MINIMIZING REGULATION COSTS IN MULTI-AREA MARKETS

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Abstract - In a power system with many fast and/or large changes in the generation or the consumption, for example in a system with large amounts of wind power, the frequency control is more complicated to handle efficiently. Minimizing regulation costs for the system operator in such a system requires the possibility to simulate the frequency control, but the existing methods for calculations are neither efficient enough with respect to computation time nor accurate enough. This paper shows how the frequency control can be optimized, thereby reducing the regulation costs, using a multi-area model combined with a DC load flow. The multi-area modeling is described and the optimization is applied to a numerical example.

Keywords - frequency control, regulating market, optimization, multi-area models

1 INTRODUCTION

1.1 Frequency control

Frequency control is necessary to ensure both quality and security in a power system. To avoid frequency deviations the generated power and the consumption must be equal. The consumption varies all the time. When the consumption exceeds the generation, the frequency decreases, and vice versa. Different practices for frequency control are described in [1]. In the Nordic power system, for instance, the frequency control is handled in two steps: primary control and secondary control [2]. Primary control is purchased on long-term contracts, and when an imbalance occurs, the generation automatically starts to change within a few seconds. The extent by which each generator changes its generation during the primary control is defined by the speed droop characteristics, measured in MW/Hz. Subsequent, the frequency is stable, but not at the nominal value.

Secondary control, