OPTIMAL OPERATION OF COMBINED HEAT AND POWER BASED POWER SYSTEMS IN LIBERALIZED POWER MARKETS

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Contents

Summary

In this chapter, we present combined heat and power (CHP) production technologies and related modeling techniques of the CHP plant. Then we discuss the impacts of liberalized power markets on CHP systems and present a typical unit commitment model for a CHP system with different types of components. Next, we provide a comprehensive review on the state-of-art of models and decision support tools for optimizing CHP systems, focusing on how to deal with uncertainties in the liberalized power markets. Finally, we summarize typical solution techniques used in the literature and general requirements for the models and optimization tools in the liberalized power markets.

1. Introduction

Liberalized electric power markets and combined heat and power (CHP) production technologies are actively promoted by extensive political incentives in many countries. Europe has actively incorporated CHP into its energy policy via the CHP Directive (CHP directive, 2004). The US DOE (Department of Energy) has an aggressive goal to raise the share of CHP to 20% of the US generation capacity by the year 2030 (http://www.aceee.org/policy-brief/combined-heat-and-power-and-clean-distributed-energy-poli). CHP has also received a good deal of attention by the governments of the developing countries (IEA, 2007). A liberalized power market was introduced in the early eighties in Chile (Del Sol, 2002). Since early nineties, the liberalization has been in progress in the developed countries, including UK, Norway, Sweden, Finland, USA and New Zealand. Currently, the liberalization is going on all over the world. The objective of liberalization of the power market is to achieve higher energy efficiency and lower consumer prices by introducing conditions of intensified commercial competition (Meyer, 2003). CHP production is a leading technology to respond to the market demands. It is also an excellent technology for promoting a fair competition in the liberalized power market. It is a technology for improving efficiency of energy production.

The increasing environmental concerns urge promotion of environmentally sound energy production technologies. Energy policy is giving priority to the problem of global warming. Both energy efficiency and development of new and renewable energy technologies (European Commissions, 2005) are considered key elements for dealing with this problem. The high efficiency of CHP production leads to significant savings in fuel and emissions; typically between 10-40% depending on the technique used and the system replaced (Madlener and Schmid, 2003).

CHP production means the simultaneous production of useful heat and electric power. When steam or hot water is produced for an industrial plant or a residential area, power can be produced efficiently as a by-product. Vice versa, surplus heat from an electric power plant can be used for industrial purposes, or for heating space and water. CHP is considered an environmentally beneficial technology because of its high energy efficiency when compared to conventional condensing power plants. The energy efficiency of a gas turbine is typically between 36-40% when used for power production only, but over 90% if also the heat is utilized.

Traditional CHP can find application in district heating, large commercial and institutional buildings and different industries such as paper, wood, food and semiconductors (Resource Dynamics Corporation, 2001). Recently, micro CHP systems are booming. Micro CHP implements the well established large scale CHP technologies to individual residential houses or small office buildings. In addition, CHP facilities are components of distributed energy resource (DER) systems, which are small-scale power generation technologies used to provide an alternative to or an enhancement of the traditional electric power system. The operation of DER systems is related to microgrids, which are localized groupings of electricity generation, energy storage, and loads that normally operate connected to a traditional centralized grid (macrogrids). The microgrid can function autonomously if it is disconnected from the macrogrid.

Liberalization of the power markets, technological innovation and a growing tendency towards sustainable development becomes an integral part of energy policy planning. New markets and the increased interest in new production technologies will result in a significant change in energy system planning and operation. The energy sector is one of the core application areas in operations research, artificial intelligence techniques and management sciences because energy systems are large and activities associated with operations of the energy systems are complicated. The operation of energy systems is managed based on operational (low-level) production planning.

The goal of production planning in the liberalized power markets is to determine the optimal strategies over a time horizon (day, week, month or year) so that the overall net profit can be maximized subject to production constraints. The production planning can be divided into three levels: Strategic (long-term decisions) such as alliances, long-term contracts and capacity investments; tactical (medium-term decisions) such as maintenance scheduling, fuel allocation, emissions allowance; and operational (short-term decisions) such as unit commitment (UC) and bidding. However, the usage of long-, medium- and short-term planning is a relative term and depends on the application background. E.g., in the UC context, a planning horizon exceeding one week may refer to long-term planning (Thorin, Brand and Weber, 2005; Voorspools and D’haeseleer, 2003).

