Design of Flexible Utility Systems
Proceedings of European Congress of Chemical Engineering (ECCE-6)
Copenhagen, 16-20 September 2007

Design of Flexible Utility Systems

D. Zheng, J. K. Kim, W. Kwapinski, S. Perry, R. Smith

Centre for Process Integration, School of Chemical Engineering and Analytical Science, The University of Manchester, PO Box 88, Manchester, M60 1QD, Manchester, UK

Abstract

In order to meet the energy demands from industrial processes, utility plants must convert fuel and water into steam, electricity, and rotational power. Site utility systems are operated with different scenarios or operating conditions, due to variable conditions, such as different electric power tariffs, changing load in processes and variable ambient temperature. A novel methodology for the design and transient analysis of site utility systems has been developed to improve operability and cost-effectiveness of utility systems. There exist transient periods in which operating conditions of utility systems are changed from one scenario to another. The system must satisfy steam and power demands that change significantly according to process users' demands in both steady periods and transient periods. In this study, such transient behaviour is systematically investigated by using dynamic modelling and simulation of site utility systems, which enables flexible utility systems to be designed. Operating policies at steady-state are optimised to maximize the system efficiency or minimise costs, while variation of steam conditions (flowrate, pressure) are kept within acceptable bounds. Transient analysis is performed to check the feasibility of utility system design, analyze the operability and reliability of utility systems, and provide operating strategies in both steady-state operations and transient periods. Better understanding of transient phenomena can lead to cost savings as better use of equipment and/or less using standby capacity. A case study is presented to illustrate significant benefits which can be gained from the modelling framework and transient analysis.

Keywords: flexible utility systems, transient analysis, dynamic models

1. Introduction

The design and optimisation of site utility systems is one of the most challenging topics in process engineering, as the complexity of equipment networks and choice of operating conditions present significant challenges to optimise utility systems in practice. Traditionally, the design of utility systems has been proposed by considering a constant site configuration and fixed conditions. Some authors (Papoulias and Grossmann 1983; Petroulas and Reklaitis 1984) developed linear formulations to model utility units and others employed non-linear models to improve the accuracy of system calculations (Bruno, Fernandez et al. 1998). Recently, more dynamic factors have been introduced into design procedures for utility systems. Multiperiod optimisation was applied for retrofit of an existing utility plant (Hui and Natori 1996); discrete sizes have been accounted for utility units (Shang 2000); operation scenarios and equipment redundancy also improve the flexibility of process utility systems (Varbanov 2004; Aguilar 2005). However, such approaches are based on steady state assumptions and sometimes cause some practical problems in industrial practice.

There exist transient periods in which operating conditions of utility systems are changed from one scenario to another. Operating costs in transient periods have been assumed in the past to contribute to only a small potion of total operation cost. Little transient research has been done for utility system design in the past. However, there is always spare capacity to meet changing demands, according to transient behaviour. Dynamic simulation has been applied in energy systems and water/steam transport systems. Utility equipment has been modelled to analyze transient response to the periodic load changes (Kim, Kim et al. 2001; Cao, Jin et al. 2005). Although dynamic simulation has been performed to analyze transient behaviour of power plant (Shin, Jeon et al. 2002; Wischhusen and Schmitz 2004), industrial utility systems are more complex for variable steam main levels, different steam paths and many kinds of steam users.

In this study, such transient behaviour is systematically investigated by using dynamic modelling and simulation of site utility systems, which enables flexible utility systems to be designed. A case study is presented to illustrate significant benefits which can be gained from the modelling framework and transient analysis.

2. Modelling

Dynamic behaviour of a system can be described by conservation laws and motion equations. Transient characteristics of utility systems may be analyzed by using unsteady calculations. Although utility systems are dynamic, steady state models are popular for their high computational efficiency and accuracy when there are no great changes in system load. Thus, dynamic models have been developed for 'slow' utility equipment; steady and quasi-steady models can give adequate representation for fast-response equipment.

