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Islands of Optimization: A Web-Based Economic Optimization Tool

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Abstract:

The use of mathematical models and optimization is becoming an important part of the design and operation of power plants. Optimization techniques are used to make plants more profitable, to better meet the demands and opportunities of the deregulated electricity markets, and to help them comply with environmental requirements. There are areas of a power plant, or islands, where optimization is possible. Some of these areas include emissions monitoring, condenser/cooling tower subsystems, combustion optimization, and fleet-wide economic load dispatching. Depending on the island of optimization different types of models need to be developed and different optimization techniques are required.

The purpose of this paper is to discuss some of the areas where optimization is possible and highlight the types of models that are required and the optimization techniques required. It will then show how a general-purpose optimization program that can run in real-time and communicate with the plant's distributed control system (DCS) can be used in these optimization opportunities.

Introduction:

With utility deregulation and more stringent pollution regulations in place, minimization of overall generation cost for a power company has become increasingly important. One way to minimize the cost of producing power is to utilize optimization in the process. There are different types of power plants and within these types of plants various areas or islands of optimization are possible. Just like there are different types of power plants the optimization of these plants often require different mathematical models and optimization techniques. As stated by Immonen [1], depending on the application, the component performance models may be linear or nonlinear. The most rigorous formulations may be necessary for detailed analysis of component internal performance, or the modeling details may be limited to the overall economic performance of the plant.

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Optimization often includes decision on the units to be kept in service, and the units to be shut down. This often introduces a discontinuity in the model, requiring discrete modeling techniques.

Discussion of Selected Power Plant Types and Islands of Optimization:

Every optimization discussion needs to consider a model, an objective function and a set of constraints. Decisions are needed to be made to make judgments on how complex or simplified the model should or needs to be. An optimization model given flexible tools can be an evolving, refining, and learning asset. As additional interactions are understood, their effects can be quantified and formulated in equations so that the next version of the optimization can consider this. This care, feeding, refining, and development are best left to the owner or operator. In order for this to be possible, the optimization tool must provide the user with the ability to easily update models and constraints and to be able to verify the changes in an offline mode.

Coal-Fired Plants

In a coal-fired electric generating unit, there are a number of "islands" where optimization is possible. For example, the combustion process can be optimized to minimize NOx as described by Swiriski and Williams [2]. This process is highly non-linear and requires neural network model to predict the boiler emission. Another island of optimization in a coal-fired plant is steam temperature. This sub-system has been successfully controlled by use of fuzzy models. In the typical condenser/cooling tower subsystem there are often several cooling water circulating water pumps operating in parallel with one another; while the cooling tower has several fans or groups of fans that might be able to be run at several speeds. Depending on the ambient conditions at the plant it might be possible to switch the equipment selection, which could result in lower auxiliary power costs.

Combined Cycle Plants

Figure 1 shows a typical combined cycle plant arrangement. In this plant, there are two combustion turbo-generators (CTG). The hot exhaust from each CTG feeds a heat recovery steam generator (HRSG). This heat can be augmented by gas fired duct burners. The HP, IP, and LP steam produced by the HRSG is fed into a steam turbo-generator (STG). Depending on the plant demand there are often multiple equipment configurations that can satisfy the demand and some configurations are more efficient than others. This is discussed by Huff in [3]. Figure 2 shows how the plant heat rate varies by equipment configuration. At low plant demands only one CTG needs to be used and the heat rate is very poor. As the plant demand increases the plant can run in combined cycle mode with a CTG/HRSG and STG and the heat rate improves. Eventually the plant demand exceeds the capacity of one train and the second CTG must be turned on making the heat rate worse until the plant demand is large enough for both CTG/HRSG trains to be in operation.

Figure 1. Typical combined cycle plant arrangement.

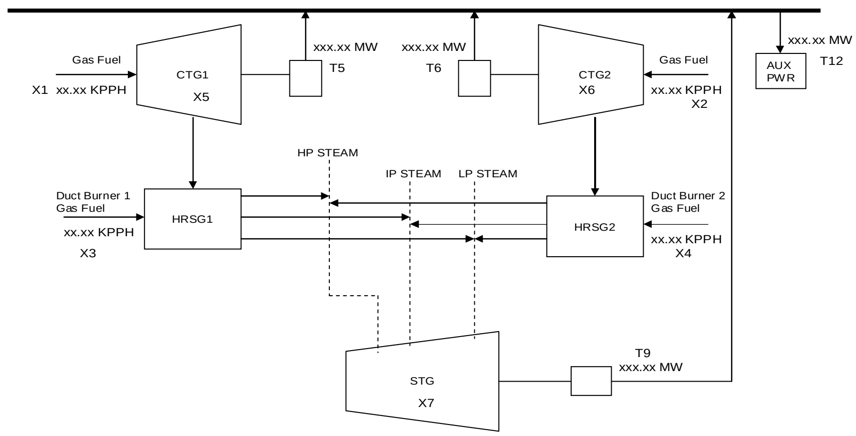

Figure 1

Figure 2. Plant heat rate variation by equipment configuration.

