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Introducing Model Predictive Control for Improving Power Plant Portfolio Performance

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Abstract: This paper introduces a model predictive control (MPC) approach to construction of a controller for balancing power generation against consumption in a power system. The objective of the controller is to coordinate a portfolio consisting of multiple power plant units in an effort to perform reference tracking and disturbance rejection in an economically optimal way. The performance function is chosen as a mixture of the ℓ_1-norm and a linear weighting to model the economics of the system. Simulations show a significant improvement of the performance of the MPC compared to the current implementation consisting of a distributed PI controller structure, both in terms of minimising the overall cost but also in terms of the ability to minimise deviation, which is the classical objective.

Keywords: Power plants; Predictive control; Model-based control

1. INTRODUCTION

This paper focuses on the power system in the western part of Denmark, where DONG Energy (DONG Energy (2007))is the largest power producer. Being a major power producer also means that DONG Energy provides a major part of the balancing reserves for the transmission system operator (TSO), who has the overall load balancing responsibility. Load balancing means making the production equal to the consumption. In 2007 approximately 30% of the installed capacity in West Denmark was wind turbines - a large share compared to other areas of Europe. This makes balance control a difficult issue due to the stochastic behaviour of the wind-based production. Today, balancing can be done partly by exporting the electricity to other parts of Europe and partly by adjusting the load of the other production units. However, with the increasing integration of wind power the current balance control system must be improved in order to be able to handle the changing conditions in the future.

The deregulation and decentralisation of the European power system complicate coordination of control actions. In UCTE (2007) it is predicted that a significant number of wind turbines will be installed in Europe. This will introduce more stochastic production, which calls for improved control of the power system to balance production and consumption in order to avoid large blackouts in the future.

The fluctuation in Denmark introduced by the wind turbines has made it necessary to commission an AGC (Automatic Generation Control) which is able to activate a reserve of ±140MW to take care of small and quick deviations (UCTE (2007)). This AGC is controlled by the TSO, which sends an activation signal to the balancing participants, who are then responsible for activating the required reserves. The reserves are activated by changing the load distribution among a portfolio of power plants.

The controller which distributes the reserve activation within the DONG Energy portfolio is responsible for maintaining the load balance within the portfolio on a seconds-to-minutes horizon, until the economic dispatch can take over and handle the short term (minutes-to-hours) load balancing. The controller is therefore referred to as the load balancing controller, not to be mistaken for the AGC at the TSO.

The portfolio is a very complex system and the optimisation and control are therefore ordered in a hierarchical fashion in order to break down the complexity as described in Mølbak (2003). The economic dispatch as well as the load balancing are handled mainly on the system level as described in Jørgensen et al. (2006).

The load balancing controller is currently based on a distributed PI controller structure and ad hoc methods to obtain the desired behaviour of the system. The requirements and wishes for the balance controller keep increasing, rapidly pushing the method to the limit of what is possible. In particular, requests for optimality according to a performance function have arisen, which cannot be guaranteed with the current system setup. Also, operation closer to the limits is required. The first versions of the load balancing controller were focused only on minimising the deviation from the reference production, but recently focus has shifted towards minimising the deviation as economically as possible. This calls for methods which are better

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suited for handling large multiple-input-multple-outpout (MIMO) systems with multiple performance measures.

Much work has been done to enhance the disturbance rejection capabilities of single power plants, see Welfonder (1997) and Lausterer (1998). However, real-time coordination of several units in an effort to perform disturbance rejection has not been reported in the literature before.

This paper presents the first step towards establishing a more stringent method for handling balance control of a power system portfolio. A model-based MIMO control solution based on Model Predictive Control (MPC) offering inherent constraint handling and systematic utilisation of feed forward is presented. A short introduction to the system is given in section 2 followed by the derivation of a simple state space model and constraints, which are used in the construction of the controller (section 3). Based on the stated optimisation goals, a performance function consisting of linear weighting and ℓ_1-norms is derived in section 4 and used to construct a controller for the system. In section 5, the controller is tested in two different scenarios illustrating the reference tracking ability and disturbance rejection capabilities of the solution. The results are compared to the current implementation of the balance controller.

2. SYSTEM DESCRIPTION

A quick introduction to the Danish power production system and the highest level of the hierarchy of DONG Energy is given here. For more details, see Jørgensen et al. (2006).