Boilers have a key role in transient behaviour because of the long response time when changing the load. In large process plants, drum boilers are used with furnace to generate high temperature and high pressure steam for heating. The transient behaviours of drum boilers are dominated by differential mass (eq.1) and energy balance (eq.2) equations for drum:

$$\frac{dM}{dt} = w_f - w_s \tag{1}$$

$$\frac{dE}{dt} = w_f \cdot h_f - w_s \cdot h_s + Q \tag{2}$$

Drum boiler model has been validated with published experimental data (Astrom and Bell 2000). Input data is feedwater flowrate, which is random controlled in the experiment. The model predicts drum pressure and water level to be compared with experimental data, shown in Figure 1. There is good agreement between model predictions and experimental data.

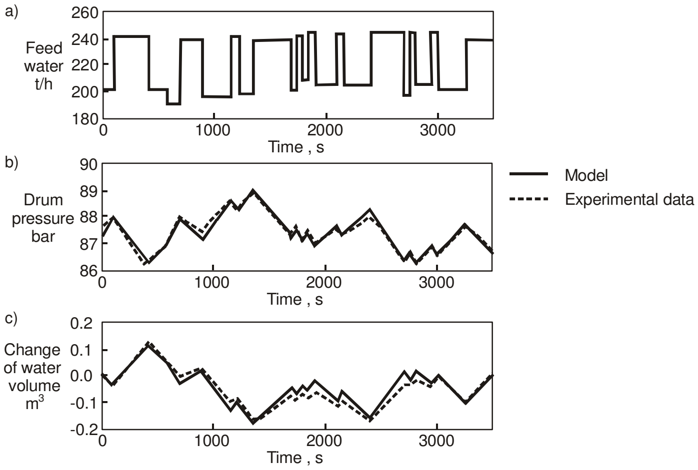

Figure 1 Boiler model validation; a) feedwater flowrate; b) water level in the drum; c) drum pressure. Solid line is model prediction. Dotted line is experiments data.

Gas turbines are well recognised to respond faster than boilers. But it would cost hours for gas turbines to start from cold state. Steam turbines also respond relatively fast, compared with boilers. Quasi-steady state models are employed for gas turbines and steam turbines when studying transient behaviour of utility system

Pipe pressure drop was neglected in steady state research on utility systems. However, in modern process plants, steam is usually obtained from cogeneration plant to improve the thermal efficiency. When steam users are far away from a steam source, e.g. several hundreds metres or more, transient behaviour of steam mains cannot be neglected. Unsteady equation for one-dimension compressible fluid has to be employed to calculate the steam flow between the nodes.

3. Methodology

Dynamic behaviour of a system can be described by conservation laws and motion equations. Transient characteristics of utility systems may be analyzed by using unsteady calculations. It is, however, inefficient to apply the unsteady simulation directly. It has been acknowledged that unsteady one-dimensional simulation gives sufficiently accurate results for utility systems. Therefore, Simplified dynamic and quasi-steady models have been developed for transient analysis in the periods of such operation changes. All the models are validated with published experimental data or more detailed models.

Utility equipment models are developed in MATLAB/SIMULINK environment, which is selected for its capabilities of build-in algorithm control design, optimisation toolbox and simulation. Dynamic simulation is undertaken in order to analyse the transient behaviour of utility systems. Based on that, a novel methodology for the design and dynamic optimisation of site utility systems has been developed to improve operability and cost-effectiveness of utility systems.

The proposed methodology aims to provide an optimised equipment network structure together with operating policies to minimise total operating cost, improving flexibility, operability and stability of the utility system. The design procedure includes problem setup, equipment network structure design and operation optimisation.

3.1. Problem setup

Due to variable conditions in industrial practice, such as peak and off-peak power tariff, ambient temperatures, flowsheet information of the system is carefully investigated to summarise steam, electric power and shaft work demand in multiple scenarios. Properties of utility equipment are also important to design a utility system, including maximum capacity and efficiency.

There are many constraints in the design of utility system. Equipment have their own physical limit, such as maximum operating temperature in HRSG, maximum pressure in drum boiler or maximum rotation rate in turbines. According to the contracts with third-party power providers, there are also limits for power importing or exporting. Other social or economic constraints often have an important influence on the design problem.