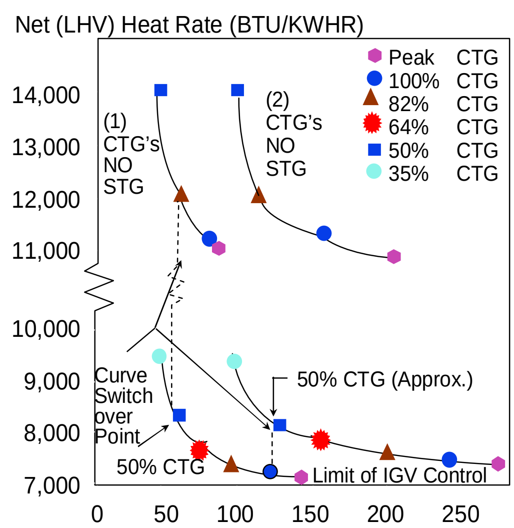

Figure 2

Hydroelectric

Many dams contain multiple hydroelectric turbo-generators. In this case the goal is to satisfy the plant demand by loading the turbo-generators so as to minimize the amount of water consumed. This is a nonlinear optimization problem. However, it is further complicated due to vibration problems occurring at certain loads. The load ranges that cause vibration to occur become "forbidden zones". The optimization program must be aware of these ranges and prevent any machine from being assigned a load that lies in one of these areas.

Cogeneration Plants

The dual goal of producing both steam and power in a cogeneration plant cause complexity in building and operating these facilities. A one-line diagram of a typical cogeneration plant is shown in Figure 3. This plant consists of six boilers that can burn gas or oil and supply steam to a common header. In addition, there are two CTGs, each with an HRSG. The steam from the HRSGs also supplies steam to the 400LB header. There are three STGs that are supplied with steam from the 400lb header and extract it at two different pressures. There are also pressure-reducing valves that can take 400lb steam and supply it to the 60lb and 9lb steam lines. There is a common air-cooled condenser on the 9lb line that can be utilized to increase the 9lb steam through the low-pressure stage of the STGs increasing the possible STG MW amount. Power is produced internally and can be purchased from the utility and sold back. Optimization of this type of plant is discussed by Putman in [4] where the goal is to dispatch the loads on the boilers and turbines so that the process steam demand and power demand is satisfied at least cost. He shows how this can be accomplished using linear programming.

Figure 3. A one-line diagram of a typical cogeneration plant.

