Practical Commitment of Combined Cycle Plants using Dynamic Programming

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***Abstract*—Due to the existence and building of an important number of combined cycle plants throughout electric power systems around the world, there exists the growing need to have a more accurate model to represent these type of power plants when solving the unit commitment problem. A commonly used optimization technique to solve the unit commitment problem is dual programming. This work focuses on solving the subproblem of scheduling a combined cycle plant using dynamic programming under a dual optimization scheme. The model used to represent the combined cycle plants is based on configurations; this new model takes into account such constraints as the feasible transitions between configurations, and the minimum and maximum time that a combined cycle plant must remain on a certain configuration. This model accurately represents the real-life characteristics of combined cycle plants like different start-up sequences and different stopping conditions. One novelty of this model is that the representation of each one of the states and configurations is done with a single integer state index that consecutively sums the time that the combined cycle plant must remain on each state or configuration. The use of this integer state index simplifies the state-space diagrams and reduces the number of integer/binary variables in the model. Another novelty is the modeling of Hybrid Combined Cycle Plants; these are the ones that use an auxiliary boiler in order to increase the production of steam.**

***Index Terms*—Combined cycle plant, configurations, dual programming, dynamic programming, transitions, unit commitment.**

I. Introduction

Due to the recent changes in the electricity industry such as deregulation, the opening of the electricity market to private investors, and an increased concern for the environment, an important number of combined cycle plants (CCPs) have been built all over the world. This, in turn, has brought new challenges to the unit commitment (UC) problem. The challenges mainly come from the need to model the CCPs in a more accurate way and then incorporate this model to the UC problem.

The short-term UC problem is basically to determine, for each hour of the next day and for up to seven days, the optimum operating point of the available hydro and thermal units in order to satisfy the forecasted level of demand with the minimum operating cost and, while doing so, meeting all the physical and operational constraints of the power system. Some of the more common constraints incorporated to the UC problem are load balance, spinning reserve, scheduled reserve, off-line reserve, must-run units, and fuel consumption among others. Constraints that are particular to thermal units include minimum and maximum up and down time limits, start-up costs, and minimum and maximum generation limits. When CCPs are incorporated to the UC problem, the following constraints must be considered: different configurations of the CCPs, feasible transitions between configurations, and transitions costs between configurations. For the regulated electricity industry, the objective when solving the UC problem is to minimize the operating costs while satisfying the demand whereas for the deregulated electricity industry, the goal of market participants is to maximize their benefits rather than satisfying the demand at a minimum cost. When network constraints are incorporated to the UC problem, and using an AC formulation, the UC problem is known as security constrained unit commitment (SCUC) [1]–[4].

This paper is organized as follows. Section II explains the operational and technical constraints of Combined Cycle Plants. The different models used to represent the Combined Cycle Plants are discussed in Section III. Section IV presents the different existent approaches used to solve the Unit Commitment problem when incorporating Combined Cycle Plants. The new model based on configurations using Dynamic Programming for Combined Cycle Plants under a Dual Programming scheme is detailed in Section V. Section VI presents a numerical example to illustrate the use of the new model for Combined Cycle Plants based on configurations. Some concluding remarks are given in Section VII.

II. Combined Cycle Plants

Combined cycle plants are generating units that have flexible operating conditions. Other generating units with flexible operating conditions are: i) fuel switching units, ii) fuel blending units, iii) constant/variable pressure units, iv) over-fire units, and v) dual boiler units [1], [5]. CCPs are made up of one or more combustion turbine (CT) generators, each one of them with its own heat recovery steam generator (HRSG), and one conventional steam turbine (ST) generator common to all the CTs. Some CCPs may have an auxiliary boiler in order to generate more steam to aid the HRSG to drive, or even drive independently, the ST. This type of CCPs are called Hybrid Combined Cycle Plants (HCCPs); this is shown in Figure 1. The most basic CCP is formed by one CT generator, one

2010 IEEE Electrical Power & Energy Conference
978-1-4244-8188-0/10/$26.00 ©2010 IEEE

HRSG, and one ST generator, and its operation is as follows: In the first stage a mixture of air and fuel is burned in the combustor of the CT. The released energy by the combustion is used to move the CT which in turn moves a generator to generate electricity. In the second stage the hot gases of the CT, that otherwise would be wasted to the atmosphere, are used by the HRSG to generate steam and that steam is used to move the ST that in turn moves a generator to produce electricity. This configuration of a CCP can reach an efficiency of up to 60%; this is an improvement of 20% - 30% with respect to conventional combustion turbines [2]. CCP have high thermal efficiency, that is, a lesser fuel consumption to generate the same energy. Less fuel consumption implies lower operating costs and and less emission of pollutants per unit of energy generated making them not only an economical option but also an environmentally friendly solution [5], [6].

