Energize your Plant by Optimizing Power Generation

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Abstract

In this work, we present ARIANE, a powerful calculation tool for optimizing the operating parameters of complex power plants, which combine the production of steam, electricity and eventually hot water. This optimization approach has been applied to industrial cases and a specific example, proposed by Elf, is detailed in the last part of this article, to show the capability of ARIANE to deal with full-scale power plant problems. At first, in the introduction of the paper, we present the general context of combinated energies production plants and the corresponding global optimization problem. In the second part, we give a detailed presentation of the approach used in the ARIANE software, which consists in coupling a realistic simulation model with a strong non linear optimization algorithm (NLP). Use of ARIANE software, following a simple methodology to build the plant is presented in the third section of this paper.

Keywords

power plants; electricity and co-generation; vapor networks; energy; non linear optimization problem; energy production cost reducing;

1 Introduction : What is a combinated power plant ? What is the corresponding optimization problem ?

Nowadays, power plants are used to generate simultaneously steam, electric power and sometimes hot water. Production of these combinated energies is the key feature of these production units. We will describe the general behavior of such a plant in the four following sections :

1.1 Networks

Steam networks, each with its nominal pressure, and also hot water networks, are the basic elements of the power plants. Each network have to produce a required flow-rate to satisfy a global requirement of process units which are "the customers" of the power plant. Production equality constraints associated with these networks are the most important of the defined optimization problem. In fact, the most important constraint of power plant is to produce, at least, the required production of steam and hot water.

Inputs of a given network come either directly from boilers or from networks at higher pressure levels, via turbines (which allow the electricity production) or valves. In these inputs, we can add the possibility of having steam, at given flow-rate, temperature and pressure, coming back from the process units.

Output temperature of the network is calculated from the characteristics of the various inputs. Note that a de-superheating valve, associated with each steam network, allows to reduce the exported vapor temperature to a required level. On hot water networks, heat-exchangers may be defined to impose an export temperature.

Blow-downs may be defined on each network to export production excess in many cases, excess of production steam has to be minimized but sometimes (if electricity is very expensive for example), it leads to produce a large excess of steam, just with the aim to produce a maximum of internal electricity.

1.2 Equipment items

A power plant presents many different type of equipment items; most important are the following:

- boilers (thermal or electric) to generate vapor or hot water. These equipment items present technical constraints, especially on the output flow-rate (a minimum and a maximum flow-rate of production has to be defined). Fuel consumed by boilers are utilities, and are defined further on. Global performances of boilers are described by specific efficiencies.
- fuel turbines which can be associated to heat recovery steam generators (a kind of exchangers which produce steam by recovering heat contained in exhaust fumes of the fuel). Note that exhaust fumes of the fuel turbines may be superheated in "post-combustion" boilers before the exchange with steam generators. This set of equipment items generates electricity in the fuel turbines and steam at different pressure levels in the following heat recovery steam generators. Note that electricity produced in fuel turbines is either internal production or specific to a co-generation contract (with another difficulty associated to the contract which may be defined with a total or only a partial resale of the production). Many constraints of the global optimization problem are due to this set of equipment items (minima and maxima technical constraints on each element, and more, either an equality constraint due to the total co-generation contract, or a minimum electric production constraint due to the partial co-generation contract).
- a set of turbines (simple turbo-alternators, extraction back-pressure turbines, condensing turbines...) or valves (with or without de-superheating) for let-down transfer of vapor from a network to another. Turbines are defined with an electric efficiency and constraints which have to be taken into account when concerning flow-rate but also produced electricity. Some turbines may have particularities, like condensing turbines whose condensing water can either be recycled directly in a de-aerator, sent to a hot-water network, or simply be waste-water of the process.
- the de-aerator, which is the water provider for boilers and de-superheating equipment items. Demineralized water, condensates of different turbines and recycling steam are mixed in the de-aerator to give the required de-aerated water, at a given temperature. Two equality constraints are associated, a flow-rate constraint, to respect the total demand of its connected items, and a enthalpy constraint, to respect the imposed output temperature of the de-aerated water.

Those are the more commonly used elements of a power plant. The problem consists in driving them "as good as possible" to minimize the total cost of the required production.

1.3 Utilities

Different fuels, electricity and de-mineralized water are the utilities of the system, each with its own price.

Considered fuels (fuel oil, fuel gas, natural gas, hydrogen or any other fuel defined by the user) are described, at least by a combustion yield, to calculate the fuel consumption in the

different thermal boilers. Supplementary options are available to consider fuel delivery constraints or a total sulfur exhaust (due to fuel combustion) constraint for example.
Electric power defined here is the consumed one, by the power plant and the process units associated. This demand is decreased by the production of internal electricity. Co-generation contract, if defined, has its own price of resold electricity.

Demineralized water, consumed in the de-aerator(s), is characterized by a price and eventually a maximum delivery constraint.

