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Power scheduling and real-time optimization of industrial cogeneration plants

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ABSTRACT

Scheduling of power and real-time optimization for three industrial cogeneration plants at one of Dow's Louisiana site is presented in this paper. A first principle mathematical model that includes mass and energy balances for gas turbines, heat recovery units, steam turbines, pressure relief valves and steam headers is used to formulate an optimization problem to recommend the best strategy to trade power. The model has detailed operational information that includes equipment status and control curves for different operating scenarios. The model can also accurately predict the effect of ambient temperature, thereby resulting in an optimal day-ahead schedule. Adjustment of power schedule is done in the real-time market 30 min prior to the hour and implementation of the dispatched power schedule is done using a model predictive controller.

1. Introduction

Efficient participation in day-ahead market for a combined heat and power (CHP) cogeneration plant requires effective decision support tools based on accurate predictions of steam and electricity production, and fuel consumption for various operating scenarios. A good survey on short term cogeneration planning that includes day-ahead market has been published (Salgado and Pedrero, 2008). Day-ahead short term planning typically consists of hourly planning intervals that require good predictions of fuel consumption and power generation by the cogeneration plant. The literature on cogeneration planning focuses on solution of the economic scheduling problem using mixed-integer linear programming (MILP) models (Marshman et al., 2010; Havel and Simovic, 2013; Mitra et al., 2013; Alipour et al., 2014). The non-linear process behavior is approximated using linearized models for turbines and boilers with constant efficiency (Marshman et al., 2010; Havel and Simovic, 2013; Mitra et al., 2013). MILP models are used to avoid numerical difficulties associated with fundamental models that are non-linear. Detailed fundamental, non-linear models of cogeneration plants have been used for design and operational optimization (Bruno et al., 1998; Varbanov et al., 2004; Koch et al., 2007; Godoy et al., 2011). Comparison of results from a case study for a cogeneration plant shows that a simplified MILP model with fixed efficiencies can lead to infeasibilities or sub-optimal solutions compared to detailed fundamental non-linear models (Bruno et al., 1998). Fundamental models have also been used for startup optimization of cogeneration processes (Tica et al., 2012; Negrete et al., 2013). Fast nonlinear model predictive control has been developed to reduce on-line computational load for startup optimization (Negrete et al., 2013). A two-tier formulation for real-time economic optimization based on steady-state models and model predictive control using dynamic models has been developed for industrial processes (Emoto et al., 1998; Rotava and Zanin, 2005; Mercangoz and Doyle, 2008). A non-hierarchal economic model predictive controller that dynamically optimizes transient and steady-state performance simultaneously has been proposed for processes where the steady-state operation is not optimal or transition cost is significant (Angeli et al., 2012; Amrit et al., 2013). A comprehensive survey on industrial model predictive technology that includes history of technology development and features of different vendor offerings has been provided (Qin and Badgwell, 2003).

The power scheduling calculations in this paper use a detailed steady-state, non-linear model that is also used for real-time optimization of the industrial process. Implementation of the optimized power schedule is done using a linear model predictive controller that uses empirical dynamic models. Fundamental

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nonlinear models with operational control strategy details will give more accurate predictions of the process and better participation in the power scheduling market compared to MILP models. The scheduling application of industrial cogeneration plants presented in this paper uses a first principle, steady-state, non-linear model with the following details:

- Model tuned continually with plant data and also used for online optimization
- Accounts for equipment that gets switched on or off
- Includes process control strategy that may use different equipment in an hierarchical manner
- Control curves and design performance curves for equipment

The scheduling application also has following capabilities

- User can input future ambient temperature
- User can switch parts of plant on or off to account for equipment contingency

The above modeling details enable the scheduler model predictions to have a close match with plant data for fuel consumption at different operating scenarios. The prediction error in fuel consumption from plant data is less than two percent over the entire operating range thereby allowing for efficient participation in the power scheduling market. Simpler linear models are not sufficiently accurate for scheduling power because they do not allow for control strategy, equipment control and performance curves, and inherent process nonlinearities.

