Real-time Dispatch of a Portfolio with Intermittent Generation via Model Predictive Control

D.S. van Hamersveld  
J. Frunt  
A. Kechroud  
W.L. Kling  
H.W.M. Barends  
Eindhoven University of Technology, the Netherlands, Department of Electrical Engineering, Electrical Energy Systems group; Den Dolech 2, Eindhoven, the Netherlands; d.s.v.hamersveld@student.tue.nl  
Eindhoven University of Technology, the Netherlands, Department of Electrical Engineering, Electrical Energy Systems group; Den Dolech 2, Eindhoven, the Netherlands; j.frunt@tue.nl  
Eindhoven University of Technology, the Netherlands, Department of Electrical Engineering, Electrical Energy Systems group; Den Dolech 2, Eindhoven, the Netherlands; k.kechroud@tue.nl  
Eindhoven University of Technology, the Netherlands, Department of Electrical Engineering, Electrical Energy Systems group; Den Dolech 2, Eindhoven, the Netherlands; w.l.kling@tue.nl  
Electrabel NL, 92, Zwolle, the Netherlands; Dick.Barends@electrabel.nl

Abstract—Most renewable energy sources are intermittent by nature and limited controllable and therefore increase the risk of increment imbalance when integrated in the production portfolio. When imbalance increases, higher imbalance fees are payed to the Transmission System Operator (TSO) and will result in higher incremental costs. This study is to determine the influence of an intelligent dispatch of the production portfolio of Electrabel NL on the imbalance reduction and economic dispatch. The result is an cost comparison based on a number of normal operating days. The second part evaluates the influence of the integration of 5%, 15%, and 25% of intermittent sources in the production portfolio. There are three scenarios simulated: no forecasting, persistence forecasting and perfect forecasting of the wind power output.

Index Terms—Aggregated multi-turbine power curve, Balance Responsible Party, Economic dispatch, Imbalance settlement, Intermittent energy sources, Model Predictive Control, Persistence wind power forecasting, Real-time dispatch.

I. INTRODUCTION

Fossil fuels are depleting and there is a need for the transition towards a more sustainable generation of energy. Many technologies are available to generate the needed energy sustainable, however most of the generators are poorly controllable e.g. wind power. The day ahead unit commitment (UC) and economic dispatch (ED) become more complex, because of the uncertainty of the real-time power output compared to the day ahead forecasting. Most renewable sources are intermittent by nature and the instantaneous power output even fluctuates during each Programme Time Unit (PTU) but especially from one PTU to another PTU. On a whole in the interconnected power system electricity consumed must be generated contemporary. If the load and generation are not in balance, the stability of the grid will be endangered. The stability is characterized by the behavior of the grid and the frequency is an indicator [1]. The high voltage grid connects the control areas. The power flow over these connections are measured in real-time and compared to the day ahead announced trades. The difference indicates the size of imbalance. Balance Responsible Parties (BRPs), in this case Electrabel NL, predict the consumption of electrical energy. They accept the responsibility for prediction errors that could lead to imbalance. The BRP schedules a production plan for the day ahead announced trades. The plan is called an E-program. All E-programs are sent to the Transmission System Operator (TSO) that is responsible for a control area, in this case TenneT. At execution time, the TSO monitors the power balance in the grid. Any deviation between E-program and real-time measurements means that at least the considered control area has an imbalance. The imbalance must be restored to zero via load frequency control (LFC). Frequency control consists of three mechanisms; primary control (PC), secondary control (SC) and tertiary control (TC) [1], [2]. The penetration of, e.g. wind power does not influence the primary control needs [3]. Most regulating capacity must be reserved for secondary control, which operates at a time scale of minutes to hours. Reduction of the amount of the deployed secondary control can take place via smarter real-time dispatch algorithms by the BRPs with the objective of balance management by taking the more accurate short-term forecasting and load steps of the production plan into account. It decreases the risk of causing imbalance when intermittent sources are integrated. Tertiary control is the economic optimization of the secondary control.