Economic target is the most important objective function for utility system design problem. But system reliability can not be omitted in industrial practise.

3.2. Equipment network structure design

Steady state models are employed to design the network structure of utility equipment, for their enough accuracy in long-term running and much more calculating efficiency.

Model parameters are regressed by using equipment operating data if possible. Then the whole utility plant is simulated in order to evaluate the overall objective functions, e.g. economic target, throughout possible structural and operating options. The corresponding optimisation can be performed to determine the design draft of the system, including equipment network structure and operation scenarios.

3.3. Operation optimisation

Transient behaviour of the system is simulated by using dynamic models of utility equipment. Steam and power supply must satisfy the process demands and assure the utility system running smoothly and safely in transient period.

Equipment sizes and operating policies, such as boiler working loads, standby capacity and steam distribution paths, are optimised to minimize operating cost, while variation of steam conditions in scenario-transition period, simulated based on dynamic models, is kept within acceptable bounds.

4. Case study

A case study presents the application of proposed methodology on a site utility system, which comprises of five working boilers, a gas turbine with heat recovery steam generator, two spare boilers and four steam turbines. A certain situation is considered by introducing burner failure in Boiler 1 at time 100s. The sizes and optimised working loads are shown in table 1, based on design results from steady state models.

Table 1 Boilers information for case study

Boilers	1	2	3	4	5	6
Size , kg/s	75	75	75	75	50	50
Load , % (option 1 and 2)	100	100	100	0	100	0
Load , % (option 3)	86.7	86.7	86.7	0	80	80

The burner failure in boiler 1 causes a sharply drop in steam generation. VHP (very high pressure steam) pressure is maintained by controlling the inlet valve of steam turbine 1. Spare boilers and part-load boilers increase their load according to variable operating options to cover the steam loss in utility systems.

Option 1: only boiler 4 comes online. Boiler 4 comes online more slowly than load decrease in boiler 1. The total steam output into the steam mains also drop sharply and maximum steam loss happens at time 950s (Figure 2b).

Option 2: boiler 4 and boiler 6 come online together. Boiler 4 and boiler 6 come online together to cover most of steam loss. Finally, boiler 4 runs at full load for high efficiency and boiler 6 offline again (Figure 2a).

Option 3: optimize the working loads based on transient analysis. When boiler 1 breakdowns, other working part-load boilers increase loads and spare boiler 4 comes online. The system response is better than Option 1 or 2 (Figure 2b).

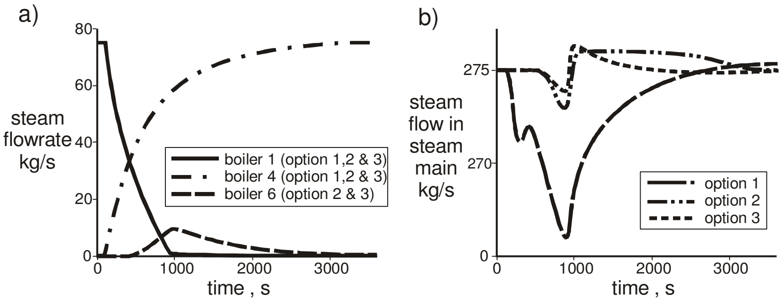

Figure 2 Transient behaviour of a) boilers and b) VHP

There are various steam distribution policies throughout network. Steam is normally provided to processes prior to steam turbines (called steam first policy), because electrical power is easier to balance than steam. In some cases, important equipment, e.g. compressors, is driven directly by steam turbines. Steam supply need satisfy the demands of such direct-drive steam turbines first (called power first policy). In other cases, when steam pressure drops, steam flowrates to processes and steam turbines reduce simultaneously (called fixed ratio). Figure 3 shows the power output of steam turbine 4 under different distribution policies.