The Danish power production can be split into two categories; *planned production* and *reserves*. The planned production is the production known ahead of time, which means long-term contracts and power sold on the power exchange 8-36 hours ahead of production time. Reserves are power production which can be activated quickly and which is used to compensate for imbalances. The reserves are a service requested by the Danish Transmission System Operator (TSO) who has the responsibility for maintaining the balance within the Danish region. There are different kinds of reserves, see Jørgensen et al. (2006) for details. For the sake of simplicity, this paper only considers the automatic reserves.

An overview of the interaction of the different subsystems is presented in Fig. 1. A short-term load scheduler (STLS) performs optimisation for the distribution of power generation resulting in a 5-minute based 24-hour production plan, which is sent to the production units. To compensate for the dead time of the production units, the production plan is issued as a reference feed-forward.

Based on the imbalances within the Danish region, the TSO generates a reference signal, and the portfolio is then expected to respond to the reference with a given dynamic response.

The load balancing controller shown in Fig. 1 serves two purposes. It manages the coordination of the production units to obtain the expected response to the TSO reference signal. The second purpose is to minimise the deviation between the actual total production and the reference production. This way, the power controller compensates for the unavoidable discrepancies that will occur due to the feed-forward nature of the STLS.

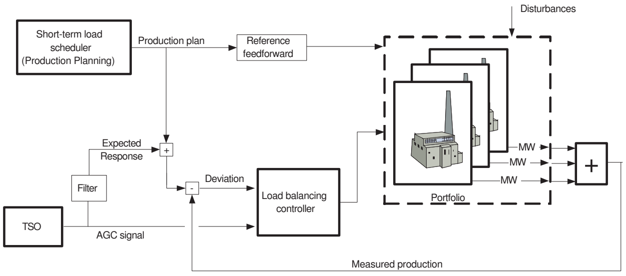

Fig. 1. Overview of the portfolio at system level

The current active portfolio consists of six units placed at five different power plants. The maximum power output of the units in the portfolio ranges from 80MW to 650MW, and the units also vary in terms of dynamic behaviour.

Note that the term 'unit' covers the physical process from fuel input to generator as well as the control system controlling the process.

3. MODELLING

As the focus of this paper is to establish a model-based method for constructing a load balancing controller, this section describes the model of the portfolio used by the controller. Fig. 2 is a schematic view of the model of a single unit. The input to the model is a reference given to the control system, and the output is the measured power output from the unit.

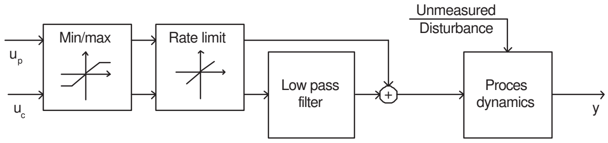

Fig. 2. Schematic of the unit model used in the controller

The input to the model can be divided into two; the production plan (u_p), which is uncontrollable by the controller and therefore regarded as a disturbance, and the balance controller input (u_c) to the system.

The unit model consists of two parts; the control system and the system process. The part of the control system influencing the model the most is the limits on the reference signals, both in form of a max/min bound and a limit on the rate of change. The dynamics of the process are approximated by a third order model with real stable poles, which in this context describes the process dynamics reasonably well.

The max/min bound in Fig. 2 is to be interpreted as

$$u_{min,k} \leq u_{c,k} + u_{p,k} \leq u_{max,k} \tag{1}$$

meaning that the sum of the inputs are bounded at each sample k.

The same applies for the rate limiter namely

$$\Delta u_{min,k} \leq \Delta u_{c,k} + \Delta u_{p,k} \leq \Delta u_{max,k} \tag{2}$$

where

$$\Delta u_{c,k} = u_{c,k} - u_{c,k-1}$$
$$\Delta u_{p,k} = u_{p,k} - u_{p,k-1}$$

The low pass filter is implemented in the control system in order to avoid abrupt changes from the currently implemented PI controllers. The actual filter implemented in the control systems varies slightly between the units, but it is typically a third order filter with three time constants of 10s.

The dynamic parts of the model are formulated as a state space model as shown in (3). The rate limitation and the max/min bound are formulated as input constraints. That is,

$$\begin{aligned} x_{j,k+1} &= A_j x_k + B_j u_k + E_j d_k \\ y_k &= C_j x_k \end{aligned} \qquad (3)$$

$$s.t.$$

$$u_{min,k} \leq u_{c,k} + u_{p,k} \leq u_{max,k}$$
$$\Delta u_{min,k} \leq \Delta u_{c,k} + \Delta u_{p,k} \leq \Delta u_{max,k}$$

for each unit $j = 1, \ldots, 6$ and $x_j \in \mathbb{R}^{N_j}$, etc.

