Self Unit Commitment of Combined-Cycle Units with Real Operational Constraints

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This paper highlights the importance of modeling correctly the operational constraints of Combined-Cycle Gas Turbines in a unit-commitment-type framework. In practise in Colombia, when given an initial dispatch by the Independent System Operator, Combined-Cycle Gas Turbine plants are operated according to the results of a heuristic simulation code. Such heuristics omit technical operating constraints such as: hot, warm or cold startup ramps; minimum hours required of gas turbine to start a steam turbine; relation between dispatched number of steam and gas turbines, load distribution between gas turbines, additional fires etc. Most unit commitment models in the literature just represent standard technical constraints like startup, shut down, up/down ramps and some of them even additional fires. However, they disregard other real-life CCGT operating constraints that are considered in this work. These constraints are important because they ensure avoiding equipment damage that can potentially put the Combined-Cycle Gas Turbine out of service, and ultimately lead to lower operating costs.

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Abstract: This paper highlights the importance of modeling correctly the operational constraints of Combined-Cycle Gas Turbines in a unit-commitment-type framework. In practise in Colombia, when given an initial dispatch by the Independent System Operator, Combined-Cycle Gas Turbine plants are operated according to the results of a heuristic simulation code. Such heuristics omit technical operating constraints such as: hot, warm or cold startup ramps; minimum hours required of gas turbine to start a steam turbine; relation between dispatched number of steam and gas turbines, load distribution between gas turbines, additional fires etc. Most unit commitment models in the literature just represent standard technical constraints like startup, shut down, up/down ramps and some of them even additional fires. However, they disregard other real-life CCGT operating constraints that are considered in this work. These constraints are important because they ensure avoiding equipment damage that can potentially put the Combined-Cycle Gas Turbine out of service, and ultimately lead to lower operating costs.

Nomenclature

A. Indices and Sets

$t \in \tau$ Hourly periods, running from 1 to *T* hours.
$c \in NC$ Combustion turbine, running from 1 to *NC* turbines.
$s \in NS$ Steam turbine, running from 1 to *NS* turbines.

B. Parameters

PCC Production cost a gas turbine unit in ($/MWh)
PBC Cost of non-served energy ($/MWh)
$\overline{G_c}$ Maximum power output of unit c (MW)
$\underline{G_c}$ Minimum power output of unit c (MW)
$\overline{G_s}$ Maximum power output of unit s (MW)
$\underline{G_s}$ Minimum power output of unit s (MW)
$\overline{GCC}$ Maximum power output of combined-cycle unit (MW)
$\underline{GCC}$ Minimum power output of combined-cycle unit (MW)
MUG Minimum number required of combustion turbine to dispatch one steam turbine
STF Steam factor relating the amount of energy produced by the steam turbine for each MWh produced by the combustion turbines
L_t Required load for the period *t* (MW)
MH Number of minutes in one hour
$te1/2/3$ Shutdown time in hours to hot/warm/cold startup
$nSe1/2/3$ Number of energy hourly blocks for hot/warm/cold startup condition
$Se1/2/3$ Energy hourly blocks for hot/warm/cold startup condition (MW)
nSr Number of shutdown energy hourly blocks
Sr Energy hourly blocks for shutdown condition (MW)
$toff$ Shutdown hours of the combined-cycle unit at the first period
ton Online hours of the combined-cycle unit at the first period
$Gt0_c$ Power output at the last period of the last day of combustion turbine c (MW)
$OnOff_c$ Status condition at the first period of the day of combustion turbine c (MW)
UT Minimum up time in hours
DT Minimum down time in hours
PAF Maximum power output of additional fire for each combustion turbine (MW)
TC_c Up ramp rate of the combustion turbine c (MW/min)
TD_c Down ramp rate of the combustion turbine c (MW/min)
RU Maximum ramp-up rate (MW/h)
RD Maximum ramp-down rate (MW/h)
CSC Startup cost of the combustion turbine c ($)
DSC Delta steam turbine cost ($)
$AUXCC$ Auxiliary consumption of the combined-cycle plant (MW)
$AUXGT$ Auxiliary consumption of combustion turbine unit (MW)
$AUXST$ Auxiliary consumption of steam turbine unit (MW)
KMH Minimum hours required online in gas turbines for a steam turbine startup

