OPERATION OPTIMIZATION OF ENERGY SYSTEMS

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Summary

A complex energy system may use a variety of primary energy sources and a combination of various equipment to produce several energy products (useful forms of energy). The same result (quality and quantity of energy products) can be obtained by various operating modes. It is of crucial importance to determine the best operating mode for systems consuming large amounts of natural and economic resources. In this article, the operation optimization problem is stated in general terms, solution methods are mentioned in brief, and an example is presented, which demonstrates the importance of applying operation optimization in energy systems.

1. Introduction

An energy system may produce a variety of products (useful forms of energy) such as electricity, mechanical work (for example, for propulsion or for driving auxiliary machinery), steam at various pressure and temperature levels, hot water, cooling, and so on. For this purpose it may use a combination of equipment (for instance, diesel engines, gas turbines, steam boilers, steam turbines, desuperheaters) and a variety of fuels (for example, coal, diesel oil, natural gas, process-generated fuel gas). For a land installation, connection to the utility grid allows for importing additional electricity, if needed, or for exporting surplus electricity.

Due to the variety of energy sources and equipment that can be used to produce the various useful energy forms (products), the interdependency between sources and equipment and the variation of technical and economic conditions with time, questions such as the following arise: For a given system under specified technical, environmental and economic conditions at any instant of time, which is the best operating mode?

An operating mode, also called "operating point," is defined by the operating properties of components and substances in the system (pressure, temperature, composition and flow rate of each fluid, power of each component, and so on).

The degree of freedom increases if the system is not restricted to cover the loads but can import or export useful forms of energy, as is the case with a cogeneration system interconnected with the utility grid.

The complex structure of the system and the interdependency of its components make it impossible (except in very simple cases) to determine the optimum mode of operation at various conditions by a heuristic approach or by past experience only. Therefore, application of an optimization procedure based on a careful analysis of the system is necessary. A prerequisite of operation optimization is the existence or development of a mathematical simulation model of the system, validated by actual measurements on the plant, and the associated data reconciliation.

2. Statement of the Optimization Problem

In order to answer the question raised above, there is need to specify on what basis the operating mode will be considered as "best," that is, to specify the optimization criterion, which is called the "objective function." For operation optimization in particular, examples of optimization objectives are the minimization of total fuel consumption, minimization of operating costs, maximization of revenue, and so on. The mathematical statement of the optimization problem in general terms is the same as in *Optimization Methods for Energy Systems*, so there is no need to repeat it here. The explanations given in that article about the independent variables and constraints are also applicable here. Environmental and reliability aspects can be either treated as constraints or properly quantified and introduced in the objective function.

The optimization problem can be considered either at a particular moment or over a period of time. In order to clarify the subject, let $f(\mathbf{x})$ be a criterion of performance (for example, fuel consumption rate, cost rate of owning and operating the system), which, in general, changes with time. An objective might be the minimization of this criterion at any instant of time:

$$\min_{\mathbf{x}} f(\mathbf{x}) \qquad (1)$$

where **x** is the set of independent variables. Let it be mentioned that maximization (that is, of savings or profit) is also covered by Eq. (1), since:

$$\min_{\mathbf{x}} f(\mathbf{x}) = \max_{\mathbf{x}} \{-f(\mathbf{x})\}$$

Another objective might be the minimization of the total quantity represented by f in a certain period of time:

$$\min_{\mathbf{x}(t)} F(\mathbf{x}) = \int_t f(\mathbf{x})\,dt \qquad (2)$$

The time period of integration in Eq. (2) is selected at will, for example, day, month, year, or even the whole lifetime of the system. The function $f(\mathbf{x})$ may change with time because not only the technical but also the economic conditions may change.

Very often, the period of integration in Eq. (2) can be considered as consisting of N time intervals of length Δt_n (n = 1, 2, …, N) with steady state conditions in each time interval. Then, the integral can be replaced by a summation:

$$\min_{\mathbf{x}} F(\mathbf{x}) = \sum_{n=1}^{N} f_n(\mathbf{x}_n)\,\Delta t_n \qquad (3)$$

The solution of the optimization problem will specify the mode of operation at any instant of time, as it is defined by the values of the independent variables **x** or $\mathbf{x}_n$.

A particular class of operation optimization problems is dynamic optimization during transient conditions, for example, the optimization of path for load increase or decrease of a plant. This class is also represented by Eqs. (2) and (3).

3. Solution Methods

All methods described in *Optimization Methods for Energy Systems* can be used for the solution of the operation optimization problem. A few comments on operation optimization are made below.

The problem stated by Eq. (1) can be solved by direct application of an optimization algorithm or by the Functional Approach (described in *Functional Analysis* and *Optimization Methods for Energy Systems*). Often the set **x** includes both binary or integer variables (which specify, for instance, whether a unit operates or not), and real variables for other operating characteristics. A combination of a genetic algorithm with a linear or nonlinear (depending on the problem) programming algorithm has been proven successful for the solution of such a problem. An alternative approach is that the use of a mixed integer linear or nonlinear programming algorithm can be used.

For the problem stated by Eq. (3), there are two characteristic cases:

- If the operation in each and every time interval does not affect and it is not

affected by the operation in other time intervals, then decomposition is applicable, which in this case is performed with respect to time intervals (see *Optimization Methods for Energy Systems*). The optimization problem in each time interval is similar to the one described by Eq. (1).
- If there is interdependency between time intervals, it is necessary to apply dynamic programming techniques.

The problem stated by Eq. (2) can be solved by calculus of variations, except if it can be written in the form of Eq. (3).

4. Application Example

An application example, which is both instructive and of significant practical importance, is presented here. More examples for the various cases mentioned in the preceding section can be found in the bibliography.

