STEAM AND POWER OPTIMIZATION IN A PETROCHEMICAL INDUSTRY

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Abstract: The rational use of utilities (electric energy, steam, and water) represents nowadays the great challenge to assure the competitiveness and sustainability of industries. The proposed work presents the minimization of the cost of steam and power generation in a petrochemical company, which has production of electric energy and steam by co-generation system. In this case, there is a balance to achieve between work and heat supply and this cannot be readily defined by heuristics or localized control loops. The application of an optimization model is proposed based on needs of energy demands, and readily exposing the scenery that minimizes the power and high pressure steam level production. It was observed a potential of economy of 46 t/h in the generation of steam in boilers and could be achieved a reduction of 6 MW of electric power consumption.

Keywords: Steam, Power, Optimization, Turbines, Mixed Integer Programming, Utilities.

1. INTRODUCTION

The optimization of utility system has been explored regarding conceptual graphic tools that allows an steam network analysis and offer a better understanding of the interactions and could accelerate the application of an algorithm method (Strouvalis et al., 1998); aiding the decision of when is convenient to a factory to generate energy with an existent co-generation system or buy outer energy and heat, using MILP routine (Bojic & Stojanovic, 1998); helping the management of energy in a multi-period basis regarding a three/four level steam network; handling annual budging planning, investment decisions, electricity contract optimization, shutdown maintenance scheduling and fuel/water balance problems in a petrochemical plant with a site-model (Hirata et al., 2004); achieving benefits from an complex refinery co-generation system avoiding loss of energy in letdown valves and helping energy management problems basically using a solver tool from a common commercial spreadsheet (Milosevic & Ponhöfer, 1997).

The proposed work presents the minimization of the steam and power generation in a petrochemical company, which has a production of electric energy and steam by co-generation system. In the case study, the steam network is composed by four levels of pressure that supply either thermal (heat exchangers), process (strippers) or power (pumps, compressors and electric energy) demands. The application of an optimization model is proposed in a way that based on the definition of needs of electric energy generation, process loads and steam heat or separation demands, it can readily expose the scenery that minimizes the power and high pressure steam level production.

2. MOTIVATION AND VIABILITY

A petrochemical industry and its associated second generation industries in a petrochemical site consume steam in various areas of their productive processes. These applications can be related to machine drives, stream heating, or separation processes (strippers, etc). These applications also demands different temperature and pressure conditions, needing to operate with four steam pressure levels, such as Super High Pressure Steam (VS - 113 kgf/cm^{2}g and 525°C); High Pressure Steam (VA - 42 kgf/cm^{2}g and 400°C); Medium Pressure Steam (VM - 18 kgf/cm^{2}g and 315°C) Low Pressure Steam (VB - 4.5 kgf/cm^{2}g and 225°C). In the case study of this work, the petrochemical industry generates VS in the Process Unities furnaces (70% in mass) and in the Utility

Unity Boilers (30% in mass). Power is produced by two steam turbo generators and a heavy duty gas turbine – power can also be purchased from the off-site supplier. The normal production of VS is about 1150 t/h and the other levels of steam are produced by the extraction of turbines that generate work with the feed of VS and also by pressure letdown valves with desuperheater systems to complement the needs of steam in the headers. The pressures in the VA and VM headers are controlled by acting in the relation of extracted and exhausted of the machines or by letdown valves, and this control does not necessarily generate optimized scenery.

The optimization means the minimization of cost of energy, which is defined here as the sum of cost of VS produced in the auxiliary boilers, cost of power produced or imported and cost of using letdown valves. Nevertheless, the optimization of a steam and power system in Rankine cycle with such dimension and complexity is not an easy problem, because of the several and different applications involved and the connections of the pressure levels (Milosevic & Ponhöfer, 1997; Eastwood & Bealing, 2003). The potentiality in optimization is apparently huge, due to dimension of the scale of production in a petrochemical company (industry of intensive capital) and due to the continuous regime of production. Depending on the model, an annual economy of 2 to 5% of the energy bill could be achieved, besides the environmental advantages of reduction of emissions and withdrawn of superficial water (river).

For steam, the most basic procedure used to administer the commitment between the demands of several steam levels and the generation of VS is the relationship of extraction and condensation in the turbo-machines (huge process compressors and turbo-generators). This is done to increase the readiness of VA or VM (in agreement with each machine) by extraction or to use all the useful energy accomplishing work (by expanding VS to exhaust steam), without extracting smaller pressure steam whose low demand would cause need of steam relief. This extraction and condensation relationship is not free – there is a balance among these steam rates for a given load (electrical or mechanical) demanded by each machine. Within this relationship and regarding the operational and mechanical limits of the system and their equipments, however, it could be achieved an optimized distribution for each scenery of steam demands for production of energy (electric, thermal or work). Other optimization form is to alternate the operation among different drives from same equipments (for example, pumps with electric motor and steam turbines drives). The total optimization of the system, however, is not the target of the current control loop of the steam system and neither is possible of being achieved by the operation people in a practical and fast way. However, the application of a computational tool that can show the best scenery (smaller cost of generation of VS and power, avoiding use of pressure letdown valves and the use of relieves) is very useful and can be implemented from definitions of each scenery inputs. The implementation of this tool is proposed in this paper, with optimization of a real scenery as an example.

3. METHODOLOGY

The method involves two main tools: a Steam Model and an Optimization Model. The first is necessary to collect the non-freedom degrees, process dependant variables and operational definitions – this is made importing data from the DCS system and by some manual inputs. This tool was constructed in a commercial available spreadsheet, in the most rigorous form possible, in order to minimize balance errors. Even if some steam measurement is not available in DCS, it was tried to evaluate this value indirectly, with mass and/or thermal balances, suppliers' performance curves, project data, and so on. High precision balance is the key to minimize errors in the data to be exported to the optimization model. This data has to be in a form in which is included eventual errors, to guarantee that the steam balance is closed.

The second tool imports data from the Steam Model and performs the optimization from a constructed model of the steam and power system, equipments and network constraints. The results can be applied as a guideline for engineers and operators in day-to-day routines or as a project tool, showing best configurations for alternative selections.

The "real scenery" refers to a specific state of the steam network of the petrochemical industry, selected in a random way. In the case study, it refers to the situation of June 6 (2005), 06:00 PM, when it was being generated about 1205 t/h of VS and it was observed openings in VS/VA pressure letdown valves (42.5 t/h), VA/VM (50 t/h) and VM/VB (62.4 t/h). This situation can be observed in Figure 1. Some steam consumers do not possess flow measurement, and this is the case of most of the steam flows of VB level; nevertheless, there are in the company evaluations of these normal daily demands, and the application of these values leads to a balance that reflects reasonably the situation. So, using the available data, the steam material balance was defined. So, the modelling of the steam network is made respecting the thermal demands and the requested power of the machines in this day and time. The data exported from the model then will be submitted to an appropriate optimization routine and the result will be compared with the steam balance observed in real conditions, as a way of verifying the potential earnings.

4. DEFINITIONS

Generating equipments: these are the steam sources of the several existent steam levels and they can be variable or fixed. Some of these sources are also consumers of steam of higher level, generating by extraction a lower class steam. Fixed steam sources are related to equipment, in which the steam consumption is fixed and dependent on the process loads, but also produce steam of smaller pressure in the outlet. Then, according to Figure 1:

- VS is generated by the process furnaces (fixed generation) and auxiliary boilers (variable generation);
- VA can be generated by the turbines 12-TBC-01/21, 47-TG-01/02, 112-TBC-01 and by the letdown valves 10-PV-51 and 46-PV-12 - variable generation;
- VM can be generated by the turbines 14-TBC-01/21, 112-TBC-01 and for the letdown valves 10-PV-52 and 46-PV-13 (variable generation), as well as by other fixed generations (as example: 14-TBC-02/22, 48-B-01 B/C/D);
- VB can be generated by the letdown valves 10-PV-13, 110-PV-04 and 46-PV-14 (variable generation), as well as by other fixed generations (as example: 12-TBB-11, 114-TBC-01);

Consumers: these represent the several steam levels demands. These demands can be:

- Thermal: Heating of another fluid with steam. As the steam leaves the system definitively (as condensate or exhaust steam), these are not considered steam generator equipments;
- Process: Steam injection directly in other equipments (as strippers, ejectors). As the steam leaves the system definitively, these consumers are not steam generators equipments;
- Power: the power consumers can also be steam generator equipments, when extracted steam is produced.

Letdown Pressure Valves: these are control valves that, allied with desuperheater systems, have the function of adjust the pressure and temperature of some steam level, sending excesses to the lower level or supplying the next lower level in order to increase its pressure. The use of letdowns reduces the efficiency of the system and should be avoided.

