Elucidation of the power exchange market and Matlab MPC toolbox implementation to reduce portfolio imbalance

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Elucidation of the power exchange market and Matlab MPC toolbox implementation to reduce portfolio imbalance

By: D.S. van Hamersveld
I. Abstract

Implementation of large amounts of distributed generators (DG) can disturb the balance between supply and demand. Large disturbances can, worst case scenario, lead to a blackout of the electricity grid. It is hard to predict the output of DG’s 24 hours in advance. Most of the DG’s are poorly controllable and are not 100% predictable. Predictions of load are very accurate (±1.5% to ±2.5% error 24 hours ahead). To maintain balance between supply and demand, solutions need to be found to minimize unwanted imbalances. One solution to minimize unbalance is a new control mechanism that is developed in the robotics and is called Model Predictive Controller.

Before proceeding on the MPC, the power exchange market and imbalance market are elucidated to understand why it is important to implement a smart prediction controller that dispatch large power plant portfolios with conventional power plants. The two most important key players acting on these markets are TenneT B.V., who is the Dutch Transmission System Operator (TSO), and Program Responsible Parties (PRP) that compile the E-program and accept the responsibility regarding prediction of customer behaviors.

If an unwanted power deviation occurs, the frequency will drop or rise. To avoid large frequency deviations, every production unit larger than 5 MW and connected to a voltage level larger than 1 kV must reserve a maximum 3% of the nominal power output for primary control power. This power is used to stop frequency decline and ends with a static offset after 30 seconds. The primary capacity is automatically deployed via a proportional controller at production unit level. Secondary power reserve, or reserve capacity, is deployed up to 15 minutes after the event occurs and restores the frequency to its nominal value. Reserve capacity is offered to the TSO and positioned inside the price bid ladder per energy content and price per MWh. The size of the disturbance determines how much reserve capacity is deployed and the corresponding prices. Secondary control is usually deployed via the delta signal which is added to the running E-program.

All the information to deploy the portfolio merges at the dispatch center. Most favorable form of dispatch is economic dispatch. Important parameters are the fixed costs and the variable costs. These costs determine the marginal costs, which is the price for producing one unit more or one unit less. Based on these costs the economic dispatch is configured and prices, i.e. bilateral and DA prices and the for reserve capacity, are determined. Most power is traded via bilateral contracts and 12% is traded via the Day Ahead (DA) market.

To react within a short time frame, to avoid portfolio imbalance, it is necessary to implement a quick and predictive controller that takes the step response model of the conventional plant into account. It will calculate the optimal dispatch scenario by reducing the deviation from the E-program and cancel out disturbances caused by distributed generators. This report will focus on the feasibility of the implementation of a MPC with the use of the MPC toolbox. The MPC theory that is used in the Matlab toolbox works on the Least squares method or the Quadratic Programming model. These theories are based on minimizing the cost function which will not be capable of optimizing the energy content per PTU, because of the elimination of negative and positive faults and can only take hard constraints into account. Therefore a new cost function must be developed in further research.
II. Acknowledgement

My thanks goes out to Dhr. D. Barends and Dhr. G. Langeslag to invite me and gave me the opportunity to view the dispatch center of Electrabel and explained the control algorithms behind the dispatch center. These visits gave a clear view of the power exchange market and the data acquisition inside the dispatch center.

Second I would like to thank Dhr. J. Frunt who guided me through this report and who helped me with encountered problems with interesting discussions.

I am looking forward to the coming nine months of the graduation project which will be done for Electrabel.
## III. Abbreviations

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AGC/RTD</td>
<td>Automatic Generation Control of production portfolio</td>
</tr>
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<td>APX</td>
<td>Amsterdam Power Exchange</td>
</tr>
<tr>
<td>ARR</td>
<td>Annual Revenue Requirement</td>
</tr>
<tr>
<td>CMPC</td>
<td>Constrained model predictive control</td>
</tr>
<tr>
<td>CP</td>
<td>Clearing Price</td>
</tr>
<tr>
<td>DA</td>
<td>Day Ahead Market</td>
</tr>
<tr>
<td>Dif</td>
<td>Difference between reference signal and MPC output</td>
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<tr>
<td>E</td>
<td>Energy</td>
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<td>ETSO</td>
<td>European Transmission System Operators</td>
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<tr>
<td>FC</td>
<td>Fixed Costs</td>
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<tr>
<td>FVR/LFC/SC</td>
<td>Load frequency control</td>
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<tr>
<td>GWh</td>
<td>Gigawatt per hour</td>
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<tr>
<td>IET</td>
<td>Import, Export and Transit. Trading via interconnections</td>
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<tr>
<td>k</td>
<td>Least Squares optimization</td>
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<tr>
<td>kWh</td>
<td>Kilowatt per hour</td>
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<tr>
<td>LS</td>
<td>Least Squares optimization</td>
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<td>m</td>
<td>Control horizon</td>
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<td>MC</td>
<td>Marginal Costs</td>
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<tr>
<td>MCP</td>
<td>Market Clearing Price</td>
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<tr>
<td>MIMO</td>
<td>Multiple Input Multiple Output of a control mechanism</td>
</tr>
<tr>
<td>MPC</td>
<td>Model Predictive Controller</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt per hour</td>
</tr>
<tr>
<td>n</td>
<td>Number of PTU</td>
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<td>NMa</td>
<td>Office of energy and regulation</td>
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<tr>
<td>NPFC</td>
<td>Network Power Frequency Characteristic</td>
</tr>
<tr>
<td>OC</td>
<td>Overnight Costs or Investment Costs</td>
</tr>
<tr>
<td>p</td>
<td>Prediction horizon</td>
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<tr>
<td>P</td>
<td>Power</td>
</tr>
<tr>
<td>PRP</td>
<td>Program Responsible Party</td>
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<td>PC</td>
<td>Primary Control</td>
</tr>
<tr>
<td>PTU</td>
<td>Program Time Unit [15 minutes for the Netherlands]</td>
</tr>
<tr>
<td>QP</td>
<td>Quadratic Programming optimization</td>
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<tr>
<td>SC</td>
<td>Secondary control</td>
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<tr>
<td>SISO</td>
<td>Single Input Single Output of a control mechanism</td>
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<tr>
<td>SPV</td>
<td>Set Point Value</td>
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<tr>
<td>T = Delt2</td>
<td>Sampling time</td>
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<tr>
<td>TC</td>
<td>Tertiary control</td>
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<tr>
<td>TCE</td>
<td>Time Control Error</td>
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<tr>
<td>tf</td>
<td>Transfer function</td>
</tr>
<tr>
<td>TIE</td>
<td>Interconnections between control areas</td>
</tr>
<tr>
<td>time</td>
<td>Time in seconds (time = k x T&lt;sub&gt;s&lt;/sub&gt;)</td>
</tr>
<tr>
<td>TSO</td>
<td>Transmission system operator</td>
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<tr>
<td>TWh</td>
<td>Terawatt per hour</td>
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<tr>
<td>UCTE</td>
<td>l'Union pour la Coordination du Transport de l'Electricité [Union or the coordination of electricity transmission]</td>
</tr>
<tr>
<td>VC</td>
<td>Variable Costs</td>
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1. Introduction

Electric energy plays an important role in our daily lives. When everything operates the way it is designed, nobody recognizes the presence of this important energy carrier. When a failure occurs, there is nobody who can deny the presence of electrical energy. Especially when often used apparatus like the television or the computer fails. The importance of electrical energy is distinguished, but (1) where does it come from, (2) how does transportation take place and, main goal for this report, (3) how is it traded?

The answer of point one and two is relative short (not the focus of this report). Electrical energy comes from a generator that converts, mostly, rotating mechanical energy into electrical energy. Sources that produce this mechanical energy are heat (fueled by coal, natural gas, nuclear, biomass, etc also known as power plants with the Rankine cycle), wind energy, hydropower. Generation of electrical energy can also occur in static materials like photovoltaic's (solar cells) and small innovative sustainable technologies like the electrical attraction between sweet and salt water. However, what takes place after generation?

First (i), trading of the generated electrical energy takes place. This is done in conformity with contracts or the Amsterdam Power Exchange. Second (ii), transportation of electrical energy to our home, businesses and industries takes place via overhead lines and cables buried in the ground, at every moment of the day.

The points mentioned above (i, ii) are very important with respect to the reliability of the grid and selling prices of the electrical energy (interaction between demand (consumption or electrical load) and supply (generation or production)). The reliability of the grid is one of the most, maybe the most important key factor in the power exchange market. If the consumption is lower than generation, overproduction occurs and the frequency will increase. Increase of frequency ($f > 50$Hz) will result in higher angular velocities of the rotor of the generators. In addition, accurate equipment cannot fulfill their requirements (think of hospital equipment). When the consumption is higher than production, over-consumption occurs and will decrease the grid frequency ($f < 50$ Hz). If not controlled, this can eventually lead to a standstill of the large generators. Most of the apparatus are equipped with components that are influenced by changing frequencies (f). Examples are the capacitor and inductor. A change of frequency will change their complex impedance.

\[ X_L = j \cdot 2 \cdot \pi \cdot f \cdot L \]

Equation 1: Complex impedance of an inductor

\[ X_C = j \cdot \frac{1}{2 \cdot \pi \cdot f \cdot C} \]

Equation 2: Impedance of a capacitor

This means that the production of electrical energy must always be equal to the electrical load in the grid. The frequency is an important measure to determine if the power is in balance. If the frequency is exactly 50 Hz, supply and demand is in perfect equilibrium.
\[ \sum_{i=1}^{m} P_{\text{produced}} = \sum_{j=1}^{n} P_{\text{load}} + \sum_{k=1}^{a} P_{\text{gridlosses}} \]

Equation 3: Balance in power production and electrical load

To reduce the imbalance in the grid, measurements are done to predict the load and generation. These predictions are more and more accurate and so the desired generation can be determined. These predictions for generation where simple in the past. Large controllable power plants can easily contribute to minimize the balance difference as stated in equation 3; with \( m \) is the total number of connected generators. Contribution of the largest renewable energy sources complicates the process to minimize the imbalance. The problem is renewable are partially uncontrollable and partially unpredictable [7]. The generated power is directly fed into the grid. For example, the wind speeds and solar irradiation are difficult to predict, with a few percent accuracy. Fault predictions causes differences in the predicted generation and results in imbalance of the grid. Unexpected switching of large loads also causes imbalance and also the unexpected failure of large power plants. Controllable plants must react to restore the balance between production and load.

A recent development on the current power exchange market, focused on Program Responsible Parties (see chapter 2.1.5), who have supervision of controllable production units, is the implementation of smart controllers. These controllers measure the load and generation and compare it to the predicted set points. When a deviation occurs, the smart controller changes the current settings of the production units to minimize the imbalance.

This report will elucidate the power exchange market, the imbalance market and the fees for the provoker of imbalance. New and improved controllers, like Model Predictive Controller (MPC), adapt faster and more accurate to the changing market and shifting between PTU's. Extra earnings can be gained via the bidding on the imbalance market and prevention of fees.

Via this report, a study will be done to implement, via the Matlab MPC toolbox, a real-time MPC model for the dispatch of the controllable power units, restricted by its constraints and to limit imbalance.
2. Overview of entities in power exchange market

To study the complete power exchange market, the most important entities are explained in the following paragraphs. The entities are separated in two groups: transport, retail, costumers and trading, regulation.

2.1. Transport, retail and consumers

This part explains the common entities. Most of these entities have minimum impact on the balance of the grid, with exception of the large consumers and producers in the industry. The referring website also contains information of the acknowledge entities.

2.1.1. Costumers

The costumers are the end-users. They buy or sell electrical energy from/to the retail companies. The responsible PRP or retail companies make predictions of their behaviors. Often they have a bilateral contract with the PRP/retail companies (licensee) and pay fees, which are included in the monthly bill, to the grid operator and energy trading companies.

2.1.2. Grid operators

Grid operators are responsible to build, maintain and have supervision of the local grid. They transport the electrical energy from the producers to the consumers. Every municipality determines who their grid operator is. It is impossible to switch from operator. This is stated in the Dutch electricity law "Dutch Electricity Act 1998." The retail companies make agreements with licensees according the payments.