The production plan is treated as a disturbance since it cannot be controlled by the load balancing controller. Thus each unit model has one input, one disturbance and one output.

The individual unit models can be compiled into one portfolio model by constructing large block diagonal matrices containing the individual unit models. The output matrix is also constructed as a block diagonal matrix, but has to be expanded to contain an output describing the total portfolio output, ie,

$$A = \begin{bmatrix} A_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & A_6 \end{bmatrix}, B = \begin{bmatrix} B_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & B_6 \end{bmatrix}, \qquad (4)$$

$$E = \begin{bmatrix} E_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & E_6 \end{bmatrix}, C = \begin{bmatrix} C_1 & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & C_6 \\ C_1 & \ldots & C_6 \end{bmatrix} \qquad (5)$$

This means that the input, state and output vectors of the portfolio model are

$$u_k = \begin{bmatrix} u_{1,k} \\ u_{2,k} \\ \vdots \\ u_{6,k} \end{bmatrix}, x_k = \begin{bmatrix} x_{1,k} \\ x_{2,k} \\ \vdots \\ x_{6,k} \end{bmatrix}, y_k = \begin{bmatrix} y_{1,k} \\ y_{2,k} \\ \vdots \\ y_{6,k} \\ y_{total,k} \end{bmatrix} \qquad (6)$$

where $y_{total,k} = \sum_{j=1}^{6} y_{j,k}$.

4. THE LOAD BALANCING OPTIMISATION PROBLEM

The structure of the problem is as follows:

$$\min_U J \qquad (7)$$

$$s.t.$$

$$x_{k+1} = Ax_k + Bu_k + Ed_k$$
$$y_k = Cx_k$$
$$U_{min} \leq U \leq U_{max}$$
$$\Delta U_{min} \leq \Delta U \leq \Delta U_{max}$$

where J is a performance function which has to be minimised without violating the constraints, U is a vector containing all inputs over the prediction horizon $k = 0, \ldots, N$ such that $U = [u_0^T, u_1^T, \ldots, u_N^T]^T$.

4.1 Choosing a performance function

The load balancing problem has two main objectives from which the performance function should be constructed; the deviation from the reference production should be minimised, and this should be done as economically as possible.

Definition 1. In the following the weighted ℓ_1-norm is denoted as $||\cdot||_{1,q}$ with the weight q. For a vector $x = [x_1, x_2, \ldots x_N]^T$ the weighted ℓ_1-norm is defined as

$$||x||_{1,q} = q_1|x_1| + q_2|x_2| + \ldots + q_N|x_N|.$$

The deviation can be posed as a financial objective as well, since imbalances are fined by the TSO, who has the overall load balancing responsibility in Denmark. Posing the deviation as a financial optimisation problem entails that the overall performance function has to describe the expenses for obtaining the reference production. The cost of deviations can be described by the weighted ℓ_1-norm such that

$$J_e = \sum_{k=1}^{N} ||y_k - r_k||_{1,q_{e,k}} \qquad (8)$$

where y_k is the system output vector, r_k is the system reference vector and $q_{e,k}$ is a cost vector for the deviations. The cost is summed up over the prediction horizon $k = 1, \ldots, N$.

The production plan for each plant is assumed to be economically optimal, therefore the output reference for each of the units is the production plan reference (denoted $r_{j,k}$ for unit j at sample k).

The reference to the total production is combined by two sources. One source is the summed production plans for all the power plants, and the other source is the signal from the TSO ($r_{TSO,k}$). This results in a reference vector

$$r_k = \begin{bmatrix} r_{1,k} \\ r_{2,k} \\ \vdots \\ r_{6,k} \\ r_{total,k} \end{bmatrix} \qquad (9)$$

where $r_{total,k} = r_{TSO,k} + \sum_{j=1}^{6} r_{j,k}$. Since $r_{total,k}$ has an addition from $r_{TSO,k}$, it is impossible to track all references without error in all cases where $r_{total,k} \neq 0$.

The other part of the expenses is the production costs. Intuitively, these costs should be placed on the input since they are dominated by the fuel cost. However, placing the weight on the input will make it seem beneficial to lower the input since the output deviation will not occur until some time into the future, due to the phase lag through the system. When the cost is summed over the finite horizon, the cost of lowering the input would thus yield a greater benefit than the penalty of the deviation - an unintended behaviour. Therefore the weight is placed on the output to avoid this phase lag. The production cost function is described as

$$J_u = \sum_{k=1}^{N} q_{u,k}^T y_k \tag{10}$$

where $q_{u,k}$ is the marginal cost factor and y_k is the system output.