4.1. Description of the Energy System

A combined cycle cogeneration system covers the needs of a refinery in electricity and steam at four grades (Table 1). Interconnection with the utility grid allows for the purchase of extra electricity, if needed, and sale of surplus electricity, if it is available and economical.

Grade designation	Pressure kPa (absolute)	Temperature °C
S1	4240	410
S2	1350	320
S3	370	150
S4	470	160

Table 1. Steam grades used in the refinery

The system consists of the following main components (Figure 1):
- Two gas-turbine electricity generators (GT-1, GT-2),
- Two exhaust-gas boilers (EGB-1, EGB-2) recovering heat from the gas turbine flue gases,
- One steam-turbine electricity generator (ST), and
- Four steam boilers.

A brief description of these components follows.

- *Gas-turbine electricity generators*. These have a nominal electricity production capacity of 17 MW each. They can operate on diesel oil, fuel gas, propane, or a combination of fuel gas and propane. Diesel oil is normally used for start-up only.
- *Exhaust-gas boilers*. Each boiler has a nominal production capacity of 30 t h^{-1} of high-pressure steam (S1) and 7 t h^{-1} of low-pressure stream (S5). There is no supplementary firing.

- *Steam-turbine electricity generator*. This uses high-pressure steam (S1) and has a nominal capacity of 16 MW.
- *Steam boilers.* These use fuel oil and produce high-pressure steam (S1). There are two boilers with a nominal capacity of 30 t h^{-1} each, and two boilers with a nominal capacity of 60 t h^{-1} each. Thus, the total steam capacity of the four boilers is 180 t h^{-1}.

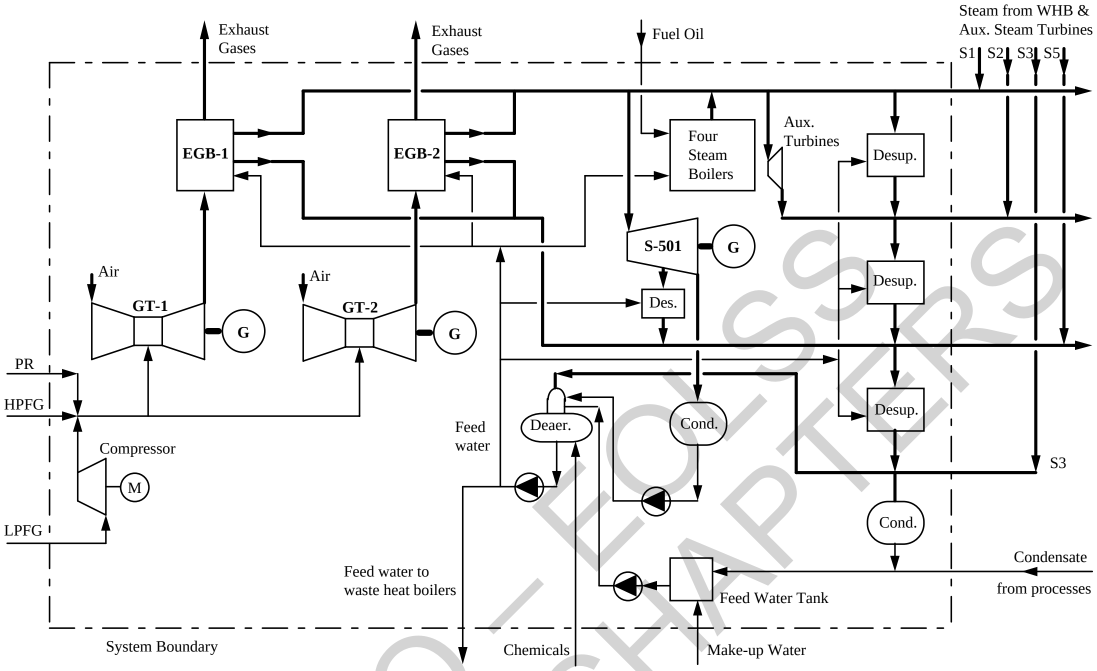

Figure 1. Simplified diagram of the combined-cycle cogeneration system

The main components are served by auxiliary equipment such as a compressor to increase the pressure of low-pressure fuel gas from 370 kPa to 2300 kPa, a propane vaporizer, water demineralization units, condensate collection and treatment units, and so on.

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Biographical Sketch

Christos A. Frangopoulos is Professor at the Department of Naval Architecture and Marine Engineering, National Technical University of Athens (NTUA), Greece. He received the Diploma in Mechanical and Electrical Engineering from the NTUA in 1971. After his military service (1971–1973), he worked as Superintendent Engineer of ship-owning companies, and as Head of the Diagnostic Center of a ship repairing company in Greece (1973–1979).

He undertook graduate studies in Mechanical Engineering with a major in Thermal Sciences at the Georgia Institute of Technology, Atlanta, USA, leading to the M.Sc. degree (1980) and Ph.D. degree (1983).

He joined the Department of Naval Architecture and Marine Engineering (NTUA) as a faculty member in 1985. He lectures on marine engineering, as well as marine and land-based energy systems in both undergraduate and inter-departmental graduate courses. His research activity is related to the development and application of methods for analysis, evaluation and optimal synthesis, design and operation of energy systems (power plants, propulsion plants, heat recovery systems, cogeneration systems, etc.) by combining thermodynamic, economic, and environmental considerations. Second Law (exergetic) analysis and internalization of environmental externalities are two particular subjects of this work. He has often given invited lectures on the results of his research in several countries.

Among his publications are more than 40 papers in journals and international conferences and one book on cogeneration (in Greek).