Relief Valves: these are existent control valves in the levels of VS and VB that are used to limit the maximum pressure of these headers, discharging steam to atmosphere.

External Clients: these are all the others industries that surround the petrochemical company and consume utilities (in this case, steam) produced in the company. External clients are considered fixed consumers – the steam is process dependant and the steam leaves the company system definitively.

Table 1 presents the syntax of the abovementioned groups.

Variable Class	Description
VS	Super High Pressure Steam Flow (t/h)
VA	High Pressure Steam Flow (t/h)
VM	Medium Pressure Steam Flow (t/h)
VB	Low Pressure Steam Flow (t/h)
V	Steam Flow (t/h)
CV	Vacuum Steam Flow (t/h)
CM	Medium Pressure Steam Condensate Flow (t/h)
CB	Low Pressure Steam Condensate Flow (t/h)
PO	Power (MW)
AD	Desuperheating Water (steam temperature control)
CO	Cost (R$)
z	Binary variable for switchable drivers

Indices	Equipments Groups Description
h	VS generators
i	VA generators
j	VM generators
k	VB generators
l	CV generators
o	VS power consumers
p	VA power consumers
q	VM power consumers
r	VB process & heat consumers and exports
t	VS relieves
u	VB relieves
oc	VS process & heat consumers and exports
pc	VA process & heat consumers and exports
qc	VM process & heat consumers and exports
ps	Power Sources (internal and external)
ms	Motor of Switchable drivers equipment
ts	Turbine of Switchable drivers equipment
ld	Letdown valves (VS/VA, VA/VM, VM/VB)

Table 1: Syntax definitions for the variables applied in the model optimization.

4. OPTIMIZATION MODEL FORMULATION

As mentioned before, the objective function to be minimized is cost of energy. This is defined in the form:

$$\text{Min}\left(\sum_{h=1}^{Nh} CO_h \times VS_h + \sum_{ps=1}^{Nps} CO_{ps} \times PO_{ps} + \sum_{ld=1}^{Nld} CO_{ld} \times V_{ld}\right)$$

The equalities constrains are defined by the steam header balances, turbines model equations and power balances.

- Material Balance in the Control Envelope (Company Steam Network):

$$\sum_{h=1}^{Nger} VS_h = \sum_{l=1}^{Nger} CV_l + \sum_{pc=1}^{Ncons} VA_{pc} + \sum_{qc=1}^{Ncons} VM_{qc} + \sum_{r=1}^{Ncons} VB_r + \sum_{oc=1}^{Ncons} VS_{oc} +$$
$$+ \sum_{t=1}^{Naliv} VS_t + \sum_{u=1}^{Naliv} VB_u$$

[VS Generations] = [Steam Condensations] + [steam exportation] + [steam injections in processes] + [losses] + [relieves]

- Material Balance in each Steam Header:

$$\sum_{h=1}^{Nger} VS_h = \sum_{o=1}^{Ncons} VS_o + \sum_{oc=1}^{Ncons} VS_{oc} + \sum_{t=1}^{Naliv} VM_t$$

$$\sum_{i=1}^{Nger} VA_i = \sum_{p=1}^{Ncons} VA_p + \sum_{pc=1}^{Ncons} VA_{pc}$$

$$\sum_{j=1}^{Nger} VM_j = \sum_{q=1}^{Ncons} VM_q + \sum_{qc=1}^{Ncons} VM_{qc}$$

$$\sum_{k=1}^{Nger} VB_k = \sum_{r=1}^{Ncons} VB_r + \sum_{u=1}^{Naliv} VB_u$$

- Material Balance and Performance Curve for Two-Stage Turbines. For a generic extraction-condensation turbine:

Material Balance:
$VS_{turbine} = VA_{turbine} + CV_{turbine}$

Performance Equation, for given rotation and power:
$VA_{turbine} = a.VS_{turbine} + b$

Each degree of freedom turbine was modeled from real data, defining the parameters 'a' and 'b'.

- Power Balance:

$$PO = \sum_{ps=1}^{Nps} PO_{ps} =$$

= [Process Dependant POWER] + [Switchable drivers motor POWER]

Two of the power sources (ps) available are turbine generators, which are also modeled to be optimized and the power variable is a second degree of freedom.

- Additional Material Balances: The optimization model also consider material balances in steam letdown valves and condensate flash drums.