C. Variables

1) Positive and Continuous Variables:

gcc_t Power output in hour t of the combined-cycle unit, production above the minimum power output $\underline{GCC}$ (MW)
g_{tc} Power output in hour t of the combustion turbine c, production above the minimum power output $\underline{G_c}$ (MW)
g_{ts} Power output in hour t of the steam turbine s, production above the minimum power output $\underline{G_s}$ (MW)
dde_t Startup power output ramp at hour t of the combined-cycle unit, production below the minimum power output $\underline{GCC}$ (MW)
nde_t Shutdown power output ramp at hour t of the combined-cycle unit, production below the minimum power output $\underline{GCC}$ (MW)
$gcct_t$ Total power output in hour t of the combined-cycle unit which is the sum of gcc_t, dde_t and nde_t. (MW)
$gvsc_t$ Power related with the wasted steam in hour t (MW)
vh_t Slack variable related with non served power by the combustion turbines when the combined-cycle unit is not coupled in hour t (MW)
$auxg_t$ Combined-cycle auxiliary consumption in hour t (MW)
gr_t Non-served energy by combined-cycle in hour t (MW)
af_{tc} Power output in hour t of the additional fire of the combustion turbine c (MW)
e_t Excess supplied power used during SU/SD and ramping (MW)

2) Binary Variables:

u_{tc} Commitment status of the combustion turbine c in hour t
u_{ts} Commitment status of the steam turbine s in hour t
y_{tc} Startup status of the combustion turbine c in hour t
z_{tc} Shutdown status of the combustion turbine c in hour t
cc_t Commitment status of the combined-cycle unit in hour t
ycc_{tc} Startup status of the combined-cycle unit in hour t
zcc_{tc} Shutdown status of the combined-cycle unit in hour t

1 Introduction

1.1 Motivation

Power plant operators and Independent System Operators (ISO) need to simulate different operating conditions for specific scenarios through mathematical models as mentioned in [1], [3] and [4] in order to ensure the power system security and reliability through those simulations. Combined cycle gas turbine (CCGT) plants, considered in the ISO simulations, are one of the most common power technologies in the world due to their high efficiency and the high level of flexibility to support the integration of renewable energy resources as presented in [9] and [13]. Hence, it is necessary to represent the operational elements of CCGTs in detail in a power system in order to simulate the correct output available in a specific period by the ISO to meet demand and avoid critical damages in these plants.

The Colombian power system has many different CCGT plants with different configurations and operating rules, highlighting the largest CCGT plant in the system, i.e., TEBSA, which is located in the north of the country and has 5 combustion turbines and 2 steam turbines (a 5x2 configuration). The actual power output depends on the thermal states of the combustion turbine units and the relationship with the steam turbines, that can only operate if the gas turbines are producing steam at the right temperature and pressure conditions. The TEBSA CCGT plant plays an important role to guarantee the reliability and security of the system. In practise, most of the existing CCGT plants in the Colombian power system do not employ a mathematical optimization model to decide the detailed operation given a dispatch. Moreover, the Colombian ISO does not dispose of a faithful technical representation of the corresponding CCGT plants. Therefore, it is important to represent the intricate operating conditions of a CCGT in an optimization model in order to improve the CCGT's performance and meet technical operating constraints such as minimum heat requirements for steam to prevent equipment failures (see Figure 1). Such real-life technical constraints are not commonly represented correctly with heuristic approximation models that are being used to operate the plant currently [19]. For example, when planning the operation of TEBSA, it is done always considering that the plant is in a hot startup condition; or, disregarding the minimum combustion units necessary to meet the minimum power output for steam turbines rule, causing equipment failures or unit commitment program deviation by the CCGT operator.

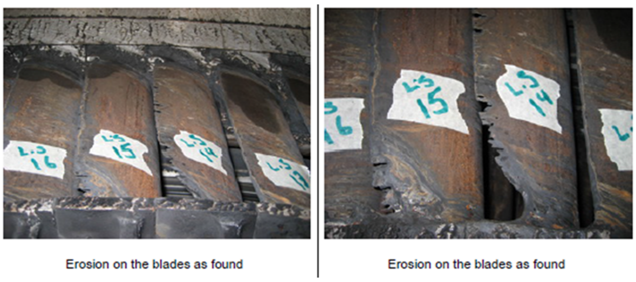

Fig. 1: Steam turbine equipment failures due to inadequate steam temperature and pressure conditions

Therefore, this paper proposes a type of self-unit commitment (SEUC) model formulated as a Mixed Integer Programming (MIP) problem to overcome these shortcomings and to represent the detailed and realistic operating conditions of a CCGT plant given a specific dispatch. The novelties of this model is twofold: first, we take into account the minimum hours required of gas turbine to start a steam turbine, to the best of our knowledge, have not been included in UC models in the literature; and second, the load distribution between gas turbines. Is important to highlight that our model does not treat the CCGT as a whole but explicitly represents each unit of the plant, gas and steam turbines separately. This is important as it allows the ISO carry out a unit commitment plan of these plants having a better accuracy of active and reactive power output to support grid constraints and attending the operational rules constraints of the CCGT, avoiding program deviations*. This model can also be implemented in a full unit commitment (UC) framework to dispatch CCGT plants in a general power system.