2.1.3. Licensee / retail companies

The NMa Energiekamer names a retail company licensee [1], because they need to have a license to produce and/or deliver the electrical energy to costumers. Costumers sign an agreement that a licensee sell or buy the electrical power for a fixed price. In addition, generation of the power must take place as denoted in the agreement. There are two forms of licensee. Trading licensees buy the energy from, or contract a producer and sell it to the costumers, like Atoomstroom [2]. Other licensees produce their own energy and contract a third party, and sell it directly to the costumers, like Nuon, Essent, and Electrabel. Because the split up of the energy market, the previous named companies produce their own energy but they have to trade with a licensee via a PRP. This licensee is often a separate company, but linked by name.

2.1.4. Metering companies

A certified company measures the consumed or produced energy. TenneT regulates the certification. Measurements are done once a year for small costumers, once per month for large costumers and once per 15 minutes per very large costumers. The costumer can choose its own measuring company independent from the licensee.

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1 www.energiekamer.nl, 12 February 09
2 www.atoomstroom.nl, 16 February 2009
2.1.5. Program Responsible Party [PRP]

Agreements between licensees and customers cause power flows in the grid. All connected users (except protected customers) are obligated to make a prediction for the next day, similar as the prediction mentioned in the introduction. Usually small consumers give their responsibility to the PRP.

Consumption (load) and production (generation) are not always in balance. There is chosen for a system that is named E-program to prevent imbalance in the grid. PRP have to be acknowledge by TenneT and the regulation is stated in the “Systeemcode”. A PRP determines the contracted power flow, in form of consumption and production, for the day ahead. The outcome is the E-program. Every licensee accommodates its power flow. The PRP makes an E-program and send it to TenneT. Deviations from the E-program receive fees from the TSO, regarding the size of deviations.

There are two types of PRP’s [4]:

1. Full acknowledgement: A PRP that has full ownership of a one or more production facilities and contract third entities for the prediction of the behaviors, determination of the E-program and trading of the energy. This means that a PRP with full acknowledgement can bear program responsibility for grid connections.

2. Trade acknowledgement: This form PRP only predicts the behaviors, determines the E-program and trades energy for third entities. They are not legally recognized to bear program responsibility for grid connections.

Register of full and trade acknowledge PRP’s can be found on the website of TenneT. Currently the international name of the PRP is Balance Responsible Party (BRP). During this study the term PRP will be used.

2.2. Trading – regulation

Regulation is an important key factor in the Dutch energy market. Without the regulation, all entities will make as much profit as possible, without concerning the grid reliability. Implementation of regulation results in exclusive rights for the transmission system operator, recognized by the government. It is in a healthy monopoly situation. A good example is the article “tragedy of the commons”[2], in which a pasture is mentioned with herdsmen, who will try to keep as much sheep on the land as possible. If every herdsman thinks “who would notice, and what small effect will it have, if I put one extra sheep on the pasture”, finally, the land would be too small to maintain all the men and animals. Without regulation, the same tragedy will occur as mentioned in “tragedy of the commons.” Therefore, the Dutch government set up entities that will safeguard the reliability of the grid by regulation.

2.2.1. NMa “Energiekamer” or former Dte [office energy and regulation]

The Dutch office of energy regulation is an entity, set up by the ministry of economic affairs, to regulate the energy market. They operate as a chamber within the Netherlands Competition Authority [NMa]. In 1998, the electricity law was established. The office of energy regulation has the obligation to create an effective energy market by implementing regulatory instruments,
regarding the “Dutch Electricity Act 1998”. A statement taken from the website present a perfect description:

“This entails safeguarding access to networks, maintaining sufficient transparency (access to essential information) and protecting consumers against potential malpractices resulting from the (inherent) dominant position of providers”.

Using different codes and laws, they established the Dutch energy market, as we know it today.

2.2.1.1. Dutch electricity act “Dutch Electricity Act 1998”

This law implements the Dutch regulation for national market to maintain the possibilities for generation, supply, transport, in- and export and enlarge the use of physical connected grids. The focus is the observation to make the grid reliable, sustainable and functional / efficient. Main supervisor is the ministry of economic affairs [3].

2.2.1.2. Systeemcode (System code)

This is the first of three codes that is derived from the “Dutch Electricity Act 1998” that implies the regulation of power reserves to prevent grid failures. In addition, the definition and regulation for PRP’s are described, with corresponding E-program, and what regulation they must fulfill to become an acknowledge PRP [4].

2.2.1.3. Netcode (Grid code)

The Netcode is the second code that describes the conditions and regulation stated for grid operators and costumer, regarding the operation of the grid, including the realization of a grid connection and transportation of the electrical energy [5].

2.2.1.4. Meetcode (Metering code)

The Meetcode is the third of the codes. This regulation is used for accurate metering, proclamation of measured data and requirements for acknowledge metering companies [6].

2.2.2. TenneT

TenneT is the Dutch TSO. The main function of any TSO is to safeguard the reliability, continuity and security of the electricity supply and administering the national grid. This will be done 24 hours a day. They also encourage the development of the electricity market and ensure proper functionality. Working principles are according the codes. Extra duty of the TSO is supervise the E-program and PRP in a non-profit manner. TenneT manages the physical grid infrastructure from 110 kV and the international grid connections.

2.2.3. UCTE

[ Citation www.tennet.org] 4

“The UCTE, l’Union pour la Coordination du Transport de l’Electricité (Union for the coordination of electricity transmission), is a technical alliance of 22 continental countries, whose grids are physically connected with each other. These countries are Belgium, Germany, the Netherlands, Luxembourg, France, Spain, Portugal, Italy, Switzerland, Austria, Greece, Poland, the Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Bosnia-Herzegovina, Yugoslavia, Macedonia, Romania, Bulgaria and a part of the Ukraine. The UTCE coordinates the interests of the grid administrators (TSOs) which operate in the aforementioned countries and guarantees safe and reliable operation of the connected grids. In order to achieve this, there are a number of rules and agreements within UCTE.

4 Description found on www.tennet.org; 18 February 2009
The objective of these is:

- to ensure that a stable frequency and voltage are maintained;
- to ensure sufficient reserve capacity;
- to reduce transmission losses and;
- to guarantee mutual assistance in the event of an emergency.

The UTCE grids supply approximately 400 million people with electricity, which amounts to about 2100 TWh a year."

2.2.4. ETSO

"ETSO was set up by a joint venture of four regional European grid organizations in connection with the European liberalization of the electricity market. ETSO is a members' organization, which is made up of the 32 grid administrators (TSOs) of all 15 Members of the European Union, as well as Norway and Switzerland. ETSO is therefore the discussion partner for the European Commission with regard to the commercial operation of the European electricity market. Within ETSO, workgroups tackle, among other things, the tariffs for international energy transmission and the capacity problems at the borders. About 350 million people are supplied with electricity via the grids represented by ETSO, with an annual consumption of approximately 2700 TWh."

2.2.5. APX

APX is one of the most experienced energy trading facilities acting in Europe. It is operating for United Kingdom, Belgium and the Netherlands. APX provide market parties with a transparent, efficient and secure electronic trading environment to trade gas and electricity. 12% of the electricity in the Netherlands is traded via the day-ahead spot market and uses price bidding to set the market prices [7]. They publish the prices and volume indices on a daily bases, safeguarded by regulation. The published prices are used as a benchmark for bilateral (specific) contracts. Most of the energy is traded via this manner [7].

Figure 1: Amount of traded energy
2.3. Schematic overview

Figure 2: Schematic overview of entities at Dutch energy market
3. Power control

As explained in chapter 1, imbalance in a grid can cause a total black out (worst case scenario). Prediction of generation and consumption is needed to prevent imbalance. These theoretical predictions can deviate from the real-time values. Any form of deviation causes imbalances. To prevent or recover from an imbalance, the responsible TSO must take action. The regulation for these actions is stated in the handbook of the UCTE (regulation for TSO)\(^5\) and the System code (regulation for all involving entities directly connected to the control area)\(^4\). As noticeable in equation 4, there are two variables to change the status of the grid. These actions are in form of increase or decrease production and / or loads. There are different forms of reserves.

- Spinning reserves \((a \text{ reserve of actual operating production unit with a maximum reserve of } 3\% \text{ per unit})\)
- Cold reserve \((the \text{ sum of all not-synchronous operating units})\)
- Load reserves \((load \text{ shedding and load connection from or to the grid to increase or decrease the load})\)

\[
\sum_{j=1}^{m} P_{\text{produced}} \neq \sum_{j=1}^{n} P_{\text{load}} + \sum_{k=1}^{c} P_{\text{gridlosses}}
\]

Equation 4: Deviation between production and consumption

This part will elaborate the necessity of control power and power reserves. Furthermore, the origin of control power is explained. An important reference document for this chapter is the UCTE handbook part 1 \([8]\).

3.1. E-program and T-program

Trading of energy takes places by external entities \((see \text{ paragraph } 2.1.5)\). To prevent overloading of the grid, the PRP must make a T(ransportation)-program. They inform the responsible grid operator the expected power flow per grid connection. The grid operator can determine if the grid is not overloaded via simulations \([9]\).

Second, the PRP has to make a planning of the scheduled import, export and transits \((IET)\) via the interconnection of the control blocks, safeguarded by the responsible TSO.

Third, the PRP has to make an E(nergy)-program. Via the E-program, the TSO is notified of the trading between different PRP’s for the day-ahead, including the IET. The notification must be done before the deadline of 13:00 on the day before the execution date \([4][9]\). The net result of the trading is the expected power transport via the, for the PRP, responsible grid connections. All import, export and transits must be given in time periods of 15 minutes, or PTU. It is important for each PRP to equal the actual energy flow with the predicted energy flow mentioned for the regarding PTU. After the E-programs are checked by TSO on consistency via simulations \([10]\), the programs are authorized \([9]\). Next a chronological time order in which the E-program evolves:

\(^{5}\) http://www.ucte.org/activities/systemoperation/operationhandbook/; 1 july 2009
<table>
<thead>
<tr>
<th>Step</th>
<th>System code Article number</th>
<th>Submission Deadline time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.6.1</td>
<td>B 8:00</td>
<td>Render the planning of IET program</td>
</tr>
<tr>
<td>2</td>
<td>3.6.2</td>
<td>B 8:30</td>
<td>The TSO adjudge the transport capacity</td>
</tr>
<tr>
<td>3</td>
<td>3.6.3</td>
<td>B 14:00</td>
<td>If point 1 and 2 do not agree, the PRP has the time till 13:00 to render a new IET planning. After 13:00 the PRP loses the right to trade via the interconnections [System code 3.6.4].</td>
</tr>
<tr>
<td>4</td>
<td>3.6.5</td>
<td>B 14:00</td>
<td>The PRP submit a E-program relevant to the responsible grid connection, including the IET planning.</td>
</tr>
<tr>
<td>5</td>
<td>3.6.16</td>
<td>B 15:00</td>
<td>If point 1 and 4 do not agree with the original E-program, the PRP must render a new E-program.</td>
</tr>
<tr>
<td>6</td>
<td>3.6.8</td>
<td>B 17:00</td>
<td>In the case the grid operator of the other control area does not accept the E-program, the E-program is rejected. According to3.6.17, the responsible PRP must make a new E-program to restore the balance in the system.</td>
</tr>
<tr>
<td>7</td>
<td>3.6.16</td>
<td>E 00:00</td>
<td>Start of the execution of the E-program.</td>
</tr>
<tr>
<td>8</td>
<td>3.7.5</td>
<td>A 17:00</td>
<td>The PRP receives an overview from the TSO with the information stated in the regarded article.</td>
</tr>
<tr>
<td>9</td>
<td>3.7.10.a1</td>
<td>A 24:00</td>
<td>The grid operators carry out a reconciliation according to the measurements. These must be before 24:00 of the fifth day of the regarding month.</td>
</tr>
<tr>
<td>10</td>
<td>3.7.10.a2</td>
<td>A 1 month</td>
<td>The grid operators submit the measurements needed for the reconciliation before the last day of the regarding month.</td>
</tr>
<tr>
<td>11</td>
<td>3.7.10.a3</td>
<td>A 1 month + 10 days</td>
<td>The TSO sends a overview of the following information:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1. Total of collected measurements</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Reconciliation price</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3. The fees of earnings</td>
</tr>
</tbody>
</table>

*B = Before execution date

E = Execution date

A = After execution date

Table 1: Overview step set up E-program
For extra clarification see the operational manual of the E-program and T-program [9].