- Inequality Constrains: Establish physical conditions and project or operation limits. This applies to turbines, valves and headers. For example, in generic turbine and VS/VA letdown valve:

$0 < VS_{turbine} < 195$
$5 < VS/VA_{-valve} < 310$

- Binary Variables: With only 1 or 0 value, this variable is used to permit selection between available drives for same equipment. Thus, it is possible to optimize the steam and power situation. The balances involved are:

a. Power consumed by motors of switchable drives equipment:

$$[\text{Switchable drivers motor POWER}] = \sum_{ms=1}^{Nms} z_{ms} PO_{ms}$$

b. Steam consumed by turbines of switchable drivers (SD) equipment:

$$[\text{VA/VB SD turbine}] = \sum_{ts_{p,k}=1}^{Nts_{p,k}} z_{ts_{p,k}} VA_{ts_{p,k}}$$

$$[\text{VA/VM SD turbine}] = \sum_{ts_{p,j}=1}^{Nts_{p,j}} z_{ts_{p,j}} VA_{ts_{p,j}}$$

$$[\text{VM/VB SD turbine}] = \sum_{ts_{q,k}=1}^{Nts_{q,k}} z_{ts_{q,k}} VM_{ts_{q,k}}$$

c. Demand of equipment that has switchable drivers: The number of these equipments that is operating is obtained from the Steam Model. Thus, the following condition must be attended:

$$[\text{Number of SD operating equip.}] = \sum_{ms=1}^{N_{ms}} z_{equip} + \sum_{ts=1}^{N_{ts}} z_{equip}$$

Analyzing the objective function, the following form can be observed:

$$f(x) = \sum_{i=1}^{r} c_i x_i$$

with $x_i \geq 0$; i=1,2,…,r
and,

$$\sum_{i=1}^{r} a_{ji} x_i + \sum_{k=1}^{s} b_{jk} y_k = b_j$$

with $y_k \in Y = \{0,1\}$; j=1,2,…,m ; k = 1,2,…,s
and,

$$\sum_{i=1}^{r} a_{ji} x_i \geq b_j \quad \text{with } j = m + 1,\dots,p$$

This is a Mixed Integer Linear Programming problem (MILP). Today there are a large amount of commercially available solvers for MILP methods. In this work, the software GAMS was applied for the Optimization Model. GAMS is an optimization platform that allows, through specific language, to formulate the problem and to solve it through the application of an optimization routine. In this problem, the solver OSL was used by applying the *branch and bound* method.

The solution for the studied scenery can be found summarized in Figure 2 and Table 2. As can be observed, savings of 46 t/h of VS can be achieved if the extraction / condensation ratio of the turbines (mainly the utilities turbogenerators) were better explored. In this case, the turbines consumption decreased, but the VA extraction increased, with decreasing in the condensate generation, leading to a more efficient condition regarding to the cycle. It was also achieved a decrease in the electric power consumption, due to the possibility of changing electric motors for steam turbines, in some pumps, compressors and fans.

The time is a relevant point if we should consider shift-to shift adjustments. In the actual stage of development of these tools, the models aren't completely automatic, since some information still should be manually inserted by people. It takes about twenty minutes to gather the additional information for the plant, input in the steam model, check the consistency by analyzing the steam headers balance, and convert the final set of date from spreadsheet format to GAMS input format. Finally, the execution time the optimization model registered was 0,015 seconds. Even without full automatic sequence, the process can be done in a work shift, with enough time to adjust the system.

It must be remembered that the formulation consider the same load for process compressors, but allow the model to select the best way to generate energy, given the price per MW in each power generator or offsite purchasing – in this case, the power load of the turbogenerators was decreased from 27 to 18 MW, due to the power consumption reduction and also due to an increase of purchasing offsite power. It also must be underlined that the optimized scenery leads to a condition where the use of letdowns was reduced to its minimum, except the VM/VB, which was reduced to 70% to its actual value.

It also must be stressed that this tool should only be applied to a steady state conditions. In practice, if there's any transient, the operators should wait for the control loops set the system to a stationary condition again. When there are no more oscillations in the system, so operators and engineers are encouraged to explore the system for a more optimized condition. There's no need to worry with transient conditions, since the steam network runs constant most part of the time. Nevertheless, to force optimization changes in a transient condition is a risky condition, reducing the steam supply reliability.