1.2 Literature Review

There are different ways of modeling CCGTs in the literature. First, there are approaches that represent individual elements of the CCGT separately by gas and steam turbine. These types of models are known as component models as considered in previous studies [1], [6], [10], [11], [12]. Second, the CCGT plant is modeled as a whole and is represented by configurations or modes as shown in [2] - [5] and [13] - [17]. In this work an individual representation is proposed but considering the constraints of a given configuration of the CCGT, as maximum and minimum power output, startup and shutdown ramps and the number of gas and steam units available.

As mentioned, modelling CCGTs can be done by configurations or by individual representations of the gas and steam turbines. In [2], [13] and [14] the authors propose a MIP Tight and Compact mathematical formulation to solve a UC problem taking in account the operation of CCGTs by operation modes or edge-bases model. The model considers ramping constraints between operation modes and minimum up/down time constraints for each configuration taking into account the startup/shutdown cost related with the transition between modes, achieving an improvement in the computational performance due to the tightness of the constraints. On the other hand, [7] proposes a Self Unit Commitment (SEUC) model based on CCGTs operation modes for modeling the thermal fatigue caused when this plants are cycling when changing from one to another mode. These works cited above do not consider important operational constraints as minimum hours required of gas turbine to start a steam turbine, minimum numbers of gas turbines to operate steam turbines, additional fires or load distribution.

In [1] and [6] the authors propose a component-wise formulation of CCGTs and incorporate it into a UC problem. For each research work the relationship between gas and steam turbines is presented, where the power generated by the steam turbine (ST) depends on the power produced by the gas turbine. In [1] the author proposes a mathematical formulation that represents each component of the CCGT considered in a UC problem of the Colombian energy market. In this work the ramping constraints are represented per minute, abiding an hourly dispatch that the CCGT has to produce. Despite the fact that in [1] the author takes into account the minimum gas turbines needed to reach minimum steam turbine power output constraint, it does not include the minimum startup hours required for the gas turbines to produce the steam needed for the steam turbines in the right qualities. Also the author does not differentiate between a hot and cold startup for the steam turbines, that is considered an important constraint to avoid future failures of this units. Another important constraint is the load distribution between combustion turbines that is necessary to guarantee a steam production given to each

**Although we do not take into account the reactive power as an output, the active power outputs for each unit of the CCGT can be used in power system analysis software by the ISO, in which the capability curve of each unit at different voltage levels is modeled .*

steam turbine in the same conditions and prevent temperature deltas in these units produced when the load between the gas turbine are not the same. Secondly, [18] propose a configuration-component based hybrid model in order to capture the benefits from both type of models. Despite in this work is presented a hybrid model, is not exactly as [18] proposal, since in this work the CCGT is represented in a component-based model into the Colombian energy market framework policies, i.e., each plant (even CCGT units) have to bid just one configuration that is used by the ISO for the day ahead UC problem. In this order of ideas, once the configuration is defined, the component-based model proposed in this work take into account the limits related with that configuration, as maximum and minimum output capacity of the CCGT, maximum and minimum up/down ramps, the startup and shut down ramps and the numbers of GTs and STs of the CCGT unit.

Another component modeled in [1] and [18] and adopted in this paper are the additional fires, which are equipment that can increase the power output of the steam turbine without increasing the power output of the gas turbines, producing more steam with a direct combustion using the Heat Recovery Steam Generator (HRSG) of each gas turbine. Therefore, each additional fire is available if the associated HRSG is available and in turn each HRSG is available if the associated gas turbine is on.

1.3 Contributions

The main contributions of this paper are highlighted below:

- We propose SEUC to represent the hourly dispatch of a CCGT, taking into account the minimum up/down constraints time for each gas and steam unit individually; up and down ramp rates and the representation of the operation rules of steam turbines by a minimum number of gas turbines required to produce steam with the right qualities.
- In this model we consider the steam turbine startup subject to the thermal state of each unit, i.e., hot or cold and the the minimum hours required of gas turbine to start a steam turbine.
- Another contribution is related with the load distribution, where we propose a mathematical constraint to guarantee an equal distribution of the load when more than one gas turbine is generating in combined cycle state with a steam turbine.

2 MATHEMATICAL FORMULATION

In this section we present the novel mathematical formulation of the self unit commitment (SEUC) model of a CCGT.