A cost on input change is added to the performance function in order to dampen the input signals to the system. Even though changing the input should not have any significant cost, leaving this part out yields a significantly degraded performance, due to rapidly changing control signals that will expose the discrepancies between model and the real system. This is formulated as a weighted ℓ_1-norm yielding

$$J_{\Delta u} = \sum_{k=0}^{N-1} ||\Delta u_k||_{1,q_{\Delta u,k}} \tag{11}$$

where Δu_k is the change in input and $q_{\Delta u,k}$ is the penalty for changing the input.

These functions can be combined into one objective function

$$J = J_e + J_u + J_{\Delta U}. \tag{12}$$

This performance function can be transformed into a linear program by variable substitution as described in Maciejowski (2002). The linear program can be efficiently minimised by a standard Linear Programming (LP) solver.

4.2 Notes on tuning the performance function

Since the price of deviating from the total production is not known until a few hours after the deviation, the price has to be estimated. The price of reserve activation at the power exchange Nordpool ranged from 0.5 to 93€/MWh over the period from 6 to 13 July 2007. Choosing it too low will make it beneficial to deviate from the total production creating steady-state offsets which should be avoided. Therefore an estimate of 80€/MWh is chosen for both positive and negative deviations.

A unit's deviation from the production plan is not penalised financially, only the deviation of total portfolio output is. However, it is desired to adhere to the production plan, which is why a weight is put on the individual unit's deviation from the production plan.

The weight on the deviation must be chosen such that it is not in conflict with the overall optimisation goal. However, as it is kept within an upper and lower bound, the actual weight does not influence the result. The upper bound on the unit deviation penalty is equal to the penalty for deviating from the portfolio reference. Otherwise, it would be optimal to deviate from the total output in case of disturbances.

The lower bound on the unit deviation penalty is equal to the price difference between the production costs of the cheapest and most expensive unit. Otherwise, it would always be beneficial to bring the cheapest unit to the maximum and the most expensive units to the minimum in steady state. And this would in turn compromise the assumption that the production plans are optimal when in steady state

5. IMPLEMENTATION AND RESULTS

The controller environment and the simulation models are implemented in Matlab/Simulink. The controller is formulated as a linear program, which means that it can be solved by an LP solver. For this purpose GLPK from Makhorin (2007) with the GLPKMEX matlab interface from Giorgetti (2007) is chosen.

5.1 Bounds and limits

Due to the formulation of constraints on the input it is possible for the production plan to move outside the operator set bounds such that the upper bound on input becomes negative or the lower bound becomes positive. The controller should not try to compensate for poorly chosen limits, so the bounds in the implementation are formulated such that

$$u_{min} \leq 0 \leq u_{max} \tag{13}$$

The rate limits on the units are load dependent since the process is significantly easier to control in some areas than in others; therefore, a higher rate of change is allowed in these areas. To linearise the constraint, it is assumed that the rate limit is constant over the prediction horizon $k = 0, \ldots, N$ with the value obtained at $k = 0$.

5.2 Reference signals

The production plans are known ahead of time and are therefore used in a feed-forward manner. Unlike the production plan the reference signal r_{TSO} is generated in real time and is therefore not known. The best guess is that it will be constant into the future. However, it is known that the portfolio is supposed to respond with a filtered version of the reference signal from the TSO, and therefore a filtered version of the signal from the TSO is added to the controller reference.

5.3 Simulations

The controller is evaluated and compared to the current implementation, which consists of a PI controller structure, via simulation against a nonlinear model of the portfolio. The controller will be evaluated in two different scenarios, and each scenario will be evaluated based on two different parameters. The first parameter is the ability to perform reference tracking and disturbance rejection, formulated as:

$$\delta = \sum_{k=0}^{K} ||r_{total,k} - y_{total,k}||_1 \tag{14}$$

which is the portfolio deviation from the reference, summed over the whole period.

The second parameter is the production costs and deviation penalties

$$c_x = \sum_{k=0}^{K} q_{e,total}(|r_{total,k} - y_{total,k}|) + \sum_{k=0}^{K} q_f^T y_k \qquad (15)$$

where y_k is a vector of plant output, q_f is a vector of fuel costs and $q_{e,total}$ is the cost of deviation of the portfolio. Since the deviation cost (q_e) fluctuates, the controllers are compared with a deviation cost of €0, €13 and €80 per MWh denoted with the subscripted x.