A. Problem definition

For this study the focus is on secondary control. When the control area is in balance, the market clearing price (MCP) of the imbalance system is approximately equal to the day ahead (DA) price of the Amsterdam Power Exchange (APX). When imbalance occurs, the MCP will change. The difference between DA and imbalance price corresponds with the extra costs per unit of energy for solving imbalance in the system [2]. To ensure balance settlement between supply and demand in the control area, the TSO must reserve sufficient regulating capacity to restore the scheduled energy transports via the tie lines (interconnections). Available reserve must be offered to
the TSO [1] in form of bids. In a fully competitive market these prices reflect the fuel costs and the flexibility of the production units. These bids are positioned on the bidding ladder in merit order [4]. If a BRP causes imbalance, it must buy or sell power from the TSO for a price determined by the bidding ladder. Usually this price is higher than its own marginal cost (MC). Therefore it is desirable to track the production plan and equalize the energy content per PTU, based on the day ahead announced E-program, without causing imbalance. The current practise for a control mechanism is a distributed PI ad-hoc control algorithm [5], [6], without any predictions of the imbalance or PTU transitions. The main drawback is the focus on minimization of the energy imbalance per PTU and not taking the successive PTUs into account (Fig. 1). This causes an offset of the instantaneous power at the end of PTU2 and introduces an imbalance in PTU3 (C1 ≠ C2).

Integration of intermittent poorly predictable energy sources, i.e., for this study wind power, increases the complexity of balance management by continuously deviating from the scheduled production plan. A new control methodology, which is named Model Predictive Control (MPC) [7], [8], obtained the interest of BRPs. Based on the plant model, a continuous on-line optimization of the input sequence is performed, by minimizing a cost function via a receding horizon principle [5], [6]. This MPC approach takes successive PTUs and very short wind power forecasting into account [9]. It will then calculate an optimal input sequence for conventional plants based on the on-line measurements of states and outputs of the past. It will continuously calculate the optimal input sequence based on the plant response in discrete steps. In Fig. 2 the MPC takes the step in the production plan into account earlier and anticipates in PTU2 on this step by increasing the volume in B2, which is cancelled out by the volumes B11 and B12. This effect of improved balance management and incorporation of a short-term forecasting can increase the motivation to enlarge the share of intermittent sources, which results in a more sustainable production portfolio without increasing the risk of paying higher imbalance fees.

![Figure 1. Concept of PID control mechanism for dispatching the production portfolio.](image1)

![Figure 2. Concept of MPC for dispatching the production portfolio.](image2)

II. MODEL PREDICTIVE CONTROL IN UNIT DISPATCH

For a general introduction to Model Predictive Control, the reader is referred to references [7], [8] and [10]. For this study a MPC algorithm is written to calculate the optimal input sequence for the production portfolio of Electrabel NL. Reference [5] has given a control algorithm which describes a multiple input and multiple output system. This method is used to describe the production portfolio.

A. Scenario

The main objective of the controller is to settle imbalances before the PTU ends while taking successive PTUs into account. The MPC receives a day ahead production plan for all individual production units. This is a production plan based on UC and ED [11]. In theory this is an economic optimal scenario which the MPC has to follow, taking balance management into account. The desired behavior of the controller for this research is at first to reduce the imbalance. Subsequently it should dispatch the remaining imbalance economically. This is done by minimizing the cost function and calculating the optimal input for the production units, based on the marginal costs, taking the technical constraints into account like minimum and maximum power output and control gradients.

B. Portfolio model

The portfolio model is composed out of the fixed state space matrices, which describe the linear discrete behavior of the production unit. It is used to calculate (predict, denoted by the cardinal of a set) the output \( \hat{y} \) and the states \( \hat{x} \) of the next step based on given estimated input \( \hat{u} \) and real variable \( x \) (1). Where, \( k \) indicates the discrete time sample and \( \hat{d} \) is the external noise added to the production unit output (the assumption is that the noise acting on the output has a static gain K of 1 [6]), i.e.,

\[
\hat{x}(k|k) = A\hat{x}(k-1) + B\hat{u}(k|k) \\
\hat{y}(k|k) = C\hat{x}(k|k) + D\hat{d}(k|k)
\]