2.1 Objective Function

The self unit commitment of the CCGT presented in this paper aims at minimizing the total operational cost of the CCGT given by the following components: (i) the cost of the CCGT in each hourly period; (ii) the cost of non-served energy, the energy related with the wasted steam and the auxiliary consumption; (iii) the startup costs of the combustion turbines; and (iv) the costs related with the additional fire, as follows:

$$\text{Min} \tag{1}$$

$$\sum_{t\in\tau}\sum_{c\in NC} PCC\cdot(g_{tc}+af_{tc})+\sum_{t\in\tau} PBC\cdot(gr_t+f_t)+$$
$$\sum_{t\in\tau}\sum_{c\in NC} CSC\cdot y_{tc}+\sum_{t\in\tau}\sum_{s\in NS} CSS\cdot y_{ts}+$$
$$\sum_{t\in\tau}\sum_{c\in NC}\sum_{cc\neq c\in NC} DSC\cdot vhdr_{t,c,cc}+\sum_{t\in\tau} CCC\cdot cc_t$$

2.2 CCGT operational constraints

This section describes the constraints related with energy balance and limits operational constraints for each unit and the CCGT.

2.2.1 Energy balance constraints:

$$gcct_t + gr_t - e_t = L_t \quad \forall t \tag{2}$$
$$0 \le e_t \le \overline{GCC} \quad \forall t \tag{3}$$

2.2.2 Combustion turbines operational limits:

$$\underline{G_c}\cdot u_{tc} \le g_{tc} \le \overline{G_c}\cdot u_{tc} \quad \forall t,c \tag{4}$$

2.2.3 Steam turbines operational limits:

$$\underline{G_s}\cdot(u_{ts}-y_{ts}) \le g_{ts} \le \overline{G_s}\cdot u_{ts} \quad \forall t,s \tag{5}$$

2.2.4 Combined-Cycle operational and commitment limits:

$$\underline{GCC}\cdot cc_t \le gcc_t \le \overline{GCC}\cdot cc_t \quad \forall t \tag{6}$$
$$cc_t - \sum_{s\in NS} u_{ts} \le 0 \quad \forall t \tag{7}$$
$$MUG\cdot cc_t - \sum_{c\in NC} u_{tc} \le 0 \quad \forall t \tag{8}$$
$$MUG\cdot u_{ts} \le \sum_{c\in NC} u_{tc} \quad \forall t,s \tag{9}$$
$$\sum_{s\in NS} u_{ts} \le \sum_{c\in NC} u_{tc} \quad \forall t \tag{10}$$
$$vh_t \le \underline{GCC}\cdot(1-cc_t) \quad \forall t \tag{11}$$

Constraints (7) to (10) represent the minimum number of combustion units necessary to have a coupled operation in combined cycle with steam turbines. Equation (10) does not allow to have more than one steam unit in line than combustion turbine units. Constraint (7) guarantees that only one steam unit will be dispatched if the plant is operating in combined cycle. And finally, constraints (8) and (9) guarantee that it will only be possible to have a combined cycle operation as long as the MUG number of combustion turbines are dispatched.

2.3 Constraints related with the Combined-Cycle operation

The following constraints represent the combined cycle operation associated with the coupled operation between combustion turbines and steam turbines.

2.3.1 CCGT Output Constraints:

$$gcc_t + vh_t = \sum_{c\in NC} g_{tc} + \sum_{s\in NS} g_{ts} - auxg_t \quad \forall t \tag{12}$$
$$gcct_t = gcc_t + dde_t + nde_t \quad \forall t \tag{13}$$

Equations (12) and (13) represent the total generation of the CCGT including the contribution of the combustion turbines, the steam turbines and subtracting the auxiliary energy consumption.

2.3.2 Steam-Combustion Coupling Operation Constraints:

$$\sum_{s\in NS} g_{ts} + gvsc_t = STF\cdot\sum_{c\in NC} g_{tc} + \sum_{c\in NC} af_{ts} \quad \forall t \tag{14}$$
$$af_{ts} \le PAF\cdot u_{tc} \quad \forall t,s \tag{15}$$
$$gvsc_{ts} \le \sum_{s\in NS}\overline{G_s}\cdot(u_{ts}+\overline{u_{ts}}) \quad \forall t \tag{16}$$
$$\sum_{s\in NS} g_{ts} \ge \overline{u_{ts}}\cdot\sum_{s\in NS}\overline{G_s} \quad \forall t \tag{17}$$

Equation (14) relates the energy produced by steam turbines as a function of the energy produced by combustion turbines. The STF relates the amount of energy produced for each MW produced by the combustion turbine. Also the energy produced by the steam turbines depend on the status of the additional fire af, which depends on the status of the combustion turbine, i.e. there are additional fires for each combustion turbine that can increase the output of the steam turbine unit until the maximum capacity of the unit. Each additional fire is represented by the equation (15).

In the same equation (14), the steam waste $gvsc_t$ is represented, which represents the amount of energy that is no longer delivered when it is not possible to take advantage of all the steam generated by the combustion turbines. This variable is defined by equation (16) and its quantity is limited by the maximum capacity that a steam turbine can deliver, as long as it is online.