The complexities of the planning problems vary depending on the scale of the energy systems and information involved in the decision-making. The production planning of the CHP system is inherently more complicated than power-only generation planning. The interdependence between heat and power generation imposes great challenge in production planning. This means that planning must be done in coordination between heat and power. Moreover, the liberalized power market introduces more uncertainties than before. Production planning needs assistance from a wide set of sophisticated modeling, simulation, optimization, and forecasting tools. The necessary optimization methods include linear programming (LP), non-linear programming (NLP), mixed integer programming (MIP) and stochastic programming. The complexity of the problems may also require application of various decomposition techniques such as Lagrangian decomposition, Dantzig-Wolfe decomposition and Benders’ decomposition.

Here we intend to introduce the main modeling methods for CHP production technologies and give a comprehensive survey on the state-of-art models and decision supports tools for the operational planning of the CHP systems in liberalized power markets. We also address optimization under uncertainty. The chapter is organized as follows. In Section 2, we give an overview of CHP production technologies and systems; and how liberalized power markets affect their operation. In Section 3, we give a uniform modeling technique for the components of CHP systems and then present a general deterministic UC model for the CHP system and next discuss how to incorporate uncertainties in the CHP model. In Section 4, we describe the solution approaches for deterministic CHP models. In Section 5, we discuss optimization under uncertainty.

2. CHP Systems and Liberalized Power Markets

Figure 1 shows different types of components of a CHP system in liberalized power markets. The components are roughly classified into four categories:

- Power and heat generation components: These include actual CHP plants, but also separate power and heat production components such as condensing power plants and district heat stations.
- Power and heat storage components such as batteries and hot water tanks
- Power and heat trade components such as various bilateral purchase and sales contracts and
- Power and heat demand side management (DSM) with the target to reduce peak power and heat demand by introducing different tariffs for peak and off-peak energy consumption.

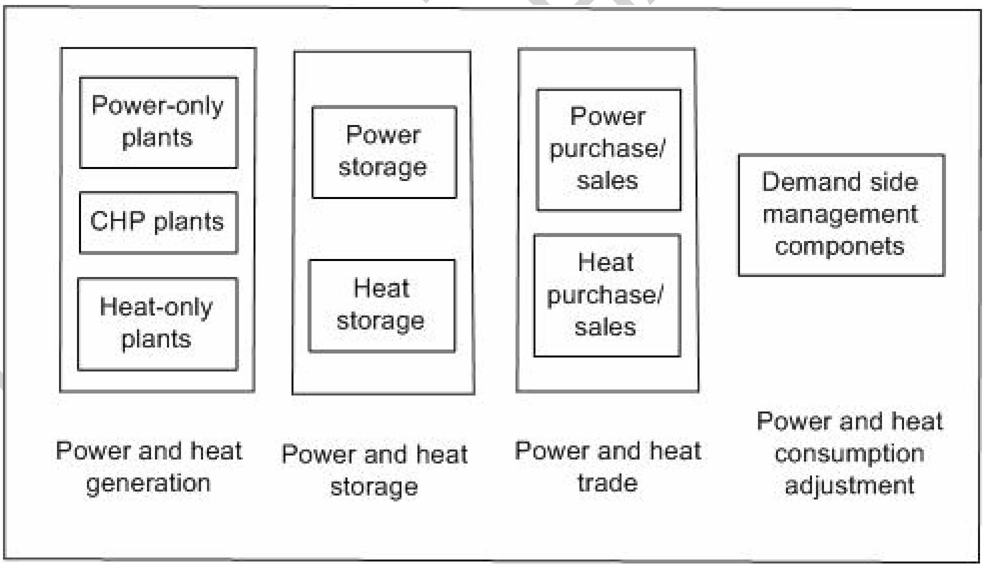

Figure 1. Different types of components of a CHP system in liberalized power markets.

Here it is worth mentioning that renewable energy sources such as solar power, wind power and hydropower can also become components of CHP systems. The inclusion of separate power and heat components makes the system more flexible and reliable under variable demand. In the following, we mainly introduce the conventional CHP production technologies.

2.1. CHP Production Technologies

CHP production technologies are conventional power generation systems with the means to make use of the thermal energy remaining in exhaust gases, cooling systems, or other thermal energy waste stream to improve the overall efficiency of the system. Typical CHP production prime movers include: combustion (gas) turbines, reciprocating engines, boilers with steam turbines, micro-turbines and fuel cells. EPA_CHP (2008) provided a detailed discussion about different CHP technologies. Here we briefly discuss the major characteristics of gas turbines and steam turbines as well as related advanced production technologies. On the one hand, the available sizes of gas turbines and steam turbines are wide: from a few dozen kW to a few hundred MW, covering almost all of the application capacities except micro applications. On the other hand, steam turbines and gas turbines account for a large share of power production capacities for sale to the grid. Power is a high value commodity as compared with heat. Advanced CHP production technologies are developed to improve the power efficiency of CHP production.