### 3.2. Power reserves

The responsible TSO receives at 15 March, 15 June, 15 September and 15 December the installed power, connected power and fuel use for the next 12 calendar months for every production unit > 5 MW [System code 2.4.1.1]. Changes in this proclamation are handled via the System code 2.4.1.2 and 2.4.1.3. Second, the TSO receives a prediction for every PTU for the execution date, before 13:00 the day before, which states the produced power, control power and the periods of time when the control power is operational [System code 2.4.1.4]. Five days after the submission date, the TSO publishes all the information on its public accessible website, making a clear overview of the total installed power and the available secondary power [system code 2.5].

As mentioned in the introduction for this chapter, there are different forms of reserves for returning to an equilibrium state in the national grid.

#### 3.2.1. Spinning reserves

According to System code 2.1.2, all operating, controllable [System code 2.1.3], connected or synchronous production units with a power > 5 MW, with a connection to a voltage level ≥ 1 kV are spinning reserves [10]. The maximum of the reserves are 3% of the nominal rated active power [System code 2.1.11]. Nowadays this is set to 1%. The actual size of reserves depends on the type of production unit. All spinning reserves are autonomously activated via a local controller.

A different form of spinning reserve is the power trading via the interconnections of the grid with connected synchronous grids [System code 2.2.5b]. Decrease / increase of the power
exchange changes the size of production capacity. The directly involved TSO’s who can support safeguarding the balance are: EON-Netz and RWE for the interconnection between the Netherlands and Germany and ELIA for the interconnections with Belgium and Statnett for the interconnection with Norway.

3.2.2. Cold reserve
Cold reserve is power reserve that is not connected to the synchronous grid, or not activated. All reserves come available in a time-period of several minutes to several hours. In the Netherlands, all production units, mostly gas turbines, that can be operational within 15 minutes account to cold reserves. Activation of cold reserves is done by the responsible TSO and is done by phone [System code 2.2.5c].

3.2.3. Dis-/connection of load
The TSO can start to shed load [System code 2.2.15], if all possible methods are applied to stop the imbalance from exceeding the boundaries [System code 2.2.5d]. Load shedding means disconnection loads and / or parts of local grids to return in state of equilibrium. Load shedding is automatically deployed. The grid operators have fixed load shedding plans and load recovery plans [System code 2.2.14]. Partial disconnection occurs via frequency-sensitivity relays that disconnect load at given frequency thresholds.

3.2.4. Self regulation of load.
Self regulation of load is a dynamic behavior of the load. If the frequency decreases, the load reduces. According to the UCTE handbook, the self regulation of load is assumed to be 1% drop of load at a 1 Hz drop of frequency [UCTE Policy 1 art. C4.1]. According to Kokkelink this self regulating effect is often underestimated and could be as high as 2%/Hz [11].

3.2.5. Forms of secondary control capacity
There are different forms of control capacity to diminish the effect of an imbalance [12].
1. Regulation capacity: Power that is offered, voluntary or contracted, to the TSO. This power is automatically activated by the FVR (Frequentie Vermogens Regeling FVR) and must be activated / starts within 30 seconds and fully operational within 15 minutes with a ramp rate of at least 7% per minute.
2. Reserve capacity: Capacity that is offered via bidding. Reserve capacity is the power that is manually activated when control power is activated for longer periods of time. It is used to restore the amount of control power. All involved producers are obligated to offer their excess power or load as reserve power. The maximum deployment time is 3 days. If necessary, complete bid of reserve power is activated by TenneT. Hence, the activation of reserve power is rare. There are three different forms of reserve power: ramp down, ramp up reserve power and decrease of load.
3. Emergency capacity: If an imbalance occurs larger than the control and reserve power, available within 15 minutes, the TSO appeals the emergency power. This power, size 300 MW, is contracted in advanced. It must be available within 30 minutes.

http://www.tso-auction.org/; 3 March 2009
3.3. Power control

When the actual production and consumption deviates from the prediction, deviation from the E-program, imbalance occurs. Small imbalances, which cause a frequency deviation of max 20 mHz, are not controlled [8]. A counter action will not take place. Imbalances larger than 20 mHz demand control action. These counter actions or control actions take place in three phases and periods of time. Two forms of imbalance can occur, overloading [more load then generation, frequency goes down, denoted as “short”] and over-generation [more generation then load, frequency increase, denoted as “long”].

3.3.1. Frequency

According to the UCTE handbook the following frequencies are set before or during imbalance. To prevent a continues control of the large power production facilities, a dead band of 10 mHz is taken into account [8].

<table>
<thead>
<tr>
<th>fa Frequency [Hz]</th>
<th>Δf step size [Hz]</th>
<th>(f-fa) [Hz]</th>
<th>Control reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>50.200 - 50.800</td>
<td>0.600</td>
<td>0.800</td>
<td>Maximum instantaneous frequency deviation in response to load switching</td>
</tr>
<tr>
<td>50.020 - 50.200</td>
<td>0.180</td>
<td>0.200</td>
<td>Maximum permissible deviation ≥ 50.2 Hz result in 100% usage of ramp down primary control accessible spinning reserves or ramp up loads</td>
</tr>
<tr>
<td>50.010 - 50.020</td>
<td>0.010</td>
<td>0.020</td>
<td>Partly ramp down primary control power</td>
</tr>
<tr>
<td>50.000 - 50.010</td>
<td>0.010</td>
<td>0.010</td>
<td>Measurement accuracy of equipment</td>
</tr>
<tr>
<td>50.000 - 49.990</td>
<td>0.010</td>
<td>0.010</td>
<td>Measurement accuracy of equipment</td>
</tr>
<tr>
<td>49.990 - 49.980</td>
<td>0.010</td>
<td>0.020</td>
<td>Partly calling up primary control power</td>
</tr>
<tr>
<td>49.980 - 49.800</td>
<td>0.180</td>
<td>0.200</td>
<td>Maximum permissible deviation ≥ 50.2 Hz result in 100% usage of primary control accessible spinning reserves</td>
</tr>
<tr>
<td>49.800 - 49.200</td>
<td>0.620</td>
<td>0.800</td>
<td>Maximum instantaneous frequency deviation in response to shortage in generation</td>
</tr>
<tr>
<td>fa ≤ 49.000</td>
<td>≥ 0.380</td>
<td>≥ 1.000</td>
<td>Responsible TSO starts procedure of load shedding.</td>
</tr>
</tbody>
</table>

Table 2: Frequency limitation for primary control

The determination of an imbalance occurs with measuring and summation of the power flow via TIE lines [13][14]. The difference between actual power exchange with other TSO and the planned control program exchange (ΔP) and the accessory frequency deviation (Δf) determines characteristics of the control area.
3.3.2. Primary control

First phase after a large imbalance occurs is Primary control. It is a joint counter action to prevent frequency to decline or rise greater than the set thresholds [14]. The primary control is activated by a proportional controller (after deployment of PC, a new frequency is established with a static offset, process is similar to a proportional controller [13]) and measures the output of every generator individually. By a closed loop, the input set points are changed and adapted to the outcome of the frequency measurements.

If an imbalance occurs of ± 0.2 Hz or more [UCTE Policy 1 art. R3.4], all regulating capacity must be activated within 30 seconds [System code 2.1.6]. If an imbalance occurs between 50% and 100% [± 0.11 Hz ≤ Δf ≤ 0.20 Hz, acc. to UCTE policy 1 art. C2.1 and art. R3.4], the reserves have a deployment time between 15 and 30 seconds [system code 2.1.7]. Imbalances ≤ 50% (≤ 0.11 Hz) have a linear relation with activation time [System code 2.1.8]. See figure 3.

![Figure 4: Activation time vs. frequency deviation](image)

30 seconds after the imbalance occurs, the frequency deviation stops decreasing and ends at a new frequency with an offset of maximum 200 mHz (180 mHz max. deviation + 20 mHz accuracy) difference of the rated frequency, see figure 4. Primary control does not restore the frequency to rated set point.

![Figure 5: Primary control action](image)
The regulation is for all UCTE members. The characterization of Dutch grid is done with data found on the website of UCTE and the Dutch TSO. This result in a prescribed quasi static-state frequency of ± 200 mHz maximal and a dynamic frequency of ± 800 mHz, see figure 4 [8].

The primary reserve or spinning reserve is set on 100% for a Δf of ±200 mHz, with subtraction of 20 mHz. Another fixed value is the largest production failure of 3000 MW [11]. This is set by the two largest power plants which are connected via one single node. The response of the generator to the frequency deviation characterized by a ratio between frequency and 100 % change of its power capability [13][17] and is called the droop or static. This is an adjustable parameter of the proportional controller of the unit.

\[ S_G = \frac{\Delta f}{f_n} \frac{\Delta P_G}{P_{Gr}} \]

Equation 5: Droop of generator

The obligated regulation capacity has a linear relation with the produced annual energy per country (i represents the Netherlands)⁷.

\[ C_i = \sum E^{prod}_i / \sum E^{prod}_{UCTE} = \frac{99.346GWh}{2.625.728GWh} = 0.037 \]

Equation 6: Primary reserve contribution coefficient

So the minimum obligated contribution of primary control in 2009 for the maximum imbalance of 3000 MW is⁷:

\[ P_{primary} = C_i \cdot 3000MW = 111MW \]

Equation 7: Obligated primary reserve power the Netherlands

The single control area is specified by its own independent frequency bias. This bias is estimated by real-time measurements. When a large imbalance occurs, the power over the interconnected lines or TIE lines and frequency deviation is measured and so the Network Power Frequency Characteristics (NPFC) is determined [13] for the year 2009.

\[ \lambda_i = \frac{\Delta P}{\Delta f} = \frac{\sum P^{TIE}_{actual} - \sum P^{TIE}_{planned}}{(f_{actual} - f_n)} = 986 \text{ MW} \text{ Hz}^{-1} \]

Equation 8: NPFC of TenneT TSO control area⁷ (2009)

The NPFC is 3.7% of the total NPFC of the UCTE. Resulting in a total NPFC of [13]:

\[ \lambda_{uo} = \lambda_i \frac{C_i}{C_t} = 26648 \text{ MW} \text{ Hz}^{-1} \]

Equation 9: NPFC of entire UCTE

⁷ Data available on: www.ucte.org; 5 March 2009
According to UCTE, the NPFC is set on 18,000 MW/Hz in 2004. The values mentioned in the calculations of paragraph 3.3.1 are taken from the website of TenneT TSO b.v and the UCTE statistical database.

3.3.3. Secondary control

Second phase is the Secondary Control (SC). As addition on the proportional controller which primary control is based on, the secondary control mechanism minimize the occurred offset to zero based on a proportional integral controller. This is a controller that restores the balance between generation and consumption and restores the frequency to its original value within the synchronous area [13]. It will activate reserve power, offered to TenneT via bidding, using AGC (Frequentie Vermogens Regeling FVR). The SC is deployed after 30 seconds, thus after deployment of PC, and has a response time from seconds to typically 15 minutes. It can be deployed parallel to PC and does not interfere with PC. If responsible the SC can take over the PC and after 15 minutes the PC is reduced to 0 [4][8].