2.3.3 *CCGT auxiliary consumption:*

$$auxg_t = AUXCC \cdot cc_t + AUXGT \cdot \sum_{c \in NC} u_{tc} + AUXST \cdot \sum_{s \in NS} u_{ts} \quad \forall t \tag{18}$$

Equation (18) represents the maximum and minimum limits of auxiliary consumption, both for steam turbines and for combustion turbines.

2.4 *Minimum up and down time constraints:*

The following constraints represent the minimum up and down time for each combustion and steam unit and CCGT.

2.4.1 *Combustion turbines minimum up and down time constraints:*

$$y_{t,c/s/cc} - z_{t,c/s/cc} = u_{t,c/s/cc} - u_{t-1,c/s/cc} \quad \forall t, c, s, cc \tag{19}$$

For the first period, variable u_{t-1} has to be replaced in constraint (19) by $OnOff$, considering the initial conditions of the combustion and steam turbines.

2.4.2 *Startup and shutdown mutually exclusive variables:*

$$y_{t,c/s/cc} + z_{t,c/s/cc} \leq 1 \quad \forall t, c, s, cc \tag{20}$$

2.4.3 *Status to reach the minimum up/down time:*

$$u_{t,c/s/cc} = OnOff \quad t = 1; \forall c, s, cc, \quad Lupmin + Ldownmin > t \tag{21}$$

2.4.4 *Minimum up time condition constraint:*

$$u_{t,c/s/cc} \geq \sum_{c,s \in N} y_{i,c/s/cc} \quad \forall t, c, s, cc \quad i \geq t - UT + CountOn \cdot max(0, 2-i) + 1, \quad i \leq t \tag{22}$$

$$1 - u_{t,c/s/cc} \geq \sum_{i \in \tau} y_{i,/c/s/cc} \quad \forall t, c, s, cc, \quad i \geq t, \quad i \geq (t - DT + 1) \tag{23}$$

2.5 *Ramps constraints:*

The following equations represent ramping constraints for the CCGT. Constraints (26) to (31) represent the startup and shutdown constraints proposed by [8].

2.5.1 *Operating Ramp Constraints:*

constraint (24) represent the ramping constraint between two consecutive hours.

$$-RD \leq gcct_t - gcct_{t-1} \leq RU \quad \forall t \tag{24}$$

2.5.2 *Hot startup ramp constraints:*

$$dde_t = \sum_{i=1}^{nSe1} Se1 \cdot y_{t+i} + \sum_{j=1}^{nSe2} Se2 \cdot y_{t+j} \quad \forall\ t + toff \leq te1 \tag{25}$$

$$y_t = 0 \quad toff \leq te1; t \leq nSe1 \tag{26}$$

2.5.3 *Warm startup ramp constraints:*

$$dde_t = \sum_{i=1}^{nSe1} Se1 \cdot y_{t+i} + \sum_{j=1}^{nSe2} Se2 \cdot y_{t+j} + \sum_{k=1}^{nSe3} Se3 \cdot y_{t+k} \quad \forall te1 < t + toff \leq te2 \tag{27}$$

$$y_t = 0 \quad \forall te1 < t + toff \leq te2; t \leq nSe2 \tag{28}$$

2.5.4 *Cold startup ramp constraints:*

$$dde_t = \sum_{j=1}^{nSe2} Se2 \cdot y_{t+j} + \sum_{k=1}^{nSe3} Se3 \cdot y_{t+k} \forall\ t + toff > te2 \tag{29}$$

$$y_t = 0 \ \forall\ toff > te2; t \leq nSe3 \tag{30}$$

2.5.5 *Shutdown ramp constraint:*

$$nde_t = \sum_{i=1}^{nSr} Sr_i \cdot zcct - i + 1 \quad \forall t \quad t \leq i \tag{31}$$

2.6 *Steam turbine startup:*

Constraint (32) defines two binary variables that allow to differentiate among cold (C) and hot (H) start of the steam turbine. Constraint (33) enforces that unless your steam turbine has been dispatched within the last 9 hours, you cannot do a hot start. Constraint (34) states that unless at least one of your combustion turbines have been connected the previous hour, you cannot do a hot start for your steam turbine. Constraint (36) introduces an auxiliary binary variable $b_{t,c}$, which will be 1 if your gas turbine has been connected during the least KMH hours, and 0 otherwise. Constraint (37) models that unless at least one of your gas turbines has been connected for the last 6 hours, you cannot do a cold start (or any startup for that matter). Finally, constraint (38) defines the new variables as binary.