All 11 unit models are compiled into one portfolio model [5], [6]. This results in multiple block diagonal matrices containing...
all individual matrices. The output matrix is extended (2) to describe the total power plant portfolio output, i.e.,

\[
C = \begin{bmatrix} C_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & C_{11} \end{bmatrix}, \quad D = \begin{bmatrix} D_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & D_{11} \end{bmatrix}
\]

The states will be directly translated to the predicted output \( \hat{y}_i(k) \), which is a function of \( u_n \) and \( x_n \) where the subscript \( n \) denotes the individual production units, obtained by multiplying with the output matrix \( C \). The controller must balance all measured disturbances \( dP_{RT}(3) \) acting on portfolio level. All the inputs \( \hat{u}_n(k) \) and predicted deviations are compiled into the tracking error vector \( \hat{Y}_i(k) \), predicted imbalance vector \( \hat{d}_i(k) \) and the optimized input vector \( \hat{U}_i(k) \) (3), i.e.,

\[
\hat{Y}_i(k) = \begin{bmatrix} \hat{y}_1(k) - PSV_1(k) \\ \vdots \\ \hat{y}_n(k) - PSV_n(k) \end{bmatrix}, \quad \hat{d}_i(k) = \begin{bmatrix} \hat{u}_1(k) \\ 0 \\ \vdots \\ \hat{u}_n(k) \end{bmatrix}, \quad \hat{U}_i(k) = \begin{bmatrix} \hat{u}_1(k) \\ 0 \\ \vdots \\ \hat{u}_n(k) \end{bmatrix}
\]

To insert the gradient constraint, the optimized input sequence is composed into the deltas (4) between the initial step \( \hat{u}_i(k) \) and \( \hat{u}_i(k+1) \) [7]. One can give the gradient constraint by inserting the constraint defined for the ramping up and ramping down gradients, i.e.,

\[
\Delta \hat{U}_i(k+i) = \begin{bmatrix} u_n(k-1) \\ u_n(k-1) + \Delta \hat{u}_n(k) \\ \vdots \\ u_n(k-1) + \sum_{i} \Delta \hat{u}_n(k+i) \end{bmatrix}
\]

C. Cost function

Based on the desired behavior of the controller, there are three minimization objectives (5). The first is the balance management, where the planned setpoint value (PSV) is a cumulative sum of the planned setpoint value at portfolio level (PSV) and the imbalance (dPRT) acting on portfolio level. The difference between the predicted energy output (\( \hat{Y}_i \)) of the portfolio and PSV \( \hat{Y} \) is penalized with the imbalance fee (Qimb) and is reset to zero at every PTU transition. The second objective is the minimization of the instantaneous deviation in power of the individual predicted output \( Y \), which is penalized with the differences in marginal costs (Qn). The last objective is limiting the active control reaction of the individual production units by penalizing (R) the change in input (\( \Delta \hat{U} \)). The minimization takes places over the complete prediction horizon (Hp = 45 minutes) and the control horizon (Hu = 22.5 minutes) for each time step k, i.e.[8],

\[
V_t(k) = \hat{y}_e^T Q_{imb} \hat{y}_e + \hat{Y}_e^T Q_n Y_e + \Delta \hat{U}^T R \Delta \hat{U}
\]

where:

\[
\hat{Y}_e(k) = \sum_{i=1}^{k+Hp} \hat{y}_i(i) - \sum_{i=1}^{k+Hp} [PSV(i) + dP_{RT}(i)]
\]

D. Weighting matrices

For this study the imbalance fee is set equal to two times the highest marginal cost. The marginal costs are variable penalties given to the power deviations from the production plan (3), an additional variable is inserted to adapt the weight of the penalty to the real-time imbalance. The desired scenario is created with the introduction of variable \( g \) (6). When the real-time imbalance is larger than zero, the plants with the lowest marginal costs are used for balance management by receiving the lowest penalty for deviating from their original production plan. When the real-time imbalance is negative, the production units with the highest marginal costs receive the lowest penalty and are used for ramping down. The other production units remain tracking their production plan. The extra 1 is added to avoid a zero penalty and limiting the degree of control freedom, i.e.,

\[
Q_{n(k+i)} = \begin{bmatrix} [MC_1 - g(k+i)] & 0 & 0 & \cdots \\ 0 & \ddots & 0 & \vdots \\ 0 & 0 & [MC_n - g(k+i)] & 0 \\ 0 & \vdots & \vdots & qt \end{bmatrix}
\]

where:

\[
g(k+i) = \begin{cases} \max(MC_n) + 1 \text{ if } dP_{RT(k+i)} < 0 \\ \min(MC_n) + 1 \text{ if } dP_{RT(k+i)} > 0 \\ 0 \text{ if } dP_{RT(k+i)} = 0 \end{cases}
\]