1.4 Energy needs

Each process unit connected to the power plant impose :

- steam demand, at each pressure level;
- hot-water demand;
- electricity call;

The sum of all unit consigns determine the power plant energy needs. Note that the description of energy needs unit by unit allows study of each unit impact on the total energy cost.

In this general framework, the optimization problem is quite simple to express: "find the optimal operating conditions (minimize the total production cost), respecting the energy needs and all others plant constraints". This is simple to express, but more difficult to solve because the global model defined leads to a non linear optimization problem, with continuous variables only.

2 ARIANE approach : a simulator coupled with a NLP optimization tool

ARIANE software is based on a two steps methodology. In the first step, a realistic simulation model calculates the real energetic cost in given operating conditions and the values of all the previously described constraints (global constraints like sulfur rejection or fuel delivery but also each technical constraint of each equipment item). This simulator can be used alone to evaluate the accuracy of a given set of parameters. In the second step, a rigorous NLP algorithm, coupled with the simulator, allows to search optimal operations parameters, in order to minimize the global energetic cost. In this context, simulator becomes the evaluation procedure of the optimizer.

2.1 **Simulation basic principles**

Each element of the power plant is a simulation module, with its own model and constraints. Some other simulation modules have been developed, to deal with power plant global constraints, for example. Power plant simulation is then obtained by the sequential simulation (in an automatically determined order) of all the simulation modules.

2.2 Optimization tool : a Non Linear Programming algorithm (NLP) based on SQP technique

The optimization tool is a specific module, a Non Linear Programming algorithm, based on quadratic successive programmation techniques (SQP) is coupled with the simulator. It receives from the simulator the measure of all the constraints (equality constraints like production demand of each network or respect of total co-generation contract, inequality constraints like technical bounds of equipment items...). The research of the optimal point, from the economic point of view, is followed by actions on defined decision variables. Main decision variables are flow-rate on equipment items (flow-rate generated by each boiler or flow-rate transferred through each turbine or valve), and also co-generation parameters, extraction rate in extraction back pressure turbines... Objective function (total cost) and all sensibilities are evaluated by running the simulator.

2.3 Use of ARIANE - Applications especially in optimization field

Use of ARIANE software allows to define easily a specific power plant configuration. Constraints are simply described through an "easy to use" HMI and global simulation and optimization models are automatically generated. ARIANE allows then multiple possibilities of studies in design, but also in exploitation.

In design, optimization allows to test the accuracy of different configurations (is it profitable to take a co-generation system, and with which contract ? is it interesting, from an economic point of view, to invest in a new boiler or in a new turbine ?). It allows the complete design and to anticipate the production capacity of a new power plant. In fact, ARIANE is a valuable predicting tool for the design or the revamping of power plants.

In exploitation, it allows to find the minimum cost to satisfy energy needs. In case of demand variations, or in case of equipment item failure, it allows to quickly re-find the optimal point. In this way, ARIANE becomes a useful decision tool in exploitation.

3 Industrial example

It's not possible to describe a complete industrial example due to the prohibitive number of required data. We will simply relate to an optimization case, based on a Elf installation.

3.1 Description of the industrial case

The studied power plant consists in 8 steam networks (with the following pressure levels : 100, 60, 21, 19, 16, 11, 3.5 and 1.8 bars). Each network has an active blow-down.

No co-generation system and no hot-water network are used in this power plant configuration.

Only 2 boilers are used to generate steam, both connected in the 60 bars steam network.

26 turbo-alternators, 1 extraction back-pressure turbine and 10 valves compose the set of transfer units in the plant.

1 de-aerator is connected on the 2.5 bars steam network, producing the water required by the two boilers.

In the figure 1, we present a partial view of the power plant configuration, provided by ARIANE software.

The particularly of this problem, is that the total coming-back of steam from the process units is higher than the total steam demand. In fact, 214.4 tons per hour of steam comes back from the power plant, and only 209.8 tons per hour are called by process units. So, a rapid analysis of the problem leads us to summarize the problem in these terms : stop the boilers and the de-aerator, and transfer as efficiently as possible the steam through the networks in order to respect all specific network demand and to maximize the internal electricity production.

3.2 Simulation of the plant

The configured plant has been simulated with the boilers "stopped", and with an "a priori" good repartition of steam in the different transfer units (flow-rates in equipment items have to be fixed in simulation runs). As a result, we obtain a total cost of 5,848 $ per hour. All constraints are satisfied, including these concerning the demand from the process units, and the total blow-down of steam reached 4,6 tons per hour.

3.3 Optimization of the plant

In our meaning, we made an optimization run just to search a better transfer of steam through the set of turbines, to maximize the internal produced electricity. The initialization module of the optimizer (it's a module which makes a quick run to initialize the optimization parameters in order to respect mass balance on each network - this module is useful to find a feasible point used as an initialization by the optimizer) has found an initial point very close to the operating point of our simulation run.