$$y_{t,s} = y^C_{t,s} + y^H_{t,s} \quad \forall t, s \tag{32}$$

$$y^H_{t,s} \leq AA_{t,s} + \sum_{j=t-8}^{t-1} u_{j,s} \quad \forall t, s \tag{33}$$

$$y^H_{t,s} \leq \sum_c u_{t-1,c} \quad \forall t > 1, s \tag{34}$$

$$y^H_{t,s} \leq \sum_c onoff^{t_0}_c \quad \forall t = 1, s \tag{35}$$

$$BB_{t,c} + \sum_{j=t-2}^{t} u_{j,c} \geq KMH \cdot b_{t,c} \quad \forall t, c \tag{36}$$

$$y^C_{t,s} \leq \sum_c b_{t,c} \quad \forall t, c \tag{37}$$

$$y_{t,s}, y^C_{t,s}, y^H_{t,s}, b_{t,c} \in \{0, 1\} \quad \forall t, s, c \tag{38}$$

Steam turbine startup depends on the temperature of the unit in each period, where the temperature depends on how many hours the unit has been off. Once defined the number of hours in which the steam turbine is in cold state KST, it is necessary to define the number of hours that must have elapsed since the first gas turbine started * in order too guarantee the temperature needed for the steam turbine startup. The following constraints represent how the steam turbine should be started taking in account the state of the unit (cold or hot startup) explained before.

Another important aspect that needs to be considered for the steam turbine startup is the power output in the first time period, taking in account that for cold startup the power output should be a low load in order to avoid thermo-mechanical damages. The following constraints represent the power output of the steam turbine unit at the startup taking into account the type of start up, i.e. cold startup or hot startup:

$$g_{t,s} \leq GSTC \cdot y^C_{t,s} + GSTH \cdot y^H_{t,s} + \overline{G}_s \cdot (u_{t,s} - y_{t,s}) \quad \forall t, s \tag{39}$$

$$g_{t,s} \geq GSTC \cdot y^C_{t,s} + GSTH \cdot y^H_{t,s} \quad \forall t, s \tag{40}$$

2.7 Load distribution between combustion turbines constrain

2.7.1 Load distribution constraint: The following set of constraints capture the fact that CCGT operators strive to achieve a similar power output among the gas turbines that operate above their technical minimum. To that purpose we introduce the following constraints, which establish the absolute value of the difference in power output between two different gas turbines.

$$gcdr_{tc} - gcdr_{tcc} \leq \Delta_{t,c,cc} \quad \forall t, cc \neq c \tag{41}$$

$$\Delta_{t,c,cc} \geq 0 \quad \forall t, cc \neq c \tag{42}$$

Note that this difference $gcdr_{tc} - gcdr_{tcc}$ could be either positive or negative; however if $gcdr_{tc} - gcdr_{tcc}$ is negative, then $gcdr_{tcc} - gcdr_{tc}$ will be positive, yielding a positive lower bound for $\Delta_{t,cc,c}$. We leave one of the sums on purpose in order to not count the power deviation twice.

This difference in power output could be penalized in the objective function value; however, we can only take it into account if both gas turbines are actually above the technical minimum†. Hence we define binary variable $\delta_{t,c,cc}$, which takes value 1 if both gas turbines are above the technical minimum:

$$u_{tc} + u_{tcc} \leq 1 + \delta_{t,c,cc} \quad \forall t, cc \neq c \tag{43}$$

$$\Delta_{t,c,cc} - \overline{GCC} \cdot (1 - \delta_{t,c,cc}) \leq vhdr_{t,c,cc} \quad \forall t, cc \neq c \tag{44}$$

$$\delta_{t,c,cc} \in \{0, 1\} \quad \forall t, cc \neq c \tag{45}$$

$$\overline{GCC} \geq vhdr_{t,c,cc} \geq 0 \quad \forall t, cc \neq c \tag{46}$$

We define KGC for a cold startup and KGH for a hot startup.

†*It should not be taken into account when one gas turbine is off, and the other one is above the technical minimum.*

Table 1 CCGT Parameters

Variable	Value	Unit
$\overline{GCC}$	800	MW
$\underline{GCC}$	210	MW
PAF	15	MW
$AUXCC$	5	MW
$AUXGT$	0.45	MW
$AUXST$	2	MW
RD/RU	335	MWh
PCC	120	$\$/MWh$
PBC	500	$\$/MWh$
CSC	15000	$
MUG	2	p.u.
STF	0.613	p.u.
NC	5	p.u.
NS	2	p.u.
$t1$	t <= 16	Hours
$t2$	16 < t <= 30	Hours
$t3$	t > 30	Hours
KGC	3	Hours

Table 2 Startup and Shutdown ramps

Hour	H-Startup	W-Startup	C-Startup	Shutdown
H1	50	50	50	210
H2	100	100	100	100
H3	150	100	100	50
H4	210	150	100	0
H5	0	210	150	0
H6	0	0	210	0

3 NUMERICAL RESULTS

We study two different numerical cases: I) One case where a CCGT is online at the end of the previous day of the analysis day, then stops at beginning of the analyzed day and starts up again for the end of the analyzed day reaching the maximum output capacity; II) The other case simulates a dispatch where the CCGT is off at the beginning of the analyzed day and starts up to reach the maximum output capacity at the end of the analyzed day.

