,ht-1} \quad [\forall g,d; ht \in \{"plateau","peak"\}] \quad (2)$$

- Start up modeling between peak and valley hours of consecutive days:

$$\delta start_{g,d} \geq \delta on_{g,d,"valley"} - \delta on_{g,d-1,"peak"} \quad [\forall g,d] \quad (3)$$

- Within each day, only of type of maintenance is possible:

$$\sum_{mt} \delta mant_{g,d,mt} \leq 1 \quad [\forall g,d] \quad (4)$$

- Computation of accumulated EOH of generator *g* at the end of day *d* since the last maintenance of type "minor", "hgpi" and "major":

$$eoh_{g,"day1",mt} = EOH^{ini}_{g,mt} \quad [\forall g,mt] \quad (5)$$

$$\Delta eoh_{g,d,mt} = KSTART_g \cdot \delta start_{g,d} + \sum_{ht} KHOURS_g \cdot HOURS_{d,ht} \cdot \delta on_{g,d,ht} \quad [\forall g, \forall d \neq "day1"] \quad (6)$$

$$eoh_{g,d,"minor"} \geq eoh_{g,d-1,"minor"} + \Delta eoh_{g,d} - M \cdot \left(\delta mant_{g,d,"minor"} + \delta mant_{g,d,"hgpi"} + \delta mant_{g,d,"major"} \right)_{[\forall g, \forall d \neq "day1"]} \quad (7)$$

$$eoh_{g,d,"hgpi"} \geq eoh_{g,d-1,"hgpi"} + \Delta eoh_{g,d} - M \cdot \left(\delta mant_{g,d,"hgpi"} + \delta mant_{g,d,"major"} \right)_{[\forall g, \forall d \neq "day1"]} \quad (8)$$

(9)

$$eoh_{g,d,"major"} \geq eoh_{g,d-1,"major"} + \Delta eoh_{g,d} - M \cdot \left(\delta mant_{g,d,"major"} \right)_{[\forall g, \forall d \neq "day1"]} \quad (10)$$

The last three equations assure than the number of accumulated EOH of each type of maintenance type is reset to 0 whenever maintenance working takes places.

- Duration of maintenance: the unit must be off during the days where the unit is being maintained:

$$\sum_{daux=d}^{d+MDAYS_{g,mt}} \delta on_{g,daux} \leq M \cdot \left(1 - \sum_{mt} \delta mant_{g,d,mt} \right) \quad \forall g,d \quad (11)$$

- Maximum number of EOH before maintenance type *mt*:

$$eoh_{g,d,mt} \leq EOH^{\max}_{g,mt} \quad (12)$$

VI. Results

This section illustrates the performance of the optimization model for an actual CCGT plant operating in the Spanish power system. It should be noted that due to confidentiality reasons, the values of $MDAYS_{g,mt}$, $EOH^{\max}_{g,mt}$, $MCOST_{g,mt}$, $KSTART_g$ and $KHOURS_g$ is not disclosed. Also for confidentiality reasons, a maintenance cost half of the actual value has been used in the simulations to illustrate how the results of the model can be applied to the long term maintenance operation and the short term operation planning. An horizon of three years (2011-2013) has been considered. The overall optimization problem size contained 55000 constraints, 23000 variables, out of which 9000 where discrete. A tolerance of ±10% over the monthly contracted gas is allowed within the optimization period. Daily market forward prices (peak, valley and plateau) estimates where used.

Fig 1 shows the number of monthly start-ups of the units for the simulated case study and the mean level of daily spread. The total number of annual start-ups accounted for 83, 69 and 42 in 2010, 2011 and 2012 respectively. It should be noted that the number of monthly start-ups is somehow correlated with the level of spread (and other variables such as the mean value of daily market price). For instance, in January 2012 the plant was started almost every day (25 times) due to the high level of spread (representing in general a low valley price)