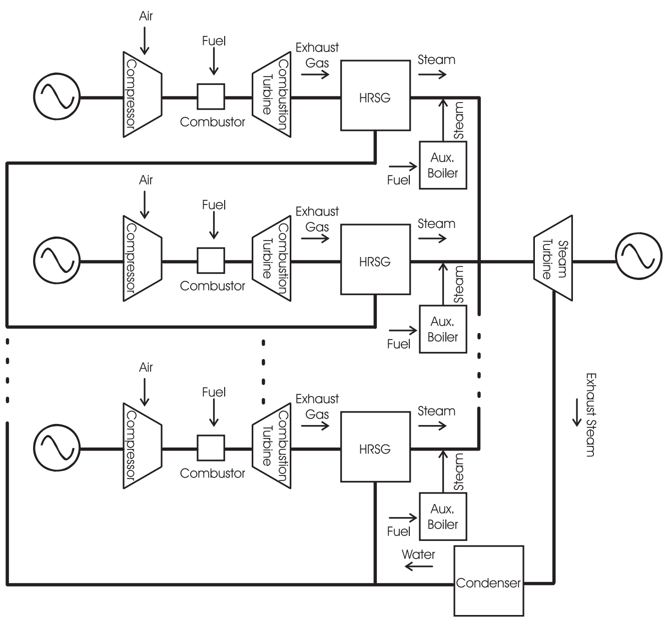

Fig. 1. Schematics of a CCP with Auxiliary Boiler

CCPs have different *configurations* and each configuration may have several *states*. The generation capacity of a CCP changes depending on which configuration the CCP is on, and the transition costs from one configuration to another are by no means negligible. CCP configurations are dependent on the different combinations that can be formed with the CT generators, HRSGs, and the ST generator; for instance, CT generators can be operated with or without their associated HRSGs whereas the ST generator cannot be operated without at least one HRSG available. The number of states for a given configuration is the number of periods, *i.e.* hours, that the CCP must remain on that configuration. If it takes for a given CCP three periods to complete the cold start-up sequence, then the start-up configuration has three states. The transitions between configurations must follow operational and time constraints; these are imposed by the number of periods that a CCP must remain on a given configuration and also by the rules that dictate to which configuration it is feasible to transition to [1], [2], [5].

III. Modeling of Combined Cycle Plants

There are at least three different ways to model CCPs. These are: i) aggregated model, ii) model based on configurations, and iii) model based on physical components. A brief descriptions of each one of them is presented next.

The *aggregated model* ignores all the components of a CCP and considers it as a single equivalent unit; hence, the scheduling of the CCPs is done as if they were conventional thermal units. This is a very simplistic model since the commitment of the equivalent unit results in an on-off state therefore ignoring all the different configurations and technical constraints of the CCP. At the end, the configuration of the CCP in real time is left to the plant operators. This model is currently in use by ISO NE, NYISO, MISO, and PJM [7]. The model currently used by the Electric Research Institute of México (IIE, acronym in spanish) is also an aggregated model. CCPs are modeled as equivalent thermal units whose power output is the sum of all the CT generators affected by a contribution factor to the ST generator. Even though the aggregated model is a "working" representation of a CCP, a more accurate model is needed to account for the different configurations and for the start-up sequences; this is the model based on configurations.

The *model based on configurations* considers the three major components of a CCP, namely CT generators, HRSGs, and ST generator. Considering these three major components of the CCP allows the representation of the minimum and maximum on and off time, transition time, start-up sequences, load ramp rates, minimum and maximum power output limits by configuration, individual heat energy requirement curves per configuration, start-up costs, and transition costs between configurations. All the possible transitions between configurations are represented by space-state diagrams. Another advantage of this model is that the availability of each one of these components can be taken into account.

IV. Solution Techniques

There are several solution techniques to solve the UC and SCUC problems when CCPs are included in the formulation. Some of these techniques are Mixed Integer Programming (MIP) [7]; evolutionary algorithms like Genetic Algorithms (GA), Evolutionary Programming (EP), and Particle Swarm Optimization (PS) [8]; and Dual Programming combined with Dynamic Programming. A variation of the latter one, called Dynamic Programming with Lagrangian Reduction of Search-Range, is proposed by [9]. The Lagrangian Relaxation (LR) technique decomposes the UC problem into a set of sub-problems in which the coupling system constraints are relaxed and included in the objective function by means of their lagrange multipliers. Each sub-problem, one subproblem per individual generating unit, minimizes the generation costs, start-up costs, and the terms including the lagrange multipliers subject to minimum and maximum on and off time constraints,