Table 1 contains input parameters that are going to be the same for both cases. Also, the startup and shutdown ramps are related in Table 2.

For the cases simulated in this work, NC combustion turbines and NS steam turbines have the same characteristics. Tables 3 and 4 show the characteristics of the combustion and steam turbine units.

3.1 Case I

Table 5 contains the initial condition information of the CCGT.

Figure 2 illustrates the results with the initial conditions considered for this case. From Figure 2 we observe that the actual CCGT

Table 3 Combustion Turbines

Variable	Value	Units
$\overline{G}$	100	MW
$\underline{G}$	50	MW
TC	5	MW/min
TD	5	MW/min

Table 4 Steam Turbines

Variable	Value	Units
$\overline{G}$	170	MW
$\underline{G}$	80	MW
$GSTH$	80	MW
$GSTC$	30	MW

Table 5 Initial conditions of units - Case I

Unit	ton/off (Hours)	$Gt0$ (MW)
GT1	8	67
GT2	0	0
GT3	0	0
GT4	0	0
GT5	8	67
ST1	8	83
ST2	0	0

operation (discontinuous red line) cannot follow the initial dispatch L due to the ramping constraints. First, the model decides to do a shutdown ramp in period 5, keeping the CCGT offline until period 15, where the model decides to do hot startup ramp. It is important to highlight that the model decides to ramp up in period 19 to reach the maximum capacity of the CCGT from period 20 to 22 due to the constraint (24).

Following a dispatch determined by the heuristic model (yellow line) will lead to deviations with respect to the scheduled production due to the incorrect representation of the technical operation rules of the CCGT. Due to technical limitations, such as the relation between number of operating hours of gas turbines and steam turbines etc., in reality the CCGT is simply not able to precisely follow the dispatch determined by the heuristic. The arising deviations (between heuristic dispatch and reality) are penalized by the system operator if the absolute difference between the hourly dispatch (heuristic) and the actual hourly generation is greater than five percent, as established in [20]. Assuming that the actual generation is the result of the model proposed in this work (discontinuous red line) and the cost of the penalty is PCC as established in [20], then the generator will be charged with a total penalty of \$ 60,957 for the Case I. Note that is is a daily penalty. So, every day in which a scheduled start-up like the one in Figure **??** happens, the CCGT faces a penalty of \$ 60,957, which is non-negligible. Moreover, the arising deviations do not only cause a penalty for CCGT generators, but also force the system operator to tap into reserves (at an additional cost) in order make up for imbalances. Both effects - the penalty and the activation of reserves - can be avoided if a more realistic model, as the one proposed in this paper, is employed used to decide dispatch.

Figure 3 shows the dispatch by unit and the auxiliary consumption. It can be seen that the model decides to keep online units GT1, GT5 and ST1 in order to meet the initial required dispatch. Regarding the start-up variable, the model decides that the generation plant turns on units GT3,GT5 and GT11. The startup of the ST2 unit is a cold startup, requiring at least 3 hours of generation combustion gas units, as can be seen in Figure 3. To reach the maximum capacity in periods 20 to 22 the model decides to dispatch all the units, using the additional fires to deliver all the required energy by the steam turbines. Finally, we want to add that the heuristic simulation model does not treat each unit individually, i.e., it does not show what happens for each gas and steam turbine. The heuristic only describes the output of the CCGT as a whole - another advantage of the proposed SEUC optimization model.

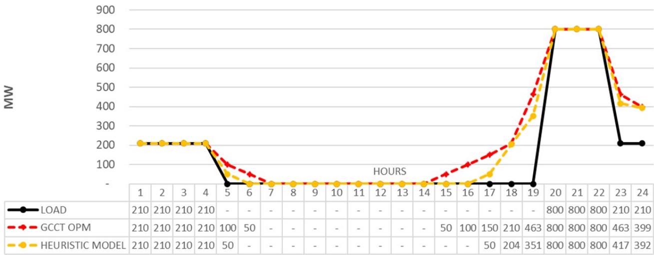

Fig. 2: CCGT power output vs. initial load for case I.