To restore the frequency, due to uncertainty of the self-regulating effect, the $K_i$ factor must be chosen slightly higher that the $\lambda_i$ [8]. If this is not incorporated, the increasing load can counteract during restoring frequency [13]. So a Frequency Control Gain (FCG) is added to scale the control power with a factor 1.1 (110%). Implementation of the FCG results in a different NPFC, called the $K_i$-factor and is related to the system droop (formed by summation of all involving generators). $i$ represent the Netherlands.

$$K_i = FGC \cdot C_i \cdot \lambda_{\infty} = 1084.6 \frac{MW}{Hz}$$

Equation 10: K-factor for secondary control

The $K_{UCTE}$-factor amounts to 19801 MW/Hz for the year 2004 [813]. To control the balance between generation and load, the Area Control Error needs $G$ to be kept at zero. If $G \neq 0$ unplanned power transport occurs between the TSO's via the TIE lines. A control area is equipped with one secondary control according to this method.

$$G = \left( \sum_i P_{\text{actual}}^{\text{TIE}} - \sum_i P_{\text{planned}}^{\text{TIE}} \right) + K_i \cdot (f_{\text{actual}} - f_{\text{n}}) = 0$$

Equation 11: Area Control Error for balanced grid

The frequency must be restored within 15 minutes after an incident occurs. The method used is called the trumpet curve and uses the following relationship. Every frequency deviation must be restored within the limits of the trumpet curve [13]. When this is not the case, the controller does not operate according the UCTE guidelines.

$$H(t) = f_0 \pm A \cdot e^{-\frac{t}{T}}$$

Equation 12: Quality of control based on Trumpet curve

Whereas $f_0$ is set point frequency of 50 Hz. A is based on frequency measurement on TIE lines. $A=1.2 \cdot \Delta f_2$, where $\Delta f_2$ is the maximum frequency deviation. The frequency must be restored
after 15 minutes to $d \pm 20 \text{ mHz}$, so the time constant $T = \frac{15 \cdot 60 \text{s}}{\ln \frac{A}{d}}$. $\Delta f_2$ can be rewritten as $\Delta f_2 = \Delta P / \lambda$. Measurements indicate a frequency drop of $\pm 30 \text{ mHz}$ preceding an incident [13]. Therefore the Trumpet relationship is adjusted. The new frequency set point is inserted in the variable $A$, resulting in the following relationship [13].

$$H^* (t, \Delta P) = f_0 \pm 1.2 \cdot \left( \frac{1}{\lambda} \cdot |\Delta P| + 30 \text{ mHz} \right) \cdot e^{-\frac{t}{T}}$$

Equation 13: Trumpet method applied for the Netherlands

Using the constants found in paragraph 3.3.2, the trumpet curve can be determined for the Netherlands, using imbalances of $\pm 250 \text{ MW}, 500 \text{ MW}, 750 \text{ MW}$ and $1000 \text{ MW}$ in a time period of $1100 \text{ seconds}$. On $t = 0$ an incident occurs. As noticeable, the frequency is restored after $900 \text{ seconds}$. Also included is the balanced situation. These are two horizontal lines at $f \pm d$ ($50 \text{ Hz} \pm 0.02 \text{ Hz}$). When supply and demand are in balance, the frequency must remain within the limits of the constant $d$.

![Figure 6: Trumpet curve for the Netherlands](image)

### 3.3.4. Tertiary control

The third phase is to restore the reserve capacity of secondary control, if necessary. The deployment is 15 minutes after an incident occurs and has no regulation for ending the time frame. Tertiary control takes over from the secondary control. Mostly TC is used to optimize the economical operation i.e. cheaper fuels or higher efficiencies or in other words lower the marginal costs and adapt the E-program. TC can be executed in different forms:

- Connecting or disconnecting production units
- Redistributing the output from generators participating in SC
- Change power exchange program via TIE
- Load control
To provide a clear vision of the deployment of control power and the accessory time frames, see Figure 7 [13] and Figure 8 [11].

<table>
<thead>
<tr>
<th>Type of control</th>
<th>Range of primary control</th>
<th>Range of optimisation</th>
<th>Range of secondary control</th>
<th>Range where primary control is still operative. It is progressively replaced by secondary control action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tertiary control</td>
<td>manual and/or automatic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secondary control</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary control</td>
<td>30 s</td>
<td>15 min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 7: Time frame for the three phases of power control

3.3.5. Time control

After an incident the frequency deviates from the original set point. This results in a difference between the synchronous area time and the Universal Coordinated Time [13]. The time offset serves as a performance indicator for the three control mechanisms and must not exceed 30 seconds. The Laufenburg control centre in Switzerland is responsible for the correction and calculation of the synchronous area time settings. Correction takes place by changing the frequency set point to \( f_n \pm 0.01 \) Hz for full time period blocks of 24 hours [13].
3.3.6. Deployment of control power

Immediately after imbalance occurs, PC is deployed, to stop further decline of the frequency. After 30 seconds there is a static frequency with an offset compared with the nominal frequency. After several seconds, SC is deployed via the delta signal, to restore the frequency to nominal value and take over from PC, which is restored to zero. After 15 minutes and longer, TC is deployed to have an optimal economic dispatch of the production units and provide extra time to start up of production units.

Figure 8: Deployment of control power
4. Economic dispatch

Dispatch is the real time operation of a PRP including managing the power unit portfolio. It is to operate and control a set of generators to manipulate their inputs to optimize the wanted dispatch scenario [15]. Inappropriate dispatch can cause different negative outcomes regarding the scenario, i.e. imbalance. Most favorable form of dispatch is economic dispatch. This means to operate the set of generators in such a way that the revenues are optimal, limited by the constraints. Not taken into account the Locational Pricing, referring to power losses pricing and congestion pricing. Used as reference for the theoretical elucidation, the first part of this chapter, is the book of Steven Stoft; Power System Economics, Design Markets for Electricity, chapter 2 and 3 [15].

Data acquisition is done to analyze the dispatch. Adaptations to sudden unexpected changes are desirable if these have positive effects on the revenues, i.e. the deployment of reserve power. Therefore, the data acquisition must be performed real time to adapt within respected time frames. This form of dispatching is Real Time Dispatching (RTD). Before the simulation of a Model Predictive Controller (MPC), all the variables are elucidated. To determine or estimate the set points, constants and a set of variables used during the simulation. Note, not all variables and constants are taken into account during the simulation, but these points are important for further research on this topic. A schematic overview is given in Figure 9 of the data acquisition.

![Figure 9: Data acquisition of RTD system](image)

After the calculation the optimal economic dispatch is determined, Set Point Values (SPV) are send to the production units.
4.1. Financial data flow

The first input is the financial aspect of the RTD system. Main variables are the DA-prices and determination of the marginal and fixed costs of each production unit separately.

Trading takes place via different contracts or auctions and via different markets. To gain an optimized economic dispatch environment, the PRP must have access to RT measurements and data. Acting on a sudden change in supply and demand, and so the changing market clearing price (MCP), can gain much extra revenues. Every form of data must be evaluated before acting. To find the best scenario, the markets must be clarified. Mean thought of this part is “should we buy the energy on the DA market or is more beneficial to generate it ourselves?”.

4.1.1. Decentralized and centralized market

There are two forms of trading, decentralized and centralized. Decentralized trading is via bilateral contracts (see obligatory), meaning a supplier directly sells the energy to a consumer. These forms of contracts are extremely flexible. Specifications can be implemented in the contract as desirable for both parties [15]. This flexibility comes with a price. When the price is too high, the consumer can buy its energy on a dealer market. The dealer market is based on buying the energy for a low price, reserves it, and then sells it for a higher price when the market prices are higher [15]. There is no fee, but the dealer buys it for a lower price and sells it for a higher price and the difference is called the spread.

Second form of trading is centralized trading. Suppliers can bid their energy on an auction which is centrally arranged. An advantage for the consumer is the single price. No more searching for the best price. This form of trading enhances the competition and presents an indication of how much a unit of energy is worth [15], but decreases the flexibility. There are different forms of centralized auctions: the forward markets and the spot market. Forward markets mean auction and biddings done in advance of the actual execution date. Spot market is the Real Time market when the actual transportation of energy takes place [15].

4.1.2. Day ahead market

The DA market also defined as forward market. This means that the energy is submitted via bidding to an auction. There are different auctions which all have their advantages and disadvantages. Most auctions are centralized markets that mediate in supply and demand and set the prices for the day ahead. There are simple auctions which do not make use of make-whole side payments. This is an additional payment to overcome expensive start ups of large units and solves the unit commitment problem. This to prevent lose of supply. More complicated markets make use of these make-whole side payments [15]. Several operating markets are Belpex (Belgium), Nordpool (Scandinavia) and APX (England, Netherlands, Belgium).

**Power exchange:** Is the simplest auction in its form. There are no complicated bids. There is only one price for all the energy supplied. This is the same price paid to all involving generators. It can use multiple rounds of bidding or uses multipart bids [15].

**Transmission rights market:** A transmission market determines the congest ability of the trades set in the DA market. Buyers and sellers must find each other and make provisional
energy trades. The TSO determines the congestion of the grid without concerning the price. If the trades are not contingent on the outcome of the DA market, extra transmission right must be bought [9][15].

**Power Pool:** This is the most complex form of power trading, because the implementation of make-whole side payments. Sellers, of which the price of energy is lower than the cost price of producing, receive the make-whole side payment. This results in different prices, for different suppliers, at the same period of time. Biddings are done via multipart bids and cover all important aspects concerning a generator operating costs and physical constraints [15].

**Complex bids power exchange:** Complex DA market includes all three types of market mentioned above [15].

**Dealer:** A dealer buys the energy in the bilateral market and sells it when the revenues are optimal [15].

The auction which facilitates the Dutch energy auction is Amsterdam Power Exchange [APX]. There are two main forms of trading and the third, strip market, is not taken into account.

**4.1.2.1. APX: Day-Ahead and Hour-Ahead market**

The core activity of the APX is the DA market\(^8\), which exist of two different types of bidding. Spot Limit Orders are individual hourly instruments in which the energy is traded for each hour of the execution date. The price is in €/MWh. Second form is the spot block orders. Those are freely definable set of individual hourly instruments for a consecutive set of hours\(^8\). The execution is subjected to maximum payment condition (buy: guarantees a maximum buying price) and minimum income condition (sell: guarantees a minimum selling price regardless to market conditions)\(^8\). All instruments are traded in blocks of 0.1 MW or multiples thereof. After market closure, APX start matching the bids and send the results to the bidders. The traded energy must be announced to TenneT b.v. via a PRP to test the congestion of the grid\(^8\)[9].

They receive all the bids electronically from all the involved entities and determine the DA-market price, based on the intersection between the demand and supply curves, for each hour of the next day. This clearing price is the average price of the regarding hour and can be used as a reference price for trading energy.

This form of auction can result in unaccepted bids. The bids are compared and the result is not always the acceptation of the cheapest bid. Bids much fulfill certain criteria before they can be accepted or matched\(^8\). Some criteria’s are:

- Similar size of spot block orders
- Matching prices of maximum payment conditions and minimum income conditions.
- Cheapest spot limit order.
- Grid congestion

The reference price (\(\lambda\)), or hourly load price, is the average price calculated over all submitted bids per hour. For simplicity reasons, instead the determination of the supply and demand curves, the following relationship is used to determine the selling price of energy in units of

\(^8\) [www.apxgroup.com; 12 March 2009]
€/MWh [12]. The numerator states the summation of the final costs of a spot block order in Euros. The denominator states the summation of total traded energy in MWh.

\[ \overline{\lambda} = \frac{\sum_{i=1}^{n} \lambda_i \cdot E_i}{\sum_{i=1}^{n} E_i} \]

Equation 14: Average energy selling price

4.1.2.2. APX: Intraday market

The spot market is called the intraday market (forward market is the DA market). Power can be traded two hours prior to the executed PTU. The reason to set up an intraday market is to trade excess power that becomes available after closure of the DA market[15]. The power then can be traded on the intraday market. Market players can use the available energy to ensure market stability and reduce imbalance costs. The intraday market can be used to decrease the imbalance caused by unexpected events two hours prior to the execution PTE.

The bids of the intraday market are complicated. Bids will be submitted in form of maximum power. There is set a high price and low price. See Table 38.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Last (MW@€)</th>
<th>Volume (MW)</th>
<th>Open (€)</th>
<th>High (€)</th>
<th>Low (€)</th>
<th>Close (€)</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>02APR09 - 1H 12</td>
<td>10.00@51.0</td>
<td>25.0</td>
<td>60.00</td>
<td>60.00</td>
<td>51.00</td>
<td>51.00</td>
<td>-9.00</td>
</tr>
<tr>
<td>02APR09 - 1H 16</td>
<td>15.00@42.0</td>
<td>15.0</td>
<td>42.00</td>
<td>42.00</td>
<td>42.00</td>
<td>42.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 3: Intraday market bids

Example 1: Use instrument 02APR09 - 1H 12 as reference. As noticeable a bid is submitted with a maximum power of 25 MW. Low price minimum required to solve the unit commitment problem is € 51.-- and the high price with addition of MC is € 60.-- to buy the total power of the bid. Demand is not that high and the intersection of demand and supply is at 10 MW @ € 51.--.