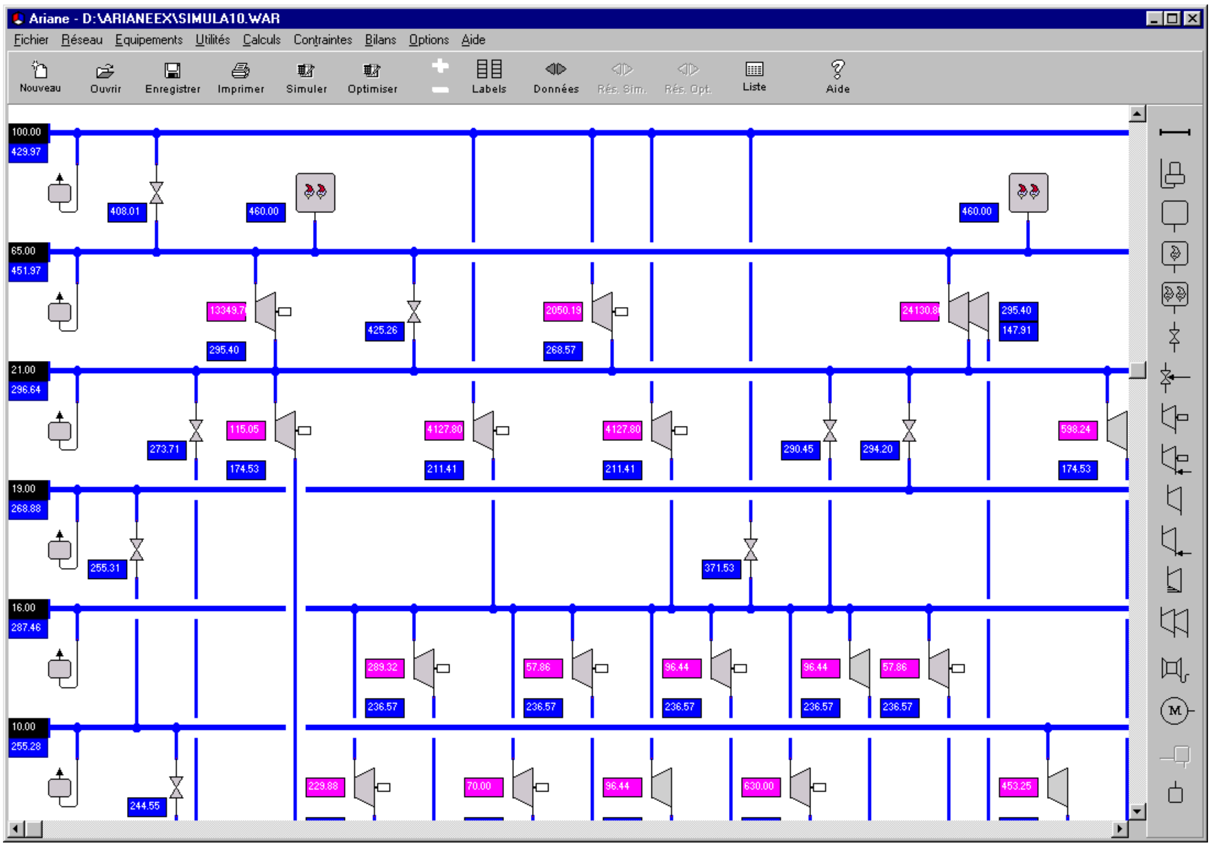

figure 1 : partial view of the power plant configuration provided by ARIANE software

The run takes more than fifty iterations and gives a surprising result. The cheapest of the two boilers (the one with the better combustion yield) produces 169 tons per hour of steam and the total blow-down of the power plant reaches 173.6 tons per hour. In contrast with our "a priori good solution", these 169 tons per hour of steam, generated by the boiler, cross through several turbines, to finally be rejected as blow-down on the 3.5 bars network. In fact, after analysis, electricity generated through the turbines with these tons of steam represent a gain more important than the cost of generating them in the boiler. The optimum point found by the optimizer corresponds to a cost of 5,202 $ per hour, i.e a gain of 11 percents in this specific case.

This experience shows us how a rigorous mathematical model is often better than our mental perception to find the real optimum point of a given problem, even if it seems very simple. In this specific case, others constraints may oblige to avoid this solution, but from a strict cost point of view, it was interesting, in this case, to generate wasted steam.

4 Conclusions

We have proposed here an optimization tool dedicated to combinated power plants. Based on a simulator coupled on a rigorous SQP algorithm, this tool has shown its capability to solve large optimization problems. As a little example, we have shown here that an optimization tool can often be useful, even if the solution seems to be a priori quite simple. ARIANE is a software which allows intuitive data input and can then be used without being an optimization specialist. For this reason, ARIANE can be used as a valuable tool in design and exploitation of power plants without preliminary training.

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