The following section gives a description of the steady-state, non-linear process model for the cogeneration plants that includes gas turbines and steam turbines along with the associated control strategies. Section 3 presents model validation for the steady-state model including details on steady-state detection algorithm and parameter fitting procedure. Section 4 goes over the power scheduling calculations and the associated multiple optimization cases. These cases are done for both the day-ahead market and also the real-time adjustment of the power offer. Section 5 details the implementation of the scheduler that is performed using a real-time optimizer and an associated linear model predictive controller. Section 6 goes over results for model validation, power scheduling calculations and scheduler implementation. Stability of model parameters over the entire operating range is shown for model validation. The power schedule offer curve variation with ambient temperature and equipment contingency is illustrated. The effectiveness of optimized power schedule implementation using a linear model predictive controller is also shown for plant datasets.

2. Process description and model

The chemical site has three combined heat and power (CHP) plants (cogeneration plants) with seven gas turbines and five steam turbines capable of meeting the steam and electrical power needs of other chemical production facilities. Surplus power is produced that allows Dow to participate in the day-ahead Mid-Continent Independent System Operator (MISO) power market. Power is scheduled in the MISO day-ahead market close to production cost and adjustments to the power offer are made in real-time market 30 min prior to each hour. A steady-state model of the process that includes component material balances, energy balances and thermodynamics is developed in Aspen Plus Optimizer, AspenTech's equation oriented environment. A steady-state model is appropriate for scheduling power in cogeneration plants because the process dynamics for exported power are fast with a settling time of 3 min as compared to the scheduling interval of each hour.

Table 1
Unit operations and equations.

Unit operation	Equations
Compressor	Isentropic compression with performance curves
Combustor	Stoichiometric reactions
Turbine	Isentropic expansion with performance curves
Duct burners	Stoichiometric reactions
Heat exchangers	Material and enthalpy balances with heat transfer calculations
Boilers	Material and enthalpy balances with heat transfer calculations
Pumps	Pressure rise with design performance curves
Mixers	Material and enthalpy balances
Flash drum	Vapor–liquid separation at fixed temperature and pressure
Valves	Material and enthalpy balances with pressure drop calculations
Splitters	Material and enthalpy balances
Tier rate models	Split range control strategy equations
Calculators	Custom calculations

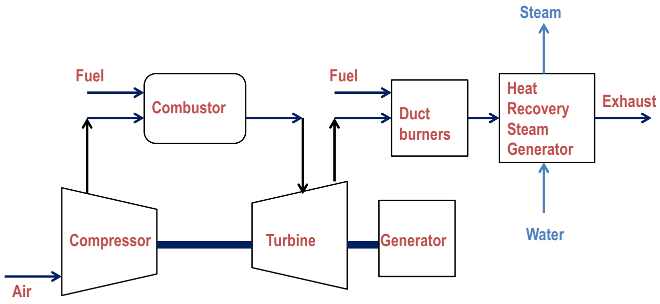

Fig. 1. Gas turbine.

The process model consists of equations describing gas turbines, steam turbines, heat exchangers, steam headers, fuel headers, condensate system, pressures relief valves, pumps and compressors. The process model in the equation oriented environment is also augmented with additional equations for process control strategy and equipment control specifications. The typical unit operations used as building blocks in the steady-state process model along with the associated equations are listed in Table 1. The overall steady-state process model consists of approximately 18,000 equations and can be expressed as

$$f(x, u, d, b) = 0, \quad y = h(x, u, d, b) \tag{1}$$

in which y are outputs, u are inputs, x are states, d are measured disturbances, and b are model parameters. The limits for the variables can be expressed as

$$u_{\min} \leq u \leq u_{\max}, \quad x_{\min} \leq x \leq x_{\max}, \quad y_{\min} \leq y \leq y_{\max} \tag{2}$$

The process modeling details for gas turbine, steam turbine and header pressure control are listed below.

2.1. Gas turbine

The gas turbine model consists of compressor, combustor, turbine, duct burners and heat recovery section as shown in Fig. 1. Design curves are used to characterize the compressor and turbine efficiencies instead of using a fixed efficiency over the entire operating range. Ambient air is raised to a higher pressure and temperature without any heat of reaction in the compressor. Fuel is injected in the combustor that provides mixing, burning and dilution. The mixed hot gas enters the turbine section, where it