2.1.1. Steam Turbines

Steam turbines are widely used for CHP applications in the USA and Europe. Steam turbines are one of the oldest and most versatile prime mover technologies still in general production used to drive a generator or mechanical machinery. Power generation using steam turbines has been in use for about 100 years. Figure 2 shows a schematic boiler/steam turbine system.

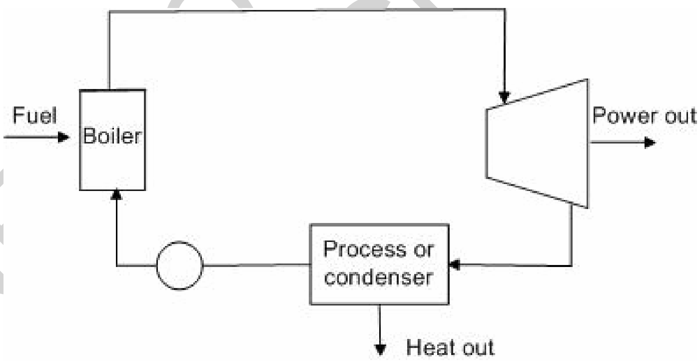

Figure 2. A schematic boiler/steam turbine system.

The thermodynamic cycle for the steam turbine is the Rankine cycle. The cycle consists of a heat source (boiler) that converts water to high pressure steam. The water is first pumped to elevated pressure, which is medium to high pressure depending on the size of the unit and the temperature to which the steam is eventually heated. Then it is heated to boiling temperature corresponding to the pressure, boiled and superheated. The water is eventually transformed into pressurized steam. Next, the pressurized steam is expanded to lower pressure in a multistage turbine, then exhausted either to a condenser at vacuum conditions or into an intermediate temperature steam distribution system that delivers the steam to the industrial or commercial application. The condensate from the condenser or from the industrial steam utilization system is returned to the feed-water pump for continuation of the cycle.

Steam turbines used for CHP can be classified into two main types: backpressure and extraction as shown in Figure 3.

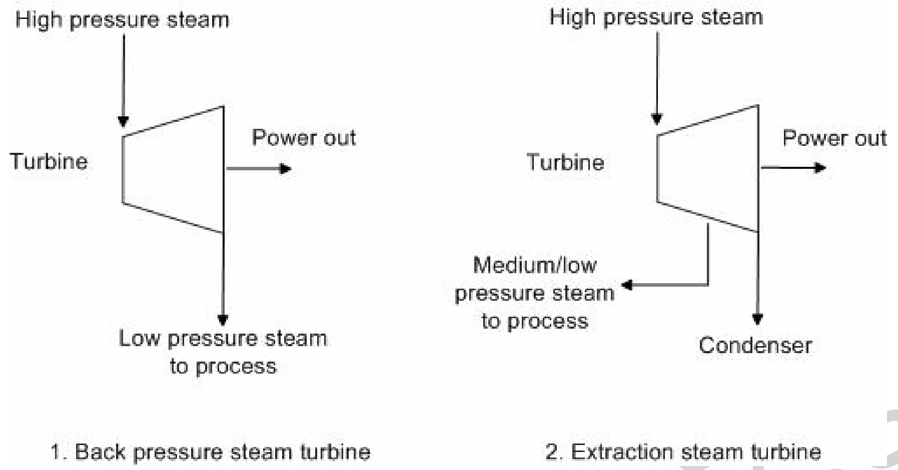

Figure 3. Back pressure and extraction turbines.

The backpressure turbine (Figure 3.1) exhausts its entire flow of steam to the industrial process or facility steam mains at conditions close to the process heat requirements. The exhaust pressure is controlled by a regulating valve to suit the needs of the process steam pressure. The extraction turbine (Figure 3.2) has opening(s) in its casing for extraction of a portion of the steam at some intermediate pressure. The extracted steam may be used for industrial process purpose or sent to boiler feed-water heaters to improve overall cycle efficiency. Extraction flows may be controlled with a valve, or left uncontrolled.

