Simple Models for Model-based Portfolio Load Balancing Controller Synthesis

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Abstract: This paper presents a collection of models of so-called 'effectuators', i.e., subsystems in a power plant portfolio that represent control actions with associated dynamics and actuation costs. These models are derived in order to facilitate higher-level model-based control synthesis of a portfolio of generation units existing in an electrical power supply network, for instance in model-based predictive control or declarative control schemes. We focus on the effectuators found in the Danish power system. In particular, the paper presents models for boiler load, district heating, condensate throttling and wind turbine effectuators. Each model is validated against actual measurement data. Considering their simplicity, the models fit the observed data very well and are thus suitable for control purposes.

Keywords: Power system control, Dynamic modelling, Power plant control, Load regulation

1. INTRODUCTION

Currently a large part of the world is deeply concerned about global warming and the consequences that might follow from emission of green house gases. This has among other things led to the signing of the Kyoto Protocol (United Nations, 1998). Throughout Europe, this has given use to a very ambitious project to increase the share of energy delivered by renewable sources such as wind (UCTE, 2007). In Denmark the goal is to increase the share of electrical energy coming from renewable sources from 24% in 2005 to 36% in 2025 as found in Transport- og Energiministeriet (2005).

Due to the geography of Denmark much of this renewable energy has to come from wind turbines. Given the stochastic behaviour of the wind turbines, a flexible power system and good load balancing control is needed, in order to avoid blackouts.

DONG Energy owns and operates a portfolio of power plants in Western Denmark as shown in Fig. 1. With respect to the communication with the Transmission System Operator (TSO), this portfolio is considered as one entity both regarding deviations and activation of reserves. To accommodate this, DONG Energy has created a load balancing controller to minimise the deviation of the portfolio from the reference as well as distribute the ordered reserve activation.

In Edlund et al. (2008) we showed through simulations that it was possible to significantly decrease the deviation between the portfolio output and the reference by introducing a model-based control scheme for the balance controller. The focus was to show that it is possible to gain better economics and decrease the deviation, and only little attention was paid to the models used in the

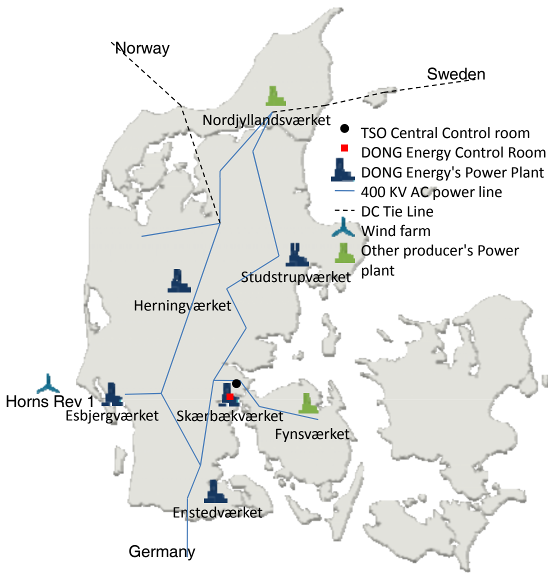

Fig. 1. Generators participating in balance control in Western Denmark

control scheme. In this paper we focus on the models of the generation units. A control strategy for how to coordinate the individual effectuators is not discussed in this paper.

In the existing literature there are many detailed models of parts of the energy system, used to describe the dynamic behaviour of individual system components, such as de Mello (1991); Weber and Krueger (2008); Welfonder (1997). However, the aim in this paper is to construct simple models which are suitable for controller synthesis of a model-based control scheme for load balancing control.

There are many ways to manipulate the output from the portfolio to follow the references. Here we shall use the term *effectuator* as a unifying term for all of them.

Definition 1. An effectuator is a process or part of a process in a power system that represents control actions with associated dynamics and actuation costs allowing the power output to be manipulated.

Some parts of the power system, eg power plants, contain multiple ways of changing the power output and will therefore be treated as providing more than one effectuator. Regarding the effectuators as individual system is a novel approach when comparing to eg Lausterer (1998).