	Case	
Steam and Energy Rates	**Actual**	**Optimization**
VS Generation (t/h)	1207.6	1161.2
VS/VA letdown stations (t/h)	41.4	20.0
VA/VM letdown stations (t/h)	49.8	20.0
VM/VB letdown stations (t/h)	62.4	43.1
VB Relieves (t/h)	0.0	0.0
Power Demand (MW)	58.0	52.0
VA/VM turbines from changeable drives equipaments (t/h)	32.4	58.4
VA/VB turbines from changeable drives equipaments (t/h)	46.9	67.9
VM/VB turbines from changeable drives equipaments (t/h)	9.0	8.8
VS for two stages compressors and generators (t/h)	1091.8	1066.8
VA from two stages compressors and generators (t/h)	466.0	506.5

Table 2: Summary of main comparison parameters of actual and optimized cases for studied scenery (June 6th, 2005)

5. CONCLUSION

The approach for solving the optimization problem of a specific scenery shows that it's possible to improve earnings from a better adjust of the steam system, without any further investments. The steam model, which was one of the most challenging development tools in this work, was well succeeded in supplying the optimization model with rigorous precision collected data and it can be made with any chosen scenery. With simple sequence of steps, an engineer or operator can collect the data, and export these figures to the optimization model, which will immediately give the best way to operate the system. This can be implemented in day-to day or shift-to-shift conditions, as a tool to orient the personnel in a readily form.

Next step will be the development of a better interface between the steam model and the optimization model, in order to make the process of data collection and optimization run in a more automatic form.

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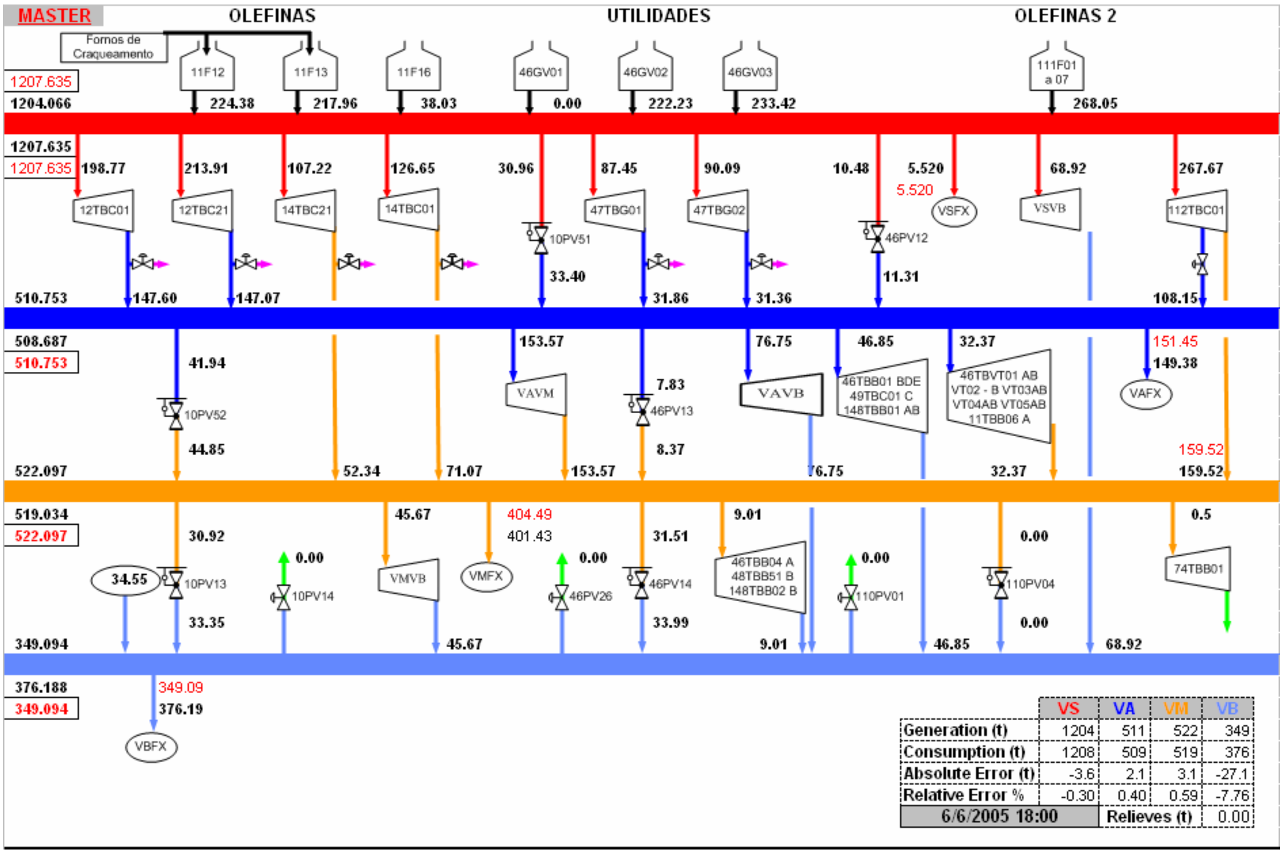