Steam turbines exhaust steam in a partially condensed state, at a pressure well below atmospheric to a condenser when used for purely power generation. Therefore, the traditional steam turbine based power plants are called condensing power plants. Between power (only) output of a condensing steam turbine and combined heat and power output of a backpressure steam turbine, essentially any ratio of power to heat output can be supplied to a facility.

Backpressure steam turbines can be obtained with a variety of backpressure controls, further increasing the variability of the power-to-heat ratio. For the steam turbine based CHP plant, power is a byproduct of heat generation with the system optimized for steam production. Consequently, the power efficiency of the steam turbine based CHP plant is not higher, from 10% to 30%.

However, the overall efficiency is high, approximating the efficiency of the steam boiler (70-90%) depending on operating conditions and age of the boiler. One of the advanced CHP production technologies is the backpressure plants with condensing and auxiliary cooling options to further improve the power efficiency of the steam turbine based CHP plants.

Here it is worth mentioning the role of the boiler for the steam turbine based generation system. The boiler acts as a buffer to separate fuels and the turbines and the fuels are burnt in the boiler. This separation of functions enables steam turbines to operate with an enormous variety of fuels from solid fuels such as coal, biomass residuals to liquid fuels such as oil to gaseous fuels such as natural gas.

2.1.2. Gas Turbines

As compared with steam turbines, gas turbines operate on the thermodynamic cycle known as the Brayton cycle. Heat is a byproduct of power generation for the gas turbine based CHP system and the power efficiency of the simple cycle gas turbine approximates 40%. The fuel of traditional gas turbine is natural gas. The modern gas turbine has demonstrated distinctive ability to accept a wide variety of gaseous and liquid fuels. To accept solid fuels, a gasifier, which transforms solid fuels into gases, needs to install. Figure 4 shows a schematic gas turbine system.

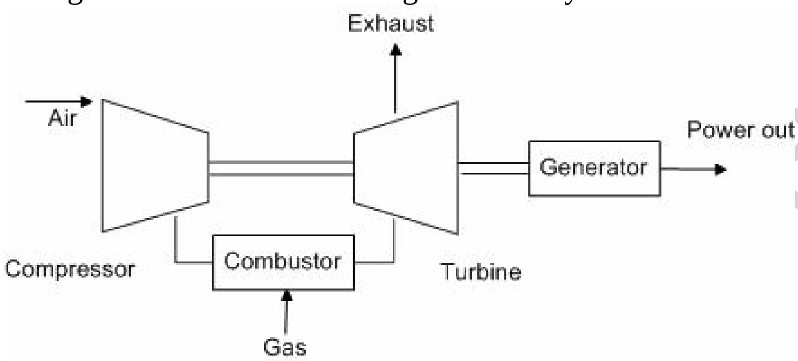

Figure 4. A schematic gas turbine system.

Gas turbine system has an upstream compressor coupled to a downstream turbine with a combustion chamber in-between. In a Brayton cycle, atmospheric air is compressed in a compressor and mixed with gas in the combustor, ignited and heated and then expanded in the turbine to generate power and at the same time exhaust heat. The quality of exhaust heat is high. For a simple cycle CHP application, a heat recovery heat exchanger can be used to recover the heat in the turbine exhaust and converts it to useful thermal energy usually in the form of steam or hot water to satisfy industrial or district heating steam requirements. Alternatively, this high temperature heat can be recuperated to drive a steam turbine in a combined cycle plant so that the efficiency of the power generation can be improved. Combined steam and gas cycle (CSGC) is one of the advanced CHP production technologies with higher power efficiency, which can extract steam at an intermediate pressure for use in industrial processes or district heating. The power efficiency of the CSGC CHP plant approximates 60%.

2.2. Characteristics of CHP Production

There are several characteristics in CHP production, which complicate the operation of a CHP system. First, electric power and heat are two energy commodities in a CHP system. They have one thing in common: they cannot be stored efficiently over a long period of time. Thus, it is necessary to balance supply and demand over a short period of time. Second, because heat cannot be transported economically over a long distance, CHP plants should be located close to where the heat can be consumed and are thus embedded in electricity networks, limiting transmission and distribution losses.

Therefore, heat must be balanced locally over a small area while power can be balanced either locally or globally (over a large area). Finally, interdependence of heat and power generation means that the production planning must be done in coordination.

These characteristics in conjunction with the new production technologies described in Section 2.1 pose challenge over the operation of a CHP system. It requires sophisticated models and efficient solution tools for handling the operation of the system efficiently.

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