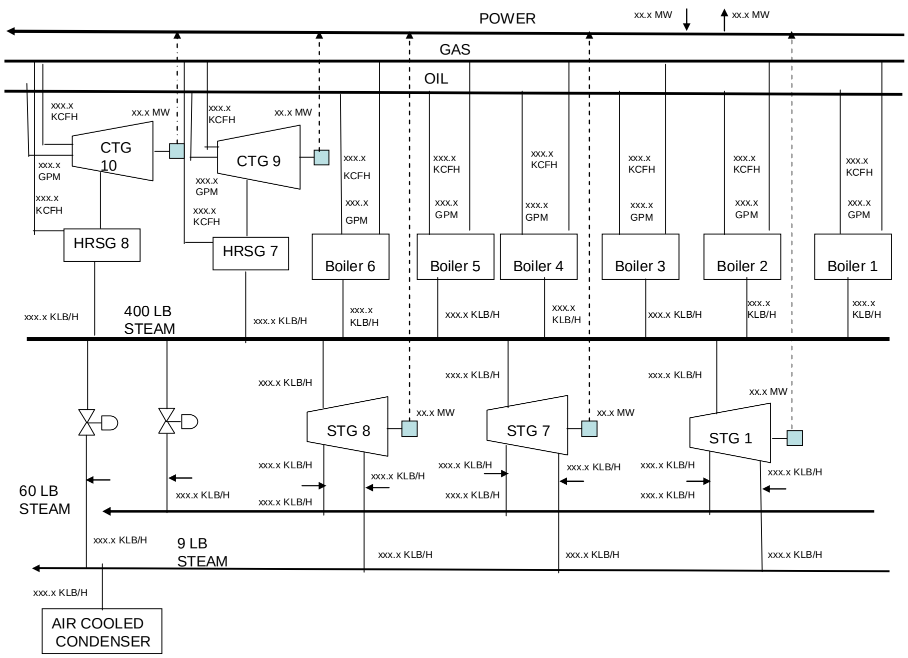

Figure 3

Fleet-wide Economic Dispatch

With the popular utility deregulation and more stringent regulations on power plant pollution, economically scheduling and operating power generation from the corporate level has become evidently important. In addition to the fact that load forecast and production scheduling are more dynamic at the corporate level; each boiler unit at the plant level also has to face the challenge of reducing exhaust gas pollution. In coal-fired units, the task normally comes down to reducing NO_X, SO_2, and opacity levels below certain limits mandated by the Environmental Protection Agency. These limitations can be normally translated to NO_X or SO_2 control setpoints during each unit's daily operation. Significant reduction in pollutant level can bring in credit (in term of dollar amount) for the company that directly leads to financial savings. However, pollution control inevitably incurs cost. These costs must be modeled and represented in the overall objective cost function. For a power company with multiple boiler units, it is often difficult to determine the load dispatch profile, and also specify the optimal pollutant control levels for all of the different units, such that the overall material and maintenance cost is minimal, while the environmental pollution constraints are also met at the same time. As discussed by Cheng and Huff in [5] with the modern day control system and advances in network technology it is possible to do a real-time, fleet-wide economic dispatch that considers not only plant heat rates but also environmental costs. This optimization required a mixture of linear and non-linear models.

Model Types:

As seen from the examples above a variety of model types is required in doing optimization. Some models are linear, such as heat vs. power on a CTG. Some are simple parabolas, such as load versus efficiency curves on boilers. In the case of combustion optimization the process is highly non-linear requiring a neural network model to be developed. Many of these models contain intercepts or constant terms that must become zero when the device is out of service. Other functions, such as the heat rate versus load curve for a combined cycle plant as shown in Figure 2, are non-linear and discontinuous depending on the equipment configuration. Depending on the optimization problem combinations of these models must be combined to form an overall plant model. Therefore, a program must exist that can solve a mix of model types and be able to handle equipment out of service and different equipment configurations.

Optimization Methods:

In the past there has been classical optimization techniques developed, some for linear models and some for non-linear. Linear programming is a classical proven optimization technique and has been used to solve problems in real-time. However, to use linear programming every individual equipment model that is part of the overall plant model must be linear. This restriction is limiting since many real-world models do not conform to this linear simplification requirement. The equipment models of much of the equipment found in a power plant are non-linear, making it very difficult to use linear programming as an optimization technique.

Non-linear optimization techniques such as Evolutionary Operation (EVOP) developed by Box [6] and later modified by Spendley [7] to form the Simplex Self-Directing Evolutionary Operation Technique (SSDEVOP) has been used for the economic dispatch of boilers and steam turbo-generators. The Self Directing Evolutionary Operation (SSDEVOP) optimal search scheme begins by constructing a matrix of test cases based on perturbations of a base case. The starting tableau for a three-variable SSDEVOP problem is as shown in Table I below.

For a generalized case with “n” variables, the starting matrix consists of the vertices of an “n” dimensional polygon containing the base case. The system is solved for each test case, and the cost of each case is determined. Beginning with the worst case, that point is reflected about the mean of the remaining points, and the cost is determined at the new point. If the new test case is better than the original point, then the corresponding row in the matrix is replaced with the new test case and the process is repeated. Otherwise, the process is repeated with the second worst case and continues until either a better solution is found or until no new point results in an improvement in cost. At this point the perturbation size is diminished and the process starts over, constructing a new starting matrix from the best case so far. The optimization search continues until either the cost function falls beneath a user-specified threshold or until the amount of calculation time allowed has expired.

TABLE I

Case	Variable X1	Variable X2	Variable X3	Cost
1	X1 - a1	X2 - a2	X3 - a3	C1
2	X1 + a1	X2 - a2	X3 - a3	C2
3	X1	X2 + 2a2	X3 - a3	C3
4	X1	X2	X3 + 3a3	C4

SSDEVOP has been used successfully for the optimization of VARS in an industrial power network as discussed in [8]. SSDEVOP can be used for linear and non-linear equations, but if convergence is to be achieved in real time, it is necessary to restrain the number of variables that need to be perturbed during the search.