The production prices used in the evaluated scenarios are fictive but based on the different types of fuel present in the portfolio. The prices used in the evaluation are shown in Table 1. The prices are assumed to contain all load dependent costs of producing power on a particular unit.

Unit	1	2	3	4	5	6
Cost	22.9	24.6	18.0	43.0	26.9	28.1

Table 1. Price in €/MWh

5.4 Scenario 1: Output disturbance

This scenario evaluates how well the controllers perform with regard to disturbance rejection. At $t = 500s$, zero-mean gaussian noise with variance 33.2 is added to the output of the portfolio (y_{total}). The noise emulates process disturbances, which should be suppressed by the controller. The production plans are constant throughout the scenario. Fig. 3 shows the scenario results with the PI controller as well as the MPC.

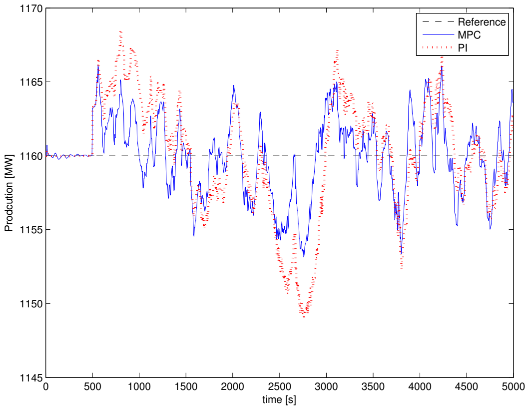

Fig. 3. Scenario 1 - Portfolio output

The results of the objective functions (14) and (15) are found in Table 2.

	δ	c_0	c_{13}	c_{80}
PI	4.29 MWh	€47782	€47837	€48125
MPC	2.84 MWh	€47677	€47714	€47904
Improvement	34%	0.22%	0.26%	0.46%

Table 2. Scenario 1 - Comparison

The input signals from the controllers are shown in Fig. 4. The MPC control signals change rapidly compared to the control signals from the PI controllers. In general, this results in a better disturbance rejection for the MPC, which reduces the deviation by 34% compared to the PI controllers as seen in Table 2. There is a large difference in the coordination of the input signals to the units. The PI controllers distribute correction signals among all units, where the MPC exploits the knowledge on economics, using the cheapest unit when extra power is needed, and using the most expensive unit when too much power is produced. This result cannot be obtained by retuning the current implementation of the PI controllers.

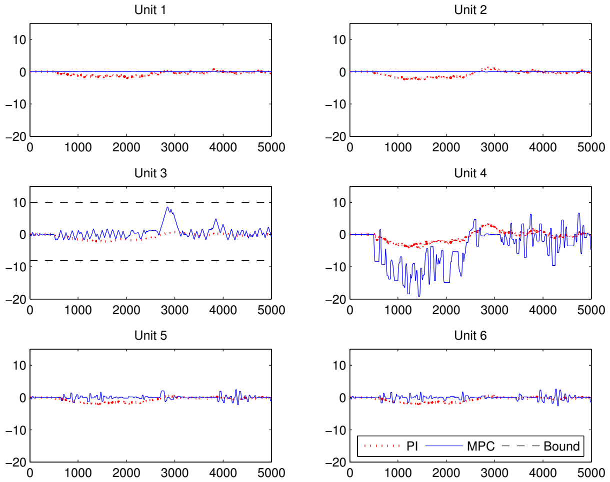

Fig. 4. Scenario 1 - Input signals

5.5 Scenario 2: Signal from the TSO

This scenario evaluates the controller's capabilities of reference tracking of the signal issued by the TSO. The production plan is the same as in the previous scenario, meaning that the production plans for the individual units are constant throughout the scenario. At $t = 500$ a signal applied from the TSO results in a total portfolio reference as seen in Fig. 5.

Table 3 shows the scenario results with the PI controller as well as the MPC.