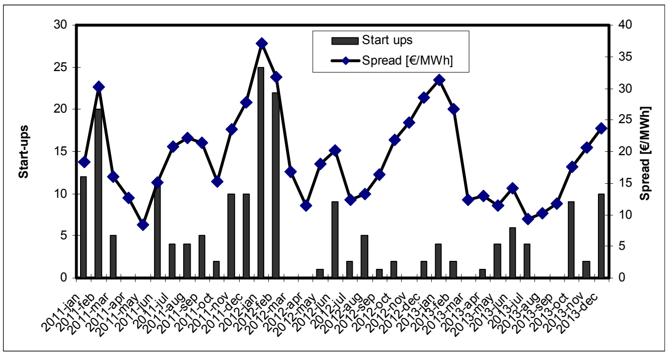

Fig 1: Number of monthly start-ups and mean value of spread during the optimization period

Fig 2 shows the statistical distribution (frequency and accumulated level of spread) of the daily spread for the three year planning horizon It should be noted that around 75% of the days the spread was lower than 25 €/MWh.

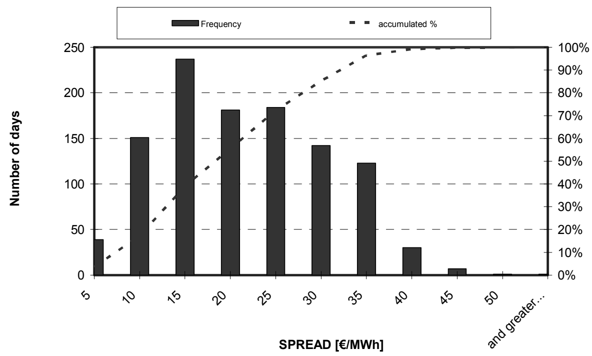

Fig 2: Frequency and accumulated level of spread

Fig 3 shows the long term planning of the unit. During the three year period the optimization program yields hgpi maintenance (type hgpi) stop scheduled in March 2012. Since the maintenance type is hgpi, the number of accumulated eoh of type minor and hgpi is reset to 0.

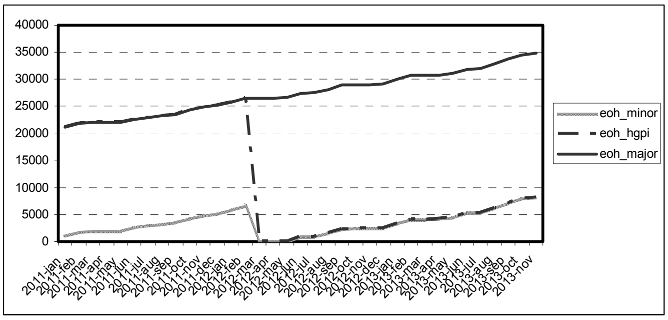

Fig 3: Number of accumulated eoh at the end of each month

The long term model can be used to estimate short term decision policies. For instance, the generating agent is concerned about whether it is convenient to start up the unit facing higher maintenance cost and lower incomes, or on the contrary remains connected even though valley prices can be lower than operating cost. As stated before, one of the main drivers of this decision is the level of spread. Fig 4 shows the frequency of start-ups according to the spread level. In addition Fig 4 the accumulated percentages of start-ups. For instance, Fig 4 shows that around 40 start ups occurred for a level of spread around 25 €/MWh. In addition, Fig 4 shows that when the unit is started up, around 35% of the times the spread was lower than 25 €/MWh. It should be noted that Fig 2 yields that the spread is lower than 25 €/MWh around 75% of the times.

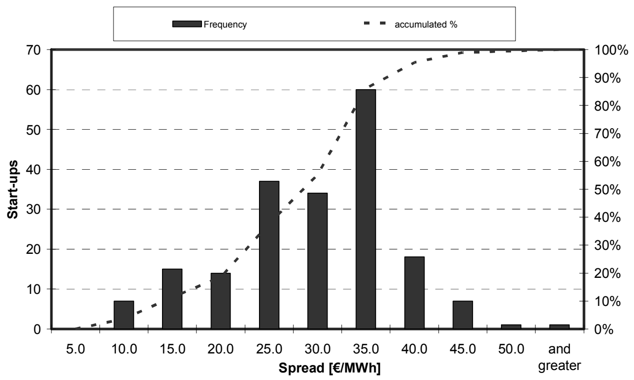

Fig 4: Level of spread at which start-up takes places

In addition, in the short term the agent should decide whether the unit should be on peak levels of demand. Histograms of the mean daily price when the unit is on or off can yield useful information to provide this information. Other useful graphs are scatter-plots daily spread vs. mean daily price for the days that the unit is on/off (they are not shown due to paper length limitations).