The optimal search method, based on the equal incremental cost method has been successfully used for the economic dispatch of boilers that feed a common header, hydroelectric turbo-generators, and for steam turbo-generators. Let's assume that there are N turbo-generators in the optimizing set, each with their own cost versus load curve, and a total load L. Then the initial assignment to each unit is L/N. The total cost is calculated together with the change in cost if the units load were to be raised by x MW and also if its load were to be reduced by the same amount. The program identifies that unit which will provide the greatest reduction in total cost if its load is lowered by x MW, and the unit that lowers the cost the most if its load is raised by x MW. The total load is re-distributed and a new total cost is calculated. This process continues until no further total improvement in cost is found.

Other non-linear techniques such as steepest-ascent also exist, but the problem remained that some of these methods only apply to non-linear models not a mix of linear and non-linear. Also, in the case of EVOP the number of variables must be limited for convergence to occur.

An optimization method that can handle a mixture of linear and non-linear equations is needed. This optimizer must also be able to handle discontinuity that occurs due to equipment being out of service.

Modern-Day Optimizer:

The modern day microprocessor-based DCS contains the computing power to solve complex iterative mathematical procedures in real-time. Therefore, the optimization techniques used no longer have to be limited. Modern day optimization solvers are commercially available. These solvers typically contain the following types of algorithms:

LP/Quadratic – This type of solver is ideal when all of the equations that comprise the plant model are linear and the objective function is linear or quadratic.

Gradient nonlinear – This type of solver is ideal when some or all of the equations are nonlinear and the functions are smooth or continuous.

Evolutionary – This type of solver is required when the equations are nonlinear and non-smooth.

All of the solvers should be able to handle integer variables as well so that equipment out of service problems can be handled easily.

Therefore, the ideal optimization package should be a general purpose solver for mixed integer linear/nonlinear optimization problems raised from power plant operations. The software should provide the user with abilities to find a solution of *x* (a.k.a. a vector of independent decision variables) in the feasible regions (which are determined by a set of equality/inequality constraints), such that the local/global minimum (or maximum) value of the objective function *J* is obtained.

The mathematical form of the optimization problem can be stated as follows:

$$\underset{x}{Min} \quad J = f(x)$$

$$s.t. \quad \begin{cases} g(x) \le 0 \\ h(x) = 0 \\ x_{i,\min} \le x_i \le x_{i,\max} \end{cases}$$

where x_i is either an integer or a real number.

To construct an optimization problem for the software to solve, all the coefficients in f(x), g(x), and h(x) need to be specified. Different values of those coefficients determine different 'cases' or 'scenarios' of the same optimization problem. For example, in the economic dispatch problem when the power demand (most likely a coefficient (cost, Right Hand Side etc.) in *g(x)* or *h(x)*) is changed, the optimal solution of *x* may be changed, and as a result, the optimization problem needs to be solved again. The new power demand coefficient can be changed manually in the offline calculation or updated online with actual plant data from the DCS. The functions g(x) or h(x) are often times individual equipment models. These models are normally determined by regression techniques or they could be the closed form equation of a neural network. Regardless, as equipment models change over time the new equations should be updated in the optimization problem. The new equipment models should be easily entered into the optimization problem via an offline interface.

The ideal optimization package should have an offline and online mode. The offline package should contain a graphical user interface (GUI) that is used to build the optimization problem, which is often called a plant model because it is comprised of the relationships or equations of the equipment in the plant that is to be optimized. The offline module should allow any number of optimization problems to be created. They can be models that represent the actual plant that it is to be optimized or they can be hypothetical plant configurations. Besides providing the capability to develop plant models this module provides the user with the ability to perform "what If" scenarios. It provides the user with a tool that lets him or her study the interactions of the plant equipment and determine the equipment configurations that provide the lowest $/hour operating cost by letting him adjust costs, demands, equipment availability etc.

The GUI of the offline program should be equipped with a web-based user interface and should allow multiple users to perform "what If" operations while not interfering with the running online optimization. The users should be able to create new models and modify existing models. It should also provide the ability to configure the online optimization process from the user interface.

In addition, to having an offline mode of operation the optimizer should also contains an online mode. In the online mode a plant model that was created using the offline package is solved in real-time. Unlike the offline mode the demands and costs should be updated from the plant DCS system and the results of the program should be made available to the DCS where they can become supervisory setpoints or used to advise the plant operators.

Conclusion:

A state of the art optimizer integrated with the DCS can benefit power generation facilities at the multi-unit level as well as the fleet management level. New optimization opportunities that arise from examining the operational aspects against known and observed economic factors can be solved. Plant equipment and unit operation characteristics can now be evaluated easily for optimum economic benefit.

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