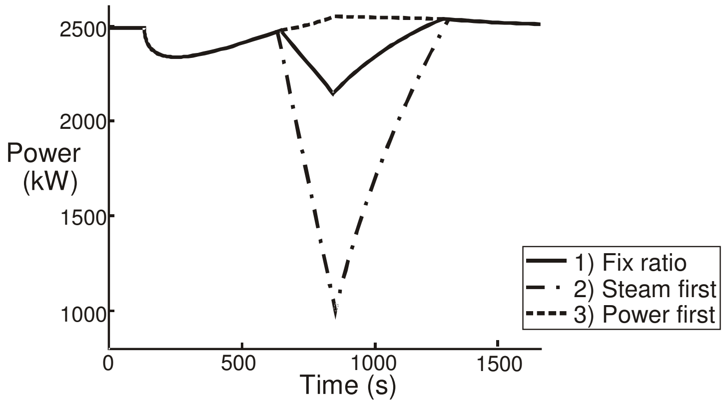

Figure 3 Power changes produced by turbine 4

5. Conclusion

Site utility systems are inevitably operated with different scenarios or operating conditions, due to variable conditions, such as different electric power tariffs, changing load in processes and variable ambient temperature. Therefore, utility systems should be flexible enough to change operating conditions (or scenarios) from one to another at minimum penalty and disturbance to the overall systems. Simplified dynamic models have been developed for transient analysis in the periods of such changes.

Excessive spare capacity is usually a feature of the design of utility systems. This arises from the many uncertainties in the operation of utility systems. This study also presents a novel methodology for the design and optimisation of flexible utility systems based on transient analysis, taking account of the necessity to use spare capacity in the utility systems optimally. Decisions on operating scenarios are made by considering variable conditions. When the operating state transits from one state to another to satisfy processes demand, it is necessary to use dynamic model to check feasibility of the system in transient periods. Operating policies at steady-state are optimised to maximise the system efficiency or minimise costs, while variation of steam conditions (flowrate, pressure) are kept within acceptable bounds. Understanding transients better could lead to capital cost savings through less standby capacity.

Acknowledge

The support from an EC Marie Curie Research Training Network "Towards Knowledge-Based Processing Systems (PRISM)"; Contract No: MRTN-CT-2004-512233 is gratefully acknowledged.

References

Aguilar, O. (2005). Design and optimisation of flexible utility systems. Centre for process integration. Manchester, University of Manchester.

Astrom, K. J. and R. D. Bell (2000). "Drum-boiler dynamics." Automatica **36**(3): 363-378.

Bruno, J. C., F. Fernandez, et al. (1998). "A Rigorous MINLP Model for the Optimal Synthesis and Operation of Utility Plants." Chemical Engineering Research and Design **76**(A3 Special issue: Techno-Economic Analysis): 246.

Cao, Y., X. Jin, et al. (2005). "Computational modular model library of gas turbine." Advances in Engineering Software **36**(2): 127-134.

Hui, C.-W. and Y. Natori (1996). "An industrial application using mixed-integer programming technique: A multi-period utility system model." Computers & Chemical Engineering **20**(Supplement 2): S1577-S1582.

Kim, J. H., T. S. Kim, et al. (2001). "Analysis of the dynamic behaviour of regenerative gas turbines." Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy **215**(3): 339-346.

Papoulias, S. A. and I. E. Grossmann (1983). "A structural optimization approach in process synthesis--I : Utility systems." Computers & Chemical Engineering **7**(6): 695-706.

Petroulas, T. and G. V. Reklaitis (1984). "Computer-aided synthesis and design of plant utility systems." American institute of Chemical Engineering Journal **30**(1): 69-78.

Shang, Z. (2000). Analysis and optimisation of total site utility systems. Department of process integration. Manchester, UMIST.

Shin, J. Y., Y. J. Jeon, et al. (2002). "Analysis of the dynamic characteristics of a combined-cycle power plant." Energy **27**(12): 1085-1098.

Varbanov, P. S. (2004). Optimisation and synthesis of process utility systems. department of process integration. Manchester, UMIST.

Wischhusen, S. and G. Schmitz (2004). "Transient simulation as an economical analysis method for energy supply systems for buildings or industry." Applied Thermal Engineering **24**(14-15): 2157-2170.