Example 2: Use instrument 02APR09 - 1H 16 as reference. The intersection of the demand and supply curve is at 15 MW @ €42.--. This means the complete bid is sold for the high price. So the demand was sufficient to sell the complete bid, or enough liquidity.
4.1.2.3. DA price curve
The curve of CP on the DA market will be used as indication to calculate the economic advantages of the dispatch strategy. If implemented, the prices (clearing price) are taken from the APX and result in the following Figure 10.

![Figure 10: APX Day-Ahead market prices of 2 April 2009]

4.1.3. Real time market
Not applied in the Netherlands.

4.1.4. Marginal costs
Marginal costs play a key role in the power exchange market. They determine the supply curve which is relevant to determine the clearing price (CP). This is the price in euro per MW where demand and supply are in equilibrium. This is the actual price of a unit of energy, with the condition that the market is not always in perfect equilibrium caused by a market failure. Changes in this price will cause shifts of the supply curves. CP is shown Figure 11 as the intersection of the supply and demand curves.

4.1.4.1. MC theory
Marginal costs are the extra costs of producing one unit more (or less), resulting in an equal price for increasing or decreasing supply. This is true for a continuous MC curve. For discontinuous MC curves, the price for producing one unit less differs from the price of producing one unit more. The discontinuous supply curve is used and the points of discontinuity are inserted. At these points the costs to produce an extra unit is distinctly greater than the savings from producing one less [15]. To formulize the statement, the constants of the supply curve are shown, showing the Variable Costs and Fixed Costs. Fixed costs (FC) is a summation of the overnight costs (investment costs or startup costs, OC), discount rate (percentage per year, r) and the life of a production unit (operational years, T) [15].

\[
FC = \frac{r \cdot OC}{1 - e^{-rT}}
\]

Equation 15: Fixed costs determination

Second are the Variable Costs (VC) are meaneely determined by the fuel costs and operational costs [15]. Most of the production units have the highest efficiency at nominal power, therefore the unit is operated at \( P_{\text{nom}} \). The point of discontinuity in the VC curve is caused by
overproduction, or dead band caused by physical limitations, and so higher failure risks are taken into account.

The MC costs are the derivates of this curve. As noticeable, there are two slopes, the slope at the left \( (MC_{LH}) \) and the right \( (MC_{RH}) \) hand of the point \( P_{nom} \). The slope of the right hand is two times the slope at the left hand. The definition of \( MC_{LH} \) is the savings of producing one unit less and \( MC_{RH} \) is the costs of producing one unit more, taken as reference production \( (P_{nom}) \) is the nominal power output of the production unit. In a continuous MC curve, the MC will become infinitely with an infinitesimal step. This is untrue. By knowing the definitions of Figure 11, the following relation is used \([15]\).

\[
MC_{LH} \leq MCP \leq MC_{RH}
\]

Equation 16: Competitive suppliers to set MCP

This relation results in the determination of the MCP. A supplier will decrease the output as long as \( MCP < MC_{LH} \) because the savings are \( MC_{LH} \) and the costs are \( MCP \) in revenues. Similarly, the supplier will increase the supply when the \( MC_{RH} < MCP \), because the marginal costs are smaller than the revenue \( MCP \).

![Figure 11: Marginal costs demand and supply curve](image)

These results are used for the centralized auctions to balance demand and supply based on MCP and \( MC^0 \). A PRP can decrease the supply if the MC is higher than the MCP and increase when the MC is lower than the MCP.
4.1.4.2. MC curves

The simulation will exist of two production units, one coal unit and one gas unit, equal in nominal power output. The following technology costs are determined [15] to calculate the Annual Revenue Requirement (ARR). Note that the FC are based on $r = 0.1$ and $T = 20$ years for gas turbines and $T = 40$ years for coal units.

$$ARR = FC + cf \cdot VC$$

Equation 17: Annual revenue

<table>
<thead>
<tr>
<th>Technology</th>
<th>VC (€/MWh)</th>
<th>OC (€/kW)</th>
<th>FC (€/MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas turbine</td>
<td>€35</td>
<td>€350</td>
<td>€4.62</td>
</tr>
<tr>
<td>Coal</td>
<td>€10</td>
<td>€1050</td>
<td>€12.21</td>
</tr>
</tbody>
</table>

Table 4: MC pricing

![Figure 12: Annual Revenue Requirements coal and gas fired production unit](image)

As noticeable, the intersection between the two ARR curves means the revenues for the coal unit are more profitable at $cf > 0.3$ and increasing with increasing capacity. Therefore, a good determination of FC and VC is needed to calculate which unit is used. In this example the MC is equal to the derivative of the VC and is set to € 35 for gas turbine and € 10 for the coal unit.

There are three basic methods to determine the priority of deployment of the production units. The first is the summation of each curve by taking the most cost efficient unit first and the expensive producing unit secondly. The theory explained in chapter 4.1.4.1. Second form is the optimization of each ARR curve, using the most efficient unit at every moment of time, if possible. Third is the aggregation of the curves or the simultaneously operation of the power units.

Using these values present an opportunity to determine a MC curve. See Figure 13, were $i=1$ represents the gas turbine and $i=2$ the coal unit.
The total capacity factor is raised to 2. This means a demand 2 times the P_{nom} of the units. Between point cf_0 and cf_{0.3}, the gas turbine produce the power most profitable. Between cf_{0.3} and cf_{1.3}, the coal unit produce the electrical energy most profitable. So optimal determination of the supply curves determine the discontinuation point at cf = 0.3 and cf = 1.3, by switching the controls from one plant to the other.

A different form of determining the MC curves is aggregating single MC curves per production unit [16]. In the range until cf = 0.3 of each unit separately, the coal unit generates the most electricity with higher revenues. For energy demand higher than cf = 0.3, the coal and gas units are producing. For power demands higher than cf = 1.7, the coal unit has reach its physical limit and stops increasing the production. In this case, the point of discontinuity is set on cf = 0.3 and cf = 1.7 [16].
4.2. Imbalance market

Second input is the adaption of the E-program caused by mismatching supply and demand. It is the concern of the TSO to safeguard the control area. Large mismatches between supply and demand result in large imbalances in the control area and need to be paid by the causing PRP [12]. If this is not possible, the TSO need to restore balance by changing the E-programs by address the SC and send out the delta signal which is added to the E-program.

When the balance between demand and supply is changed, imbalance occurs. This change causes shifts in prices per MWh, resulting in a new market to bid reserve power [15]. The reserve power can be sold for higher prices than the CP, or pay less than the MC costs (decreasing supply). Therefore, good bidding on the reserve market can increase the profits, without being the perpetrator of imbalance. The philosophy of the reserve market is: the perpetrator pays the solver.

4.2.1. Portfolio imbalance

Imbalance is the deviation between supply and demand. The prediction is explained in chapter 2.1.5 and 3.1 via the E-program. Every PRP must act conform the E-program. Inside the portfolio of the PRP there are many different forms of consumers and producers. Every entity has its own significant energy behavior. It is the obligation of the PRP to predict these behaviors and notify the TSO of the planned energy trading per PTU [4][9]. If a large consuming or producing entity deviates from its predicted behavior, imbalance occurs. It may be possible to solve the imbalance within the portfolio during the regarding PTU. When an imbalance occurs, the primary control mechanism stops further decline of the frequency. Change of energy production, within the portfolio, is necessary to diminish the imbalance of the regarding PTU. When a PRP cannot restore the imbalance, the TSO must support the causing PRP by calling up the reserve capacity. The causing PRP must pay the solving PRP the ex post set price [7].

4.2.2. Delta signal

The regarding TSO determines the imbalance of the control area by subtracting the actual measured power flow of the TIE- lines of the planned power exchange. Imbalance of the control area causes a difference not equal to zero.

![Figure 15: ACE: Ramp up (P>0) and ramp down (P<0)](image)
The ACE must be reduced to zero by actions taken inside the control area. To prevent unwanted large durations of imbalances, two mechanisms were designed which are called Load Frequency Control and Automatic Generation Control.

First is the Load Frequency Control (LFC) is also known as SC. This is arranged centralized by the TSO. They determine the balance or imbalance via the already mentioned TIE-lines. A controller determines the needed power and sends it via a LFC signal automatically to the PRP with the highest priority. This signal is the Delta Signal and the priority is determined by the imbalance price on the bid price ladder [12].

Second is the control mechanism, or Automatic Generation Control, to optimize performance of the production unit or portfolio and to reduce the deployment and response time for load changes from minutes to seconds, by replacing manual control for automatic control [17]. Note: this is not comparable with PC. After distortion of the balance, the TSO sends out a signal to all involved PRP’s and production units under its control, to change the production plan and restore the frequency. The Delta Signal is added to the portfolio imbalance to change the set points.

4.2.3. Imbalance prices and bid price ladder

When the system is in balance, the CP of the market is approximately equal to the DA price of the APX. When imbalance occurs, the CP will change. The difference is called the raw price difference [7]. See Table 5 for an indication of the total average difference over fixed time periods.

<table>
<thead>
<tr>
<th></th>
<th>APX day ahead price</th>
<th>Imbalance price TenneT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>27th may 2009</td>
<td>25th may 2009</td>
</tr>
<tr>
<td>Base (1 to 24)</td>
<td>€ 29.49</td>
<td>€ 71.28</td>
</tr>
<tr>
<td>Peak (8 to 23)</td>
<td>€ 38.72</td>
<td>€ 70.97</td>
</tr>
<tr>
<td>Super-peak (9 to 20)</td>
<td>€ 40.23</td>
<td>€ 64.21</td>
</tr>
<tr>
<td>Off-peak (1 to 7 &amp; 24)</td>
<td>€ 11.04</td>
<td>€ 57.66</td>
</tr>
</tbody>
</table>

Table 5: DA price vs. imbalance price

The raw price difference forms the base of a new market, called the imbalance market. To ensure balance between supply and demand in the control area, the TSO must have reserve capacity to change supply and prevent black outs and restore the planned energy transportations via the TIE lines. To safeguard the grid, meaning sufficient control and reserve power, the TSO has bilateral contracts with suppliers to ensure a fixed amount of control power for a fixed price and power. Control power is power with a response time less than 15 minutes. Secondly, all connected entities with a nominal power larger than 60 MW have the obligation to notify TenneT all the ramp up, ramp down and increase of load as control power in form of bids [4][8]. The height of these bids is determined by the fuel costs and flexibility of the production units. These bids and contracts are positioned on the bid price ladder merit order.
In Figure 16, there are two possible situations, A is shortage of supply (load is increased) and B with a shortage of load (load is decreased). In situation A there is a need of extra load with size Pa. To determine the imbalance price, all the bids are accepted to fulfill the new requirements and the highest bid sets the imbalance price. These are passive contributions and are awarded with the imbalance price minus the incentive whereas the negative contributions, or perpetrators, must pay the imbalance price plus the incentive [18]. Most of the time, the incentive is set to zero.

In situation B there is a shortage of size Pb. Meaning suppliers must decrease the production. This results in payments from the PRP to TenneT, because the PRP already sold the energy and now saves the fuel costs. Instead of producing energy for the DA price of +/- €50 /MWh, they can decrease the production and only pay +/- €9 /MWh, resulting in a profit of €41 /MWh. There are exceptions like restrictions by gas contracts. If the PRP will receive fines when they decrease extraction of gas from the grid, they desire a negative imbalance price. This means TenneT awards the PRP to accept the fine and cover the costs [12][18]. The perpetrator pays the costs of producing the power minus the imbalance price. It is assumed that TenneT bought excess energy for the imbalance price [19].

According to the explanation, there are two main forms of regulation power [19].

Ramp up control power:
- PRP increases production and receives the imbalance price. Perpetrator pays the imbalance price to TenneT.
- TenneT pays the PRP (when it is negative, the PRP must pay TenneT)

Ramp down control power:
- PRP decreases production and pays the imbalance price. Perpetrator pays the difference between the middle price (DA price) [19] and the imbalance price.
- PRP pays TenneT (when it is negative, TenneT must pay the PRP)
Finally when multiple bids are chosen, the regarding PRP’s receive the delta signal to adapt their running E-program.