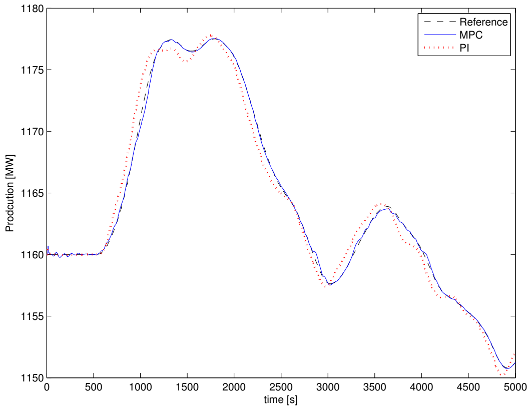

Fig. 5. Scenario 2 - Portfolio output

The results of the performance functions (14) and (15) are found in Table 3.

The results show that the MPC significantly reduces the deviation. The peak deviation is reduced from 2.7MW to 1.1MW as shown in Fig. 6, and the summed deviation is reduced by 84%. This improvement originates from

	δ	c_0	c_{13}	c_{80}
PI	1.02 MWh	€48081	€48095	€48163
MPC	0.16 MWh	€47994	€47996	€48007
Improvement	84%	0.18%	0.20%	0.32%

Table 3. Scenario 2 - Comparison

the MIMO approach of the MPC, which has a superior coordination of the portfolio that takes dynamics and constraints into account, unlike the ad hoc coordination used by the PI controllers. A result that is very difficult if not impossible to obtain by retuning the current configuration of PI controllers.

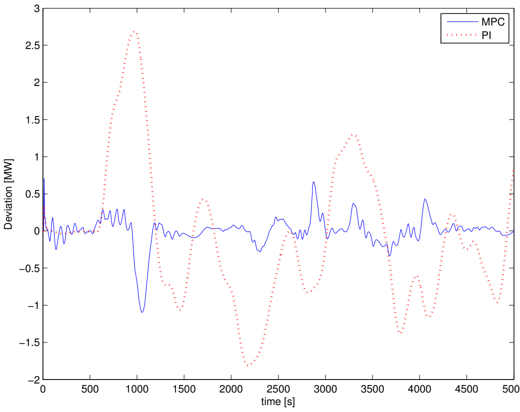

Fig. 6. Scenario 2 - Deviation

The input signals from the controllers are shown in Fig 7. Once again it is seen that when extra power is needed the MPC uses the cheapest units first, and when there is an overproduction the most expensive units are lowered in order to minimise expenses. In both cases the controller returns to the production plan when possible.

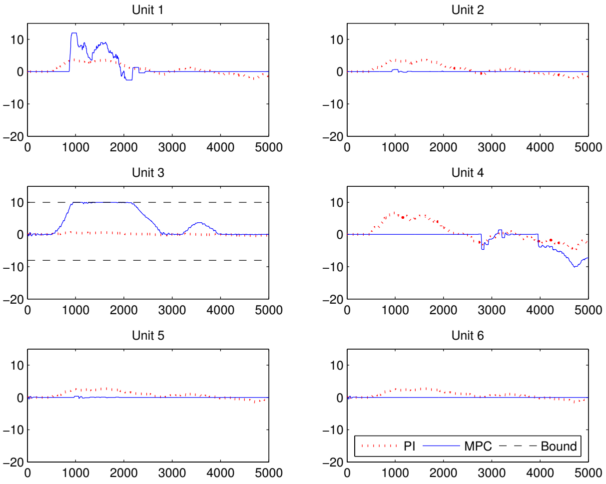

Fig. 7. Scenario 2 - Input signals

6. CONCLUSION

This paper has introduced a model-based control approach to balance control of a portfolio of power generating units. The model-based controller uses MPC, which allows constraint handling within its framework. The MPC seeks to optimise the system based on financial considerations, thus performing reference tracking and disturbance rejection in an economically optimal way.

One of the advantages of MPC is the MIMO approach, which improves the coordination of the units. The construction of the cost function as a mixture of ℓ_1-norms and linear weighting is well suited to describe the economics of the system. The choice yields a cost function, which is asymmetric around the reference, allowing for different control depending on whether the deviation is positive or negative.

Through simulations, the MPC is compared with the currently implemented load balancing controller, which is a PI controller structure. The MPC shows significant improvements both for disturbance rejection and reference tracking, and it also results in significant savings. Based on the simulations, savings of €600,000 or more per year seem likely. This improvement is the result of choosing a MIMO based approach and of the modelling of the economic behaviour in the MPC.

The portfolio in the paper is the currently active portfolio, but the goal is to incorporate more entity types than just power plant units, eg wind farms and district heating production. The model predictive controller is the first step towards developing a stringent method for portfolio control with a system containing many units, which all need to be controlled. To handle such a system, a stringent method for handling subsystems entering and leaving the portfolio will be required as well.

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