VII. CONCLUSIONS

Due to the new disposition of the generation share, plant owners have to face higher maintenance costs, reliability reduction and lower market incomes coming from a partial load operation and more frequent maintenance stops of the CCGT plant. In order to avoid the increase in maintenance cost, the alternative consists on keeping the CCGT plant connected in valley hours even though the market price may be lower than the operating cost

This paper has presented the formulation of the long term maintenance of a CCGT plant to be included within an optimization model. In the long term, the model is used to schedule the maintenance stops. In the short term and according to the level of estimated daily prices and spread, the model is used to estimate if the unit will be on, and in this case if it will be on the whole day, or started up for plateau and peak hours.

The performance of the model is illustrated using an actual CCGT plant operating in the Spanish power system, although for confidentiality reasons results have been presented for a fictitious case where the maintenance cost is half the real value.

REFERENCES

[1] Red Electrica de España (Spanish System Operator),"The Spanish electricity system 2010. Summary.", available on line at http://www.ree.es/ingles/publicaciones/publicaciones_on_line.asp

[2] Al-Khamis, T.M, Vemuri, S., Lemonidis, L. and Yellen, J. "Unit Maintenance Scheduling with fuel constraints", *Transactions on Power Systems*, vol. 7, no. 2, pp. 933-939 May 1992.

[3] Kawahara, K.; Sasaki, H.; Kubokawa, J.; Asahara, H.; Sugiyama, K.; , "A proposal of a supporting expert system for outage planning of electric power facilities retaining high power supply reliability," *Transactions on Power Systems* , vol.13, no.4, pp.1453-1458, Nov 1998

[4] Munoz Moro, L. and Ramos, A., "Goal programming approach to maintenance scheduling of generating units in large scale power systems," *Transactions on Power Systems*, vol.14, no.3, pp.1021-1028, Aug 1999

[5] Maillart, L.M.; Cassady, C.R.; Rainwater, C.; Schneider, K.; , "Selective Maintenance Decision-Making Over Extended Planning Horizons," *IEEE Transactions on Reliability*, vol.58, no.3, pp.462-469, Sept. 2009

[6] Yu Liu; Hong-Zhong Huang; , "Optimal Selective Maintenance Strategy for Multi-State Systems Under Imperfect Maintenance," *IEEE Transactions on Reliability*, vol.59, no.2, pp.356-367, June 2010

[7] Yong Fu; Zuyi Li; Shahidehpour, M.; Tongxin Zheng; Litvinov, E.; , "Coordination of Midterm Outage Scheduling With Short-Term Security-Constrained Unit Commitment," *IEEE Transactions on Power Systems* , vol.24, no.4, pp.1818-1830, Nov. 2009

[8] Camci, F.; , "System Maintenance Scheduling With Prognostics Information Using Genetic Algorithm," *IEEE Transactions on Reliability* , vol.58, no.3, pp.539-552, Sept. 2009

[9] Yong Fu; Shahidehpour, M.; Zuyi Li; , "Security-Constrained Optimal Coordination of Generation and Transmission Maintenance Outage Scheduling," *IEEE Transactions on Power Systems*, vol.22, no.3, pp.1302-1313, Aug. 2007

[10] Sánchez-Martín, P., López de Haro, S., Fernández-Caro, J. and J. de la Hoz-Ardiz, "Assessment on scheduling coal power station maintenance", en *Probabilistic safety assessment and management*. Editores Cornelia Spitzer, Ulrich Schmocker, Vinh N. Dang. Ed. Springer. Berlin, Alemania, 2004

[11] Cassady, C.R.; Kutanoglu, E.; , "Integrating preventive maintenance planning and production scheduling for a single machine," *IEEE Transactions on Reliability*, vol.54, no.2, pp. 304- 309, June 2005