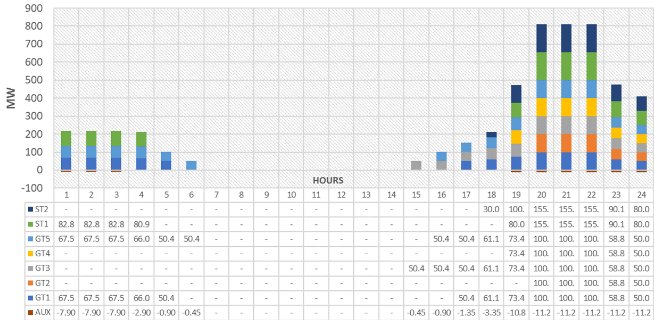

Fig. 3: Power output by unit for case I.

Table 6 Initial conditions of units - Case II

Unit	ton/off (Hours)	$Gt0$ (MW)
GT1	8	0
GT2	8	0
GT3	8	0
GT4	8	0
GT5	8	0
ST1	8	0
ST2	8	0

3.2 Case II

For this case, all the units start offline as an initial condition, as can be seen in Table 6.

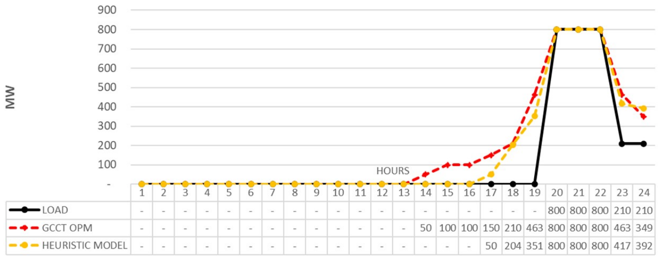

Fig. 4: CCGT power output vs. initial load for case II.

Figure 4 illustrates the results considering the initial conditions of the second case. It can be observed that to reach the initial dispatch L, a warm startup from periods 14 to 18 is required. Similar to case I, in this case here an increased ramp is necessary in period 19 to deliver the maximum capacity in periods 20 to 22. In contrast, the heuristic model makes a hot startup, not considering the state of the units before the required dispatch. This issue could generate serious problems in the medium and long term, as showed in Figure 1, where equipment damages generate unavailability of the plant thereby impacting the reliability of the power system.

Similar to case I, we calculate the arising penalties for the CCGT generator due to the arising deviations between the scheduled (heuristic) and the actual CCGT operation. In case II, these daily penalties are equal to \$ 66,093 when applying the same steps applied in the Case I. Depending on the number of corresponding start-ups per year, the arising penalties can have a significant negative effect on power plant profits, as well as system operation.

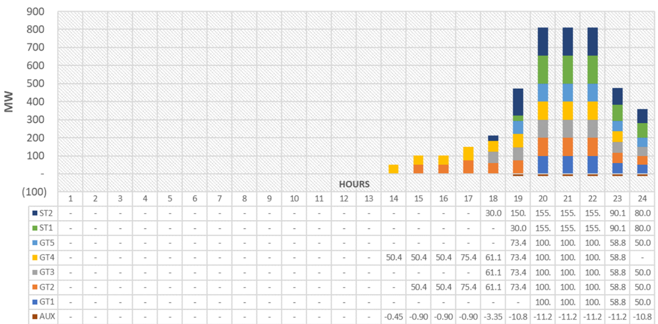

Fig. 5: Power output by unit for case II.

From Figure 5 it can be seen that the startup ramp is met with units GT2, GT3 and GT4, starting ST2 in a cold start mode in period 18. To reach maximum capacity of the CCGT all the units are delivering the maximum output and using 1 additional fire in 4.75 MW.

4 CONCLUSIONS

In this paper we propose a self-unit commitment model to optimize the dispatch of a CCGT with real operational constraints. This approach seeks to improve upon heuristic models in use currently by CCGT operators in the Colombian electric power system. We highlight the importance for ISOs and generation companies to employ precise tools, as the model proposed in this paper, when planning operating decisions, as they can avoid economic penalties for CCGT operators as well as deviations from scheduled output for the ISO.

Apart from other standard constraints in the literature, we propose an original formulation for individual gas and steam turbine units that guarantee specific characteristics of the steam. Those characteristics, which are actually in place in large CCGTs, are necessary to minimize the impact of thermo-mechanical fatigue produced by the energy output changes required by the system operator. Employing a realistic optimization model helps to increase the useful time of the CCGT units and the reliability of the CCGT, minimizing future failures and avoiding penalties due to deviations to the program, once the output of the proposed model in this work can be followed by the CCGT in real time. We also propose a novel operating constraint that allows for an even load distribution among individual gas turbines - a constraint that is being imposed in real-life CCGTs.

In future research we want to extend this work from a self- to a full Unit-Commitment, considering all power plants of the system. Such a model would help the ISO in order to improve the solution of the dispatch in the Colombian power system, where CCGT plants play an important role.

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