4.3. Generation

Third is the actual generation and deployment of the power unit portfolio. Every generator or set of generators have their specific dynamic behaviors and are characterized by a set of constants which characterize the step response. Accurate determination of the behavior can reduce the chance of imbalance in the portfolio of the PRP. The sets of generators need maintenance and failure or risk management to take outages into account. Unwanted outages can cause a large unwanted imbalance and so high imbalance prices. The perpetrator will pay, so accurate monitoring of the power unit is necessary to determine a fixed maintenance scheme to prevent unwanted outages.

4.3.1. Production unit output

One day ahead, the E-program is determined. This schedule forms the working principle and guideline of the portfolio and RTD system. Every PRP accept the risks of prediction errors, so quick adaptations to mismatching of prediction errors are needed. Accurate monitoring of the power output influences the deviation of the E-program. Figure 17 gives an overview how balance is defined.

As noticeable, there are two curves: E-program (curve E) and the production curve of the production unit (curve P). If the PRP is in balance the integral per PTU of the two curves are equal [20].

$$\int_{PTU_a}^{E(t)dt} = \int_{PTU_a}^{P(t)dt}$$

Equation 18: Balance E-program and power production

The behavior of the production unit cannot follow the block shaped steps of the E-program, because the production unit response time in seconds and ramp rate in MW/minute or %/minute. These limitations cause a deviation between the two curves. As long as Equation 18
holds, the system is in balance. The negative effect is the two surfaces $A_1$ and $A_2$, this cause the deviation but not imbalance. The surfaces must be equal to maintain balance according to Equation 18. The same holds for $PTU_{n+1}$. In $PTU_{n+2}$ imbalance occurs. The step size from $PTU_{n+1}$ to $PTU_{n+2}$ is too large. The production unit is limited by the ramp rate and cannot follow curve E. The boundary condition set in Equation 18 cannot be met. Imbalance occurs.

\[(a) A_1 = A_2 \]
\[(b) B_1 = B_2 \]
\[(c) C_1 \neq C_2 \]

Equation 19 a to c: Determination of imbalance

The size of imbalance is $C_1 - C_2 = \Delta E_3$. To overcome these imbalances, accurate monitoring of the power output and production unit behaviors is necessary. A third option is implementation of controllers with dynamic behavior models (linked to the behaviors of the units) [21].

Second, requirements for optimal control / dispatch of the portfolio are the technical limitations. Two already mentioned; the ramp rate and response time [20]. The others are:

- **Adjustable set points**
  - Minimum limit
  - Lower set point limit
  - Set point value or nominal power
  - Upper technical limit
  - Maximum limit

- **Control range**

These values are needed to determine the working area and depend on the type of production unit [20].

![Figure 18: Production unit set points](image-url)
4.3.2. Power unit discontinuities

It is obvious that the maintenance scheme must be taken into account during deployment of the life span of the production unit. Every unwanted trip of a unit, causes large imbalance during the regarding PTU. During maintenance the production unit cannot operate and this is incorporated in the deployment schedule of the PRP.

4.4. Obligatory

Second and last input is the contracted, bilateral or bids, power generation. The summation of the contracts determines the E-program and the planned power exchanges.

4.4.1. Bilateral contracts

Every full acknowledge PRP must predict the behavior of the consumers, prosumers\(^9\) and producers \(^[4][8]\). Prediction of the behavior also determines the energy transport and exchanges. Most of the energy is traded via bilateral contracts and on the APX, see paragraph 2.2.5. The E-program is based on the energy trading that takes place during the regarding PTU. The defined E-program is used as reference set point during operation of the production portfolio.

4.4.2. Regulation

Every producer >60MW must notify the TSO about all the reserve capacity that is available during the PTU in forms of bids on the imbalance market. Therefore, via regulation like System code \(^[4]\), a reservation of capacity, meaning control and reserve power, must be taken into account. For more information about regulation power see chapter 3.

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\(^9\) Prosumers are customers who act as consumers and also as producers.
5. Model Predictive Controller

Due to the liberalization of the energy market, ad-hoc control schemes were designed. With the upcoming of new technology, especially computer calculation speed, new opportunities creates new possibilities to calculate more accurate the behavior of the plant and the response to changing set points. During the transition to a liberalized market, most of the control mechanisms were designed ad-hoc and were based on a proportional integral-controller to obtain the desired dispatch. By the upcoming of distributed generators, the controller is pushed to the limits of its capability. Most controllers are designed to limit the deviation between prediction and generation. Today the controllers control the deviation as economically as possible [21]. Nowadays there is a new and promising development in control mechanisms. This new and promising technology is called Model Predictive Control. It is a class of discrete time controllers which determines a new manipulated input signal on a prediction of future outputs of the system [22]. All the predictions are based on the model of the process. The main idea is or technique behind MPC is the principle of moving horizon or receding horizon.

5.1. Problem definition

To start this chapter, two variables need to be distinguished. P of actual power in MW and E is energy in MWh.

As seen in paragraph 4.3.2, portfolio imbalance can a.o. be a result of badly configured control mechanisms or excessive influence of distributed generators. In Figure 17 there is imbalance in $PTU_{n+2}$ of $C1-C2=\Delta E_3$. This is the result of only match the energy content of the reference signal with the output energy of the production unit. Faster control mechanisms with prediction of the output in multiple successive PTU’s have the capability to decrease the portfolio imbalance. As seen in Figure 17, the imbalance in $PTU_{n+2}$ is zero. This is accomplished by inserting a small imbalance in $PTU_{n+1}$.

The energy content of B2 is less and introduction of a small imbalance B12 with regarding energy content, reduces the total imbalance. As noticeable, the imbalance is $B12 < \Delta E_3$ (see chapter 4.3.1). The MPC calculates the optimal dispatch of the production unit with all
constraints taken into account. It sets out an optimal path, of an in advanced fixed horizon, to reduce imbalance to a minimum. It basically reduces all quadratic imbalances to a minimum. It works on the philosophy: you lose some, you win more.

5.2. Working principle of MPC

For simplicity, this report focuses on Single Input Single Output (SISO) systems instead of Multiple Input Multiple Output (MIMO) systems. During evolvement of this project, all explained variables are reflected to the load balancing system or RTD system.

The MPC controller calculates new inputs based on the measurements of inputs and outputs done in the past and the desirable output based on the plant response in a discrete time periods. These measurements are linked to a dynamic model of the plant. Figure 20 represents the basic concept of a MPC model [22][23]. In this figure, there can be different variables distinguished:

- Input or manipulated variable \( u(k) \)
- Step size \( \Delta u_{k+1} \)
- Predicted output or measured output \( y(k+1|k) \)
- Reference signal \( r(k) \)
- Sample time \( T \) [s]
- Step \( k \) [interval]
- Control horizon \( m \) [interval]
- Prediction horizon \( p \) [interval]

\[ \begin{align*}
\Delta u(k+1) & \quad \text{input } u(k) \\
\text{past} & \quad \text{future} \\
\text{reference } r(k) & \quad \text{predicted output } y(k+1|k) \\
\text{control horizon } k+1 & \quad \text{prediction horizon } k+p
\end{align*} \]

During the past, the plant responds to changes of the input. Every change comes with a step change of \( \Delta u_{k+1} \). The reaction of the plant is recorded, dynamic behavior, and is used to predict new the output that is desirable in the future. The desirable output is \( r(k) \) and is used as a reference value. The optimal input change \( \Delta u \), and so the manipulated variable, is calculated by minimizing a quadratic objective function of the tracking error prediction minus reference \( (y_{k+1} - r_{k+1}) \). This is referred as a cost function \( J \) [23].

5—34
\[ J = \text{Min} \sum_{i=1}^{p} \left[ \mu_i \cdot (y_{(i+1/2)} - r_{(i+1/2)})^2 \right] + \sum_{i=1}^{m} \lambda \cdot (\Delta u_{(i+1/2)})^2 \]  

Equation 20: Quadratic optimization function

In the above formulated equation, there are two new inserted variables. These are the weighting matrices, in orders of 0, 1 or exponentially increasing. \( \mu \) represents the weightings of the error \( y_{(k+1/2)} - r_{(k)} \) over the prediction horizon (p) and \( \lambda \) represents the weightings of \( \Delta u_{(k+1/2)} \) over the control horizon (m).

The translation to the RTD load balancing system is relative easy for this report. Used as reference value \( r_{(k)} \) is the outcome of the E-program, the output \( y_{(k+1)} \) is the response of the production unit(s) and the input \( u_{(k)} \) is the reference value computed by the MPC. The optimization function or cost function is referred to minimize the deviation in power during the 15 minutes of the regarding PTU(n). The control horizon (m) and prediction horizon (p) will be tuned during simulation.

There are two classes of optimization algorithms, the relatively simple Least Squares model (LS model) which is unconstrained and the Quadratic Programming model (QP model) which takes constraints into account [25]. These constraints are formulated in paragraph 4.3.1. Most important constraints are minimum and maximum power output and the ramp speed.

**5.3. Set up simulation of MPC in matlab**

The essence of this report is to understand and implement the MPC toolbox in Matlab and not to clarify the algorithm behind MPC. The goal is to build a normal operating MPC controller and understand the principle.

**5.3.1. Dynamic model production unit**

To implement MPC, the basic set up and behavior of a power plant is needed. Electrabel handed a schematic representation and constraints of two production units used in the Netherlands. Next is an overview given of the variables of the two production units:

- **Eemshaven**
  - Gas fired production unit
  - Ramp rate or gradient of +5 MW/min and -5 MW/min
  - Maximum operating setpoint value of 350 MW
  - Minimum operation setpoint value of 120 MW
  - Time constant \( \tau \) of 10 seconds
  - Response time of 0 seconds

- **Gelderland**
  - Coal fired production unit
  - Ramp rate or gradient of +3 MW/min and -3 MW/min
  - Maximum operating setpoint value of 600 MW
  - Minimum operation setpoint value of 240 MW
  - Time constant \( \tau \) of 180 seconds
  - Response time of 120 seconds
Figure 21: Schematic representation of production unit

As noticeable, there are multiple blocks in this overview. To make a close loop feedback MPC controller, the transfer function of this system must be calculated via Laplace transformation of a time function.

In the overview there are different variables and signals. The first are the block parameters, named $G_{i}(s)$. Where $i=1$ represents a time delay or response time (shift in phase angle), $i = 2, 4, 6$ are the gains or time constants $\tau$ in seconds ($K = 1 / \tau$) and $i = 3, 5, 7$ are integrals. The following step is the calculation of the Laplace transformation of each block [24].

\[(a) a = 10s\]
\[(b) \tau = 0s\]
\[(c) G_{1}(s) = \int_0^\infty e^{-st} \cdot e^{-\tau t} dt = \int_0^\infty e^{-(s+\tau)t} dt = \frac{1}{s+\tau}\]
\[(d) G_{2,4,6}(s) = \int_0^\infty \frac{1}{\tau} e^{-st} dt = \int_0^\infty e^{-\tau t} dt = \frac{1}{\tau} \frac{e^{-\tau t}}{s} = \frac{1}{s} \]
\[(e) G_{3,5,7}(s) = \int_0^\infty \frac{1}{s} e^{-st} dt = \int_0^\infty e^{-\tau t} dt = \frac{1}{s} \frac{e^{-s\tau}}{s} = \frac{1}{s} \frac{e^{-\tau t}}{s} = \frac{1}{s}\]

Equation 21 a to e: Laplace transformations Eemshaven

The time delay is transformed to a high order continuous Pade function. The rate limiter and the saturation or min/max function are discontinuities. These discontinuities will be implemented as constraints.
Second is the determination of the transfer function of the production unit Eemshaven, via all signals denoted with letter C.