The last penalty is put on the deviation from the production plan at portfolio level (PSV) and is named \( q_t \). This penalty can be user defined, hence for this purpose the penalty is set equal to the largest marginal cost to get a smaller degree of freedom in the economic optimization for the individual units. Second, the imbalance is defined by the deviation at portfolio level and not on the individual production units. It is needed to track the total portfolio planned setpoint value (PSV). During the PTU, the deviation of the energy program is multiplied with \( Q_{imb} \). At the transition of a PTU the penalty is doubled. To ensure the summation only takes place at the transition of PTU, the penalty is multiplied with a sinusoidal function \( E \) with a frequency of \( \frac{2\pi}{T_{SU}} \), whereas the Ts is the sampling time, which is in this research 30 seconds. The i denotes the position in the prediction horizon, combined with k it determines the PTU transitions. The function is added to the original imbalance penalty (7), which increases the penalty prior to every PTU transition. This is done to ensure balance management during the PTU and improved balance management prior to the end of the PTU, i.e.,

\[
Q_{imb(k+i)} = [Q_{imb} + E \cdot Q_{imb}]
\]

Where:
\[ E = \left(1 + \left(\cos(2 \cdot \pi \cdot \frac{T}{PTF} \cdot (i + k - 1))\right)\right)^4 \]

**E. Constrained MPC**

According to [7], assuming no disturbances or measurement noise, the past input \( \gamma \), the past states \( \Psi \) and the prediction matrix \( \Theta \) can be determined by iteration of the state space model (2). The past input \( \gamma \), the past states \( \Psi \) are used to determine the tracking error when initial state \( x(k) \) and the past input \( u(k-1) \) are applied to the "past" matrices. Via the tracking error \( e \), the optimal input sequence \( \Delta U \) is calculated by minimizing the tracking error via the prediction matrix. For this research, the interests are on the production plant outputs, therefore the A and B matrices are multiplied with the output matrix \( C \) [7]. The past and prediction matrices, used for the imbalance settlement, are the cumulative summation of the matrices \( \gamma \) (8), \( \Psi \) (8) and \( \Theta \) (9).

\[
\Psi_e = \begin{bmatrix} \Psi \\ \vdots \\ \Psi \end{bmatrix}, \quad \gamma_e = \begin{bmatrix} \gamma \\ \vdots \\ \gamma \end{bmatrix}, \quad \Theta_e = \begin{bmatrix} \Theta \\ \vdots \\ \Theta \end{bmatrix} \quad \text{As explained in reference [7], the Hessian matrix (10) and} \quad \text{the free offset tracking error (11) can be determined, which} \quad \text{can be inserted in a quadratic programming solver to minimize} \quad \text{the cost function (5).}
\]

\[
H = 2(\Theta^T Q \Theta + R + \Theta_e^T Q_{imb} \Theta_e) \quad \text{(10)}
\]

\[
G = -2(\Theta^T \varepsilon(k) + \Theta_e^T \varepsilon_{imb}(k)) \quad \text{(11)}
\]

These constraints can be written as a finite set of linear inequalities (12) based on the iteration of the state space matrices (2). Where \( yct_{max} \) and \( yct_{min} \) are the minimum and maximum operating nominal power output per production unit.

\[
\begin{bmatrix} \Theta \\ -\Theta \end{bmatrix} \Delta U(k) \leq \begin{bmatrix} yct_{max} - (\Psi x(k) + \gamma u(k-1)) \\ (\Psi x(k) + \gamma u(k-1)) - yct_{min} \end{bmatrix} \quad \text{(12)}
\]

**F. Verification methodology**

To compare the MPC with the currently in use Real-Time Dispatch (RTD) controller, two criteria are used for the comparison [5]. The first is the fuel costs (FC) were the marginal costs are based on the heat curves of the production units. Because of the current fuel prices and CO2 emission certificates, the fast controllable high efficient units have lower marginal costs compared to the slow controllable units, based on coal and less efficient gas units. The second criteria is the imbalance, which is the absolute summation of the energy imbalance per PTU for the simulation day. For an estimation of the imbalance prices, the reader is referred to references [2], [12]. The comparison is based on the registered outcome of the RTD controller during 18 days where no abnormalities occur like trips or power limitations. The results of the RTD are subtracted from the simulated MPC results where negative results indicates an improved dispatch by MPC. The assumption made is that the linear plant model describes the plant perfectly and the production units do not have unpredicted deviations from the predicted output.

**G. Integration of intermittent energy sources**

The MPC optimizes the input sequence based on a prediction horizon of 45 minutes. For this very short forecasting horizon the persistence forecasting model [9] is very suitable. To simulate the integration of 5%, 15% and 25% of intermittent sources in the production portfolio, an aggregated multi turbine power curve [13] is approximated based on wind speed measurements at the North Sea, with a mean (\( \mu \)) of 12.7 m/s and a standard deviation (\( \sigma \)) of 3.2 m/s. The required area depends on the nominal power of a single wind turbine and the simulated amount of wind power [14]. The reference values are day ahead production schedules for a normal operating day for each production unit. Summation of the individual production plans is the portfolio production plan. The wind power is included as a negative load [6] with a mean of 123 MW, 370 MW and 617 MW and a standard deviation of 64 MW, 194 MW and 325 MW.

**III. RESULTS**

**A. Comparison MPC**

The economic dispatch reduces (Fig. 3) approximately 1,800 euro (\( \approx 0.2\% \) of initial production plan) on average for a single simulation day. Situations occur where the RTD has an improved economic dispatch of the imbalance, because the fast controllable units, which have the lowest marginal costs, will change in power output to counter balance the change in power output of the slow production units with high marginal cost. This increases the portfolio gradient to have an improved balance management.

The balance management shows promising results. Improved imbalance settlement, decreases the production imbalance with 83% at average for the end of day results. The main imbalance reductions are gained during hour 4 to 10 and 16 to 24, which are high ramping hours in the scheduled production plan (Fig. 4). During the day when the production plan is at constant load, the reduction is almost zero.
B. Integration of intermittent energy sources

To evaluate the strength of MPC, three different wind power forecasting techniques are simulated for four levels of integration. The savings of the total cost of production are significant, because the marginal cost of the wind turbines are assumed to be zero. The imbalance increases, when enlarging the size of the wind park which will cause larger power fluctuations, see table I and Fig. 5. As expected, the production units with high marginal costs are suppressed in power output, down to minimum power output. The large imbalance, when 25% wind is integrated, is a reaction on the unsolvable large wind power fluctuations in PTU 7. There is a large wind lull, which causes an increase of the imbalance if it is not accurately predicted. Integrating wind power reduces the fuel costs with 3.4%, 9.8% and 15.8% of the TCS for the simulated scenarios.

IV. Conclusion

During normal operation (no large steps in the production plan) the total cost of production decreases, because of an improved economic dispatch by the MPC. The total cost of production increases before the transition to PTUs with a large step. Production units with high marginal costs, which are the plants with a longer response time and lower gradients, are forced to ramp up and plants with low marginal costs, which are plants with fast response times and high gradients, are forced to ramp down. This is a desirable behavior because the MPC algorithm anticipates on the load step by increasing the portfolio gradient and control area. If the production units are forced to their minimum power output the portfolio gradient is limited and will cause more and higher imbalances. Compared to the currently-in-use dispatch algorithm the MPC will decrease the total costs of production further. Secondly the MPC has improved balance management, which decreases the risk of causing imbalance when intermittent sources are integrated into the portfolio. Persistence prediction is sufficient for active participation in balance management, however improvement of the short-term forecast models can decrease the imbalance further when the integration level of intermittent sources is enlarged. When no forecast is made, the MPC has difficulties to minimize the imbalance because it only takes the measured values and not the continuous offset into account.

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