Fig. 1: Real scenery of 6/6/5. The red, blue, orange and cyan coloured levels indicate respectively the VS, VA, VM and VB headers and distribution lines. The consumers and generator are grouped with definition. It can be observed the increase of steam after each letdown valve because of the desuperheater water injection (temperature control). The oval VB "supplier" represents the steam generated from VM condensate flash vessels. The red figures refers to the corrected values in order to close the balance (distribution of errors), a necessary condition to implement optimization. It was observed and total electric power demand of 58 MW.

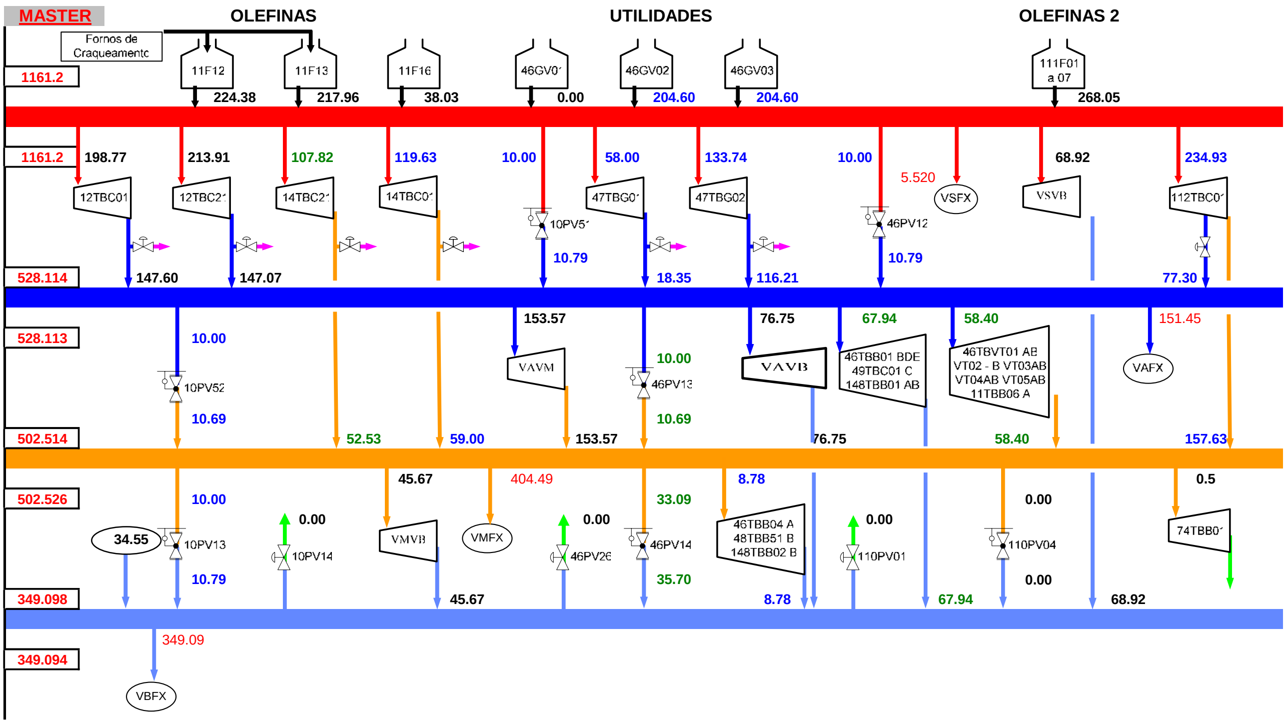

Fig. 2: Optimized scenario for 6/6/5 date conditions. The blue font represents the steam generation or consumption reduction and green are the steam increases. Along with these results, it was observed a reduction in the demanded power to 52 MW. This was possible exchanging electric motors for steam turbines.