\[(a) C_{1(s)} = R(s) \cdot G_{1(s)} \]
\[(b) C_{2(s)} = \frac{R(s) \cdot G_{1(s)} \cdot G_{2(s)} \cdot G_{3(s)}}{1 + G_{2(s)} \cdot G_{2(s)}} \]
\[(c) C_{3(s)} = \frac{R(s) \cdot G_{1(s)} \cdot G_{2(s)} \cdot G_{3(s)} \cdot G_{4(s)} \cdot G_{5(s)} \cdot G_{6(s)} \cdot G_{7(s)}}{(1 + G_{2(s)} \cdot G_{2(s)}) \cdot (1 + G_{4(s)} \cdot G_{4(s)}) \cdot (1 + G_{6(s)} \cdot G_{6(s)})} \]
\[(d) C_{4(s)} = \frac{R(s) \cdot G_{1(s)} \cdot G_{2(s)} \cdot G_{3(s)} \cdot G_{4(s)} \cdot G_{5(s)} \cdot G_{6(s)} \cdot G_{7(s)}}{(1 + G_{2(s)} \cdot G_{2(s)}) \cdot (1 + G_{4(s)} \cdot G_{4(s)}) \cdot (1 + G_{6(s)} \cdot G_{6(s)})} \]
\[(e) C_{4(s)} = \frac{R(s) \cdot G_{1(s)} \cdot G_{2(s)} \cdot G_{3(s)} \cdot G_{4(s)} \cdot G_{5(s)} \cdot G_{6(s)} \cdot G_{7(s)}}{(1 + G_{2(s)} \cdot G_{2(s)}) \cdot (1 + G_{4(s)} \cdot G_{4(s)}) \cdot (1 + G_{6(s)} \cdot G_{6(s)})} \]

Equation 22 a to e: Calculation transfer function production unit

This model is built in Matlab to determine the high order transfer function of production unit. In the case of production unit “Eemshaven”, the time delay is set on 0 seconds. Therefore the time delay is a direct feed through block and returns the transfer function to Equation 23.

\[t_f_{eemshaven} = \frac{10^3 \cdot s^6}{10^6 \cdot s^{13} + 3 \cdot 10^5 \cdot s^{11} + 3 \cdot 10^4 \cdot s^9 + 10^3 \cdot s^7} \]

Equation 23: Transfer function of production unit Eemshaven

The transfer function of production unit “Gelderland” is a higher order function, because of the implementation of the high order linear Pade function, and it is too long to present, therefore the following Matlab m-function to represent the function. Production unit Gelderland will not be used for further discussion or simulation.
5.3.2. Step response models
Matlab already inserted different forms of Model Predictive control algorithm and it will be used to implement an actual MPC and understands its basic concepts. There is one models based on the step response format of the plant model [25] and simulated during this study.

5.3.2.1. MPC based on step response models
Step response models convert the continuous time models to a discrete step function. In line with this report, the model is based on a transfer function (tf) with the Laplace variable “s”. The assumption is that the model is in steady state and response to an input change and finally returns in steady state. Step response is the output signal that results from a step input, defined as follows:

\begin{align*}
u(t) &= 0 \quad t < 0 \\
u(t) &= 1 \quad t \geq 0
\end{align*}

Equation 24: Step response model

5.3.2.2. Step response model
The sample time in this case is presented by the sample time of the dynamic response model of the production unit. Small time samples spare most of the information during transformation from continuous time model to discrete time modes. Information can disappear if larger time samples are used, but simulation time will be shortened.
As noticeable, sample time of 1 second contains more information of the unit behavior, but larger time samples will contain sufficient information to simulate the MPC. To understand MPC, this simulation will make use of sample times of 1 second ($Ts = 1$). Simulation speed is not of the essence. If $Ts > 1$, than the sampling periods $k = \text{time} / Ts$.

### 5.3.3. Implement step response based MPC in Matlab

The ease of Matlab is the existence of MPC toolboxes and user guide, for relative easy implementation of MPC. Before opening the toolbox, several aspects need to be configured.

#### 5.3.3.1. Reference signal ($P$ in MW)

First aspect is the reference signal. During normal operation of the production unit, the daily E-program is used as reference signal. However, the E-program consists of ($4 \cdot 24$) 96 PTU’s. This will take long time for simulation and tuning the parameters. Therefore, a simple reference signal is used, with small power variations that the production unit is able to overcome.

```matlab
% Matlab 2: reference signal in power steps
nstep = delt2;
time = (1:nstep:tmpc_end);
for k=1:1:PTE_tot;
PTE(k)=k*(15*60)/delt2;
end
r(time>0)&(time<=PTE(1)))=60;
r(time>(PTE(1)))&(time<=PTE(2)))=50;
r(time>(PTE(2)))&(time<=PTE(3)))=80;
r(time>(PTE(3)))&(time<=PTE(4)))=100;
r(time>(PTE(4)))&(time<=PTE(5)))=120;
r(time>(PTE(5)))&(time<=PTE(6)))=90;
r(time>(PTE(6)))&(time<=PTE(7)))=70;
r(time>(PTE(7)))&(time<=PTE(8)))=80;
r_ref=r';
```

**Figure 23: Step response and sample time production unit**

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Note: the reference signal is without the minimum power output of each production unit.

5.3.3.2. MPC toolbox

Matlab is supplied with a standard algorithm toolbox containing constrained MPC based for step response models. The step response is used for the ease, instead of state space models, to implement and understand the MPC concept and theory. There are two equal functions, CMPC and MPCSIM. The first solves the QP problem iterative and the second analytical. Therefore, MPCSIM is faster but more complicated. The used Matlab function is:

```matlab
[yp, u, ym]=cmpc(plant, model, ywt, uwt, M, P, tend, r, ulim, ylim, tfilter, dplant, dmodel, dstep);
```

Matlab 3: CMPC Matlab function

Where is:

- `yp` Matrix, M x n_y, of the predicted output of the production unit with n_y (number of outputs equal to number of tf functions) columns and number of rows equal to the sample periods. M = length(k x delt2).
- `u` Matrix, M x n_u, containing the elements of the manipulated variable (mv).
- `ym` Matrix, M x n_y, containing the predicted output from the state estimator in the controller. It differ form Y_P if plant : model and there are unmeasured disturbances.
- `Plant` Production unit model in step format
- `Model` Production unit model in MPC step format that is used for state estimation in the controller.
- `ywt` Weighting matrix, n_row x n_y, to be applied for setpoint tracking of the predicted output
- `uwt` Weighting matrix, n_row x n_u, to be applied for setpoint tracking of changes of the manipulated variable. These matrices are of size 1 ≤ n_row ≤ P. If n_row is smaller than P, then CMPC will use the last row to fill in the remaining steps.
- `M` Control horizon in form of, for this study, a scalar. CMPC interprets it as the input horizon of controllable manipulated variables.
- `P` Number of sampling periods for the prediction horizon, where P > M.
- `tend` Desired duration of simulation. tend = PTE(n) X 15 min x 60 sec.
- `r` Matrix of size n_row x n_y, containing elements of setpoints of reference trajectory for every sample period.
- `ulim` Matrix, n_row x n_u, giving the limits of the manipulated variables. If n_row < Tp, the last row will be used to fill the empty spaces. The elements are hard bounds or constrains. Three main matrices
can be distinguished: \( u_{\text{lim}} = [u_{\text{min}}, u_{\text{max}}] \), minimum input value, maximum input value and the maximum change between sample periods.

- **ylim**: Same as ulim, only constrains for the predicted output.
- **tfilter**: Is a matrix of time constants for the noise filter and the unmeasured disturbances entering at the output of the production unit.
- **dplant**: Is a model in MPC step format representing all the disturbances (measured and unmeasured) that affect the plant.
- **dmodel**: Is a model in MPC step format representing the measured disturbances.
- **dstep**: Is a matrix of disturbances to the plant. For output step disturbances, the format is the same as \( r \).

The above explained function is clarified with the following block diagram.

![Block diagram of P-step simulation](image)

**Figure 25: Block diagram of P-step simulation**

5.3.3.3. Simulation

Filling in all the above formulated inputs with reference signal of power steps in MW and small scalars \( m \) (2) and \( p \) (10), gives the following manipulated variables and predicted output figures. In this study \( y_p = y_m \).
As noticeable, the production unit output tracks the reference signal after ending the slew rate constraint. A negative effect is the ringing\textsuperscript{10} of the $U_e$ and $y_p$ signal. Calculation of the poles shows a negative real pole of -0.01975. In general, these negative real pole cause ringing. One way to minimize ringing is the make the prediction horizon significantly larger than the control horizon \[25\].

\textsuperscript{10} Unwanted large fluctuations of the signal
In this case the control horizon \( m = 2 \) and the prediction horizon \( p = 25 \times M \). As noticeable, there are no real negative poles and all the absolute values of the poles are smaller than 1 (positioned inside the unit circle) \(^{11} \).

Second problem, the energy content during a PTU is not equal to the energy content of the reference signal. This problem is caused by the optimizing the quadratic function or least squares function. This function is named the costs function \( J \) and is displayed in Equation 20. The problem is that the negative imbalance during the PTU will not cancel out the positive imbalance. Main error is caused by the quadratic function inside the summation of the prediction horizon. The goal of the MPC is to track the changing setpoints within the constraints and optimize the \( u_e \) trajectory by minimizing the deviation from the reference signal as much as possible, not to overcome deviation in the energy content during a PTU.

5.3.3.4. Changing reference signal (E in MWh)

A second reference signal that can be used is the energy content during the regarding PTU. Instead of tracking the power trajectory, now the energy content trajectory is tracked. An advantage is that the \( E \) content of both curves \( r \) and \( y_p \) must be equal at the points time = PTU\((n)\) with \( n \) is the scalar representing the end of the regarding PTU.

\(^{11} \) http://www.physiol.ox.ac.uk/Computing/Online_Documentation/Matlab/toolbox/mpc/smpccl.html
The energy content per PTU is:

\[
E_{PTU(n)} = \frac{\sum_{PTU(n)}^{PTU(n+1)} r(k) \cdot 900[s]}{3600[s]}
\]

Equation 25: energy content per PTU in MWh

Following the energy content as a reference signal, the MPC must track the E-curve and so predict and minimize the wanted E output. Equation 25 calculates the E-content in a scalar, necessary is a curve in vector form.

\[
r_{\text{int}} = \begin{bmatrix} r_{\text{ref}}(1) \\ r_{\text{ref}}(2) + r_{\text{int}}(2-1) \\ \vdots \\ r_{\text{ref}}(k) + r_{\text{int}}(k-1) \end{bmatrix}
\]

Equation 26: E-curve determination

Implementing all new variables in the simulation and remain the already tuned horizons, returns the following graphs.
Via this method, the two major constraints can be calculated via:

\[ P_{\text{min}} \leq P_{\text{set point}} = \frac{\partial y_p}{\partial t} \left[ \text{MW} \right] \leq P_{\text{max}} \]

\[ \text{Ramp} = \frac{\partial^2 y_p}{\partial t^2} \left[ \frac{\text{MW}}{s} \right] \leq \text{ramp}_{\text{max}} \]

Equation 27: Calculate constraints

As noticeable in Figure 29.2 (ramp rate), the ramp rate is larger than the in advance fixed ramp rate constraint of 0.0833 MW/s or 5MW/min. (for this simulation; time = k x \( T_s \), with \( T_s \) is 1 second, therefore 5MW / 60 s = 0.0833 MW/s). This is a major negative effect caused by the algorithm of the CMPC. It can only work with hard bounds of a matrix with elements of integers. The input \( u_{\text{lim}} \) and \( y_{\text{lim}} \) can only handle integers and no soft constraints, like Equation 27, of first and second order differentials.

5.3.3.5. Find optimum of \( m \) and \( p \)

The following assumption will be made to continue the exploration of MPC.

- Ramp rate +/- infinite
- No saturation power output, \( P_{\text{min}} \) and \( P_{\text{max}} \) are zero respectively infinite

Thus unconstrained MPC.
What are the optimal scalar values of the control and prediction horizons? To find the optimum, an iterative process is built in Matlab to find the minimum in deviation between reference signal and $y_p$ per PTU summed over all PTU's.

$$\Delta \text{Diff}_{optimal} = \min \sum_{n=PTU_{int}}^{n=PTU_{int}} \left( \sum_{t=PTU(n-1)+1}^{t=PTU(n)+1} (r_{in}(k) - y_{p}(k))^2 \right)$$

Equation 28: Ideal stipulation of optimization

Matlab 4: Iterative optimization for m and p

Note: if $M < P$ then the control horizon (m) will be equal to the prediction horizon (p). Normally the optimum can be found when the differential of the $\Delta \text{Diff} = 0$, however this optimization routine has two variables and becomes a non-convex problem with multiple minimums. Therefore the optimization routine is to find the smallest quadratic element of the matrix.
It is recognizable that there are large differences between the sum of \( r(k) \) and the sum of \( y_p(k) \). Therefore, all differences larger than 10000 and equal to zero will be ignored and left out the plot. The result is a 2-D plot which represents all differences.
It can be seen that there are different minimums of the graph with a differential value of zero, resulting in different optimum and is a non-convex problem. Therefore a plot is made that shows all the lower points. The optimum is at point \( m = 6 \) and \( p = 40 \).