The paper is structured such that the description and modelling of the effectuators are in Section 2. This is followed by a validation of each effectuator in Section 3, and a discussion in Section 4.

2. MODELLING

A description and mathematical model of each of the four types of effectuator is presented in this section. The first three effectuators are physically parts of the thermal power plants, while the fourth - wind turbines - are located elsewhere eg off-shore.

2.1 Boiler Load Effectuator

The boiler load effectuator affects the whole steam cycle. It is activated by offsetting the production reference. The boiler has an operating range, shown in the PQ-diagram in Fig.2. The district heating production (Q) is plotted along the x-axis and the power production (P) along the y-axis. There are upper and lower limits on the power production, which dependent on the current district heating production.

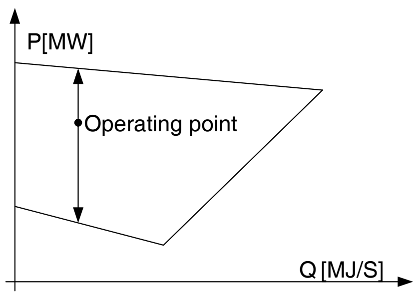

Fig. 2. Movement in the PQ-diagram when changing the boiler load

When using the boiler for control purposes the district heating production is maintained, meaning that the changes in production happens vertically in the PQ-diagram as shown in Fig. 2.

This effectuator is slow in a load balancing context (minutes), but the potential energy production is unlimited, meaning that the corrections can be maintained by this effectuator for an unlimited time period. There is a large amount of power available in this type of effectuator.

Besides the behaviour of the boiler, there is a communication delay between the load balancing controller and the power plant. However, this delay is so small compared to the dynamics that it can be neglected for this effectuator.

Effectuator Model There are two communication methods for activating the boiler load effectuator in a power plant, either through the production plan or through an input used by the balance controller to give real time corrections to the boiler load effectuator. The production plan is not controllable and is therefore modelled as a disturbance. The output of the model is the produced power from the unit caused by the boiler load effectuator.

The model is formulated as a greybox model and the dynamics are assumed to be adequately described as the following state space system

$$\dot{x}_b = \begin{bmatrix} -T_b^{-1} & 0 & 0 \\ T_b^{-1} & -T_b^{-1} & 0 \\ 0 & T_b^{-1} & -T_b^{-1} \end{bmatrix} x_b + \begin{bmatrix} T_b^{-1} \\ 0 \\ 0 \end{bmatrix} u + \begin{bmatrix} T_b^{-1} \\ 0 \\ 0 \end{bmatrix} d$$
$$y = [\,0\ 0\ 1\,]\, x_b. \tag{1}$$

where T_b is the time constant for the effectuator. u is the input given by the balance controller, d is the production plan and additional manually ordered corrections.

Upper and Lower limits The limits can be set by the operator, or can be given by the process. The limits are applied to the input such that $\underline{P_b} \leq u \leq \overline{P}_b$. It is assumed that the upper limit is non-negative and the lower limit is non-positive.

Only the limits derived from the process are described here. The upper limit can be approximated by a linear constraint as a function of the district heating production.

$$\overline{P_b} = -\alpha_{max} Q + \beta_{max} - d \tag{2}$$

where α_{max} is an approximation of the C_v value (see below) at maximum load, Q is the current district heating production and β_{max} will be the maximum power production at no district heating production.

The lower limit can be described as piecewise linear function

$$\underline{P_b} = max \begin{cases} \alpha_{min} Q + \beta_{min} - d \\ C_m Q + \beta_b - d \end{cases} \tag{3}$$

where α_{min} is an approximation of the C_v value at minimum load and β_{min} will be the minimum power production in condensation mode. The lower equation is a linear approximation of the pure back pressure line as shown in Fig. 3.

Rate Constraints The rate limits are all piecewise linear functions of power and district heating production. The rate limits are set in the control system, and can therefore be determined precisely.

The rate limit for the balance controller is the absolute rate limit minus the disturbance (d). It is assumed that zero is always in the interval between the lower and upper rate limit.

2.2 District Heating Effectuator

The centralised Danish power plants with district heating production have a possibility to bypass part of the power generation process and instead use the energy to produce district heating. Unlike power production, district heating

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