Implementing the optimum horizons returns the above displayed graphs. In Figure 32.4 (reference signal), there is still some overshoot. The cause of this is that the MPC only tries to minimize deviation between the E-curves and will not take the overshoot of the power setpoint into account. Second is the evenly distributed imbalance on period \( k \). The MPC forces the plant, via the manipulated variables, to decrease or increase the power output in advance of the coming PTU.

Figure 32: Plot of simulation E-curve with optimal horizons
6. Conclusion

Balancing and maintaining the high voltage transmission grid is one of the core activities of TenneT TSO B.V. To keep the grid in balance, TenneT TSO B.V. must have stimulants to persuade PRP’s to reserve sufficient reserve capacity, or act on the imbalance market, to overcome unwanted disturbances. These stimulants are fines for the perpetrator, complying with regulation and creating the imbalance system which provides the opportunity to sell the capacity for higher prices and gain extra profits. To prevent the fines, a good control mechanism needs to be designed to prevent unwanted deviations from the E-program and to react quickly on selling reserve capacity.

The MPC toolbox incorporated in Matlab presents an opportunity to simulate the implementation of MPC. The power output of the portfolio or single production unit must track the E-program. The outcome of the simulation is that the mechanism of the MPC toolbox cannot fulfill the requirements of economic dispatching, despite the optimization algorithm of the MPC. This algorithm operates on the principle to minimize a costs function, see Equation 20. The quadratic function inside the equation cancels out the positive and negative imbalance. The theory for the economic dispatch is that the negative faults \( r_{\text{ref}} < y_p \) cancels out the positive faults \( r_{\text{ref}} > y_p \). Therefore, the quadratic function of the costs function must be replaced. The new MPC costs function must be in form of Equation 29.

\[
J = \sum_{k=1}^{n} \left[ \sum_{t=2}^{m} \left( \mu_t \cdot (y_{(k+1 | k)} - r_{(k+1)}) \right)^2 \right] + \sum_{i=1}^{m} \left[ 2 \cdot (\Delta u_{(k+1)})^2 \right]
\]

Equation 29: New cost function for optimal economic dispatch

The first simulation cannot use the P-curve as a reference signal because the quadratic function changes the signs of negative faults.

The second reference signal is the energy content per PTU. The second simulation cannot use the E-curve as a reference signal, because of the constraints. They are first (Showing the P-curve or power setpoints) and second (showing ramp rate) order differential equations. These constraints are soft bounds and cannot be handled by the MPC. Second error is that the overshoot of the power setpoint is not taken into account and this error remains when the standard algorithm is used.

To design new algorithm, based on the MPC theory, the costs function must be re-designed. Also distributed generation must be incorporated (probably as disturbance) and it is preferable that the delta signal also is incorporated. Second is the determination of the optimal prediction horizon and control horizon. Large prediction horizon will decrease simulation speed, which can result in too late reaction to large disturbances.
Appendix 1: Matlab constraint MPC with power step reference

clear all

%adjustable constants
PTE_tot=8;
delt2=1;
accurate.

%constants MPC and function
deltl=O;
nout=1;
tfinal=l80;
tmpc_end=((PTE_tot)*15*60);
tau_e=lO;
a_e=O;
r_e=5/60*delt2;
P_min_e=120;
P_max_e=350;

%transfer function;
[num_Pade_e,den_Pade_e]=pade(a_e,l);
G_el=tf(num_Pade_e,den_Pade_e);
G_e2=tf([1],tau_e);
G_e3=tf([1],10);
H_e=feedback(G_e2*G_e3,1);
tf_el=H_e*H_e*H_e;
tf_e=H_e*H_e*H_e;

%step(tf_e)
[num_tf_e,den_tf_e]=tfdata(tf_e,'v');
%step tf to step function plant
num_el=poly2tfd(num_e,den_e,deltl,a_e);
plant_el=tfdata(tf_el,'v');
plant_e=tfd2step(final, delt2, nout,plant_el);
plotstep(plant_e);
title('stepresponse delt = 5 sec')

%simulation time and input step
timestep = delt2;
time = (1:timestep:tmpc_end);
for k=1:1:PTE_tot;
PTE(k)=k*(15*60)/delt2;
end
r«time>0&(time<=(PTE(1»)=60;
for (k>=(PTE(1))&time<=(PTE(2)))=50;
for (time>=(PTE(3))&time<=(PTE(4)))=100;
for (time>=(PTE(4))&time<=(PTE(5)))=120;
for (time>=(PTE(5))&time<=(PTE(6)))=90;
for (time>=(PTE(6))&time<=(PTE(7)))=70;
for (time>=(PTE(7))&time<=(PTE(8)))=80;
end
r_ref=r';

%CMPC
model=plant_e;
ywt=1;
and reference signal
uwt=1;
in objective function, if uwt > ywt then no
r=tfdata(model);%Weight matrix for difference between output
r=r';%weight matrix for manipulated variable move
ulim=[-inf,inf,r_e];%overshoot
ylim=[];%final time for simulation
constraints%constant or time varying reference trajectory
tfilter=[];%constraints on input
dplant=[];%min and max value of variable output
dstep=[r_ref);

M=2;%control horizon
$P=25*M$; %number of steps in the time horizon for quadratic function

$[y_e, u_e]=cmpc(\text{plant}_e, \text{model}, \text{ywt}, \text{uwt}, \text{M}, \text{P}, \text{tend}, r, \text{ulim}, \text{ylim}, \text{tfilter}, \text{dplant}, \text{dmodel}, \text{dstep});$

dif=(r_{\text{ref}}-y_e);
$r_{\text{ref}2}=r_{\text{ref}}+\text{dif};$

%stability
$Kmpc=\text{mpccon}(\text{model}, \text{ywt}, \text{uwt}, \text{M}, \text{P});$
$[\text{clmod}, \text{cmod}]=\text{mpccl}(\text{plant}_e, \text{model}, Kmpc);$
$maxpole=max(abs(smpcpole(cmod)));$

%subplot
$dy_e=\text{diff}(y_e)*60/\text{delt2};$
Appendix 2: Matlab constraint MPC with energy content reference

```matlab
clear all
PTE_tot=8;
delt2=1;

%adjustable constants
PTE_tot=8;
delt2=1;
tfinal=180;
tmpc_end=(PTE_tot)*15*60);
tau_e=10;
a_e=5;
r_e=(350/15*60);
P_min_e=120;
P_max_e=350;

%adjustable constants
PTE_tot=8;
delt2=1;
tfinal=180;
tmpc_end=(PTE_tot)*15*60);
tau_e=10;
a_e=5;
r_e=(350/15*60);
P_min_e=120;
P_max_e=350;

%transfer function;
[num_Pade_e,den_Pade_e]=pade(a_e,15);
G_e1=tf(num_Pade_e,den_Pade_e);
G_e2=tf(1,tau_e);
G_e3=tf(1,tau_e);
H_e=feedback(G_e2*G_e3,l);
tf_el = H_e*H_e*H_e;
tf_e=G_el*H_e*H_e*H_e;

[num_tf_e, den_tf_e]=tfdata(tf_el,'v');
% convert tf to step function plant
[num_e, den_e]=tfdata(tf_el, 'v');
plant_e=poly2tfd(num_e,den_e,delt1,a_e);
plant_e=tfd2step(tfinal, delt2, nout,plant_e);
end

%CMPC
clear all
model=plant_e;
ywt=1;
output and reference signal
```
uwt=1;
move in objective function, if uwt > ywt than no overshoot
tend=mpc_end-1;
ref=r_int;
trajectory
ulim=[];
ylim=[];
constraints
tfilter=[];
dplant=[];
dmodel=[];
dstep=[];

M=2;
P=25*M;
quadratic function

[y_e, u_e]=cmcp(plant_e, model, ywt, uwt, M, P, tend, ref, ulim, ylim, tfilter,dplant,
dmodel, dstep);
Appendix 3: Matlab constraint MPC optimization energy content reference

clear all

% adjustable constants
PTE_tot=8;
delt2=1;

% for time step r_ref

% step interval, 1 is most accurate, >1 less accurate.

% constants MPC and function

deltl=0;
nout=1;
tfinal=180;
tmpc_end=((PTE_tot)*15*60);
tau_e=10;
_a_e=5;
_r_e=5/60*delt2;
P_min_e=120;
P_max_e=350;

% transfer function;
[num_Pade_e,den_Pade_e]=pade(a_e,15);
G_e1=tf(num_Pade_e,den_Pade_e);
G_e2=tf(1,tau_e);
G_e3=tf(1,1);

H_e = feedback(G_e2*G_e3,1);
tf_el = H_e*H_e*H_e;
tf_e = G_e1*H_e*H_e*H_e;

% convert tf to step function plant
[num_e,den_e]=tfdata(tf_e1,'v');
plant_el=poly2tfd(num_e,den_e,delt1,a_e);
plant_e=tfd2step(tfinal, delt2, nout,plant_el);

% simulation time and input step

timestep = delt2;
time = (0:timestep:tmpc_end)';
for k=1:PTE_tot;
PTE(k)=k*(15*60);
end

% reference signal integration
r_int_MWh=zeros(size(r_ref'));

% for time r_ref

% step interval, 1 is most accurate, >1 less accurate.

for i=0:PTE_tot/delt2;
  if i==0;
    r_int_MWh=0;
  elseif i==1;
    r_int_MWh=r_ref(2);
  else
    r_int_MWh(i)=r_ref(i)+r_int_MWh(i-1);
  end
end
r_int=(r_int_MWh./3600)';

% CHPC model=plant_e;
ywt=1;
and reference signal

% Weight matrix for difference between output

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uwt=l; %weight matrix for manipulated variable move
in objective function, if uwt > ywt than no overshoot

tend=tmpc_end-l;
%final time for simulation
ref=r_int;
%constant or time varying reference trajectory
ylim=[];
%constraints on input
ulim=[1];
%min and max value of variable output
constraints
tfilter=[];
dplant=[];
dmodel=[];
dstep=[];

t=filter=[1];
dplant=[ ];
dmodel=[ ];
dstep=[1];
for M=1:5:101;
%control horizon
for P=1:10:101;
%number of steps in the time horizon for
quadratic function
[y_e, u_e]=cmpc(plant_e, model, ywt, uwt, M, P, tend, r, ulim, ylim,
tfilter, dplant, dmodel, dstep);
d1=(sum(r_ref(1:PTE(1),1)) - sum(y_e(1:PTE(1),1)))^2;
d2=(sum(r_ref(PTE(1)+1:PTE(2),1)) - sum(y_e(PTE(1)+1:PTE(2),1)))^2;
d3=(sum(r_ref(PTE(2)+1:PTE(3),1)) - sum(y_e(PTE(2)+1:PTE(3),1)))^2;
d4=(sum(r_ref(PTE(3)+1:PTE(4),1)) - sum(y_e(PTE(3)+1:PTE(4),1)))^2;
d5=(sum(r_ref(PTE(4)+1:PTE(5),1)) - sum(y_e(PTE(4)+1:PTE(5),1)))^2;
d6=(sum(r_ref(PTE(5)+1:PTE(6),1)) - sum(y_e(PTE(5)+1:PTE(6),1)))^2;
d7=(sum(r_ref(PTE(6)+1:PTE(7),1)) - sum(y_e(PTE(6)+1:PTE(7),1)))^2;
d8=(sum(r_ref(PTE(7)+1:PTE(8),1)) - sum(y_e(PTE(7)+1:PTE(8),1)))^2;
dif(P, M)=d1+d2+d3+d4+d5+d6+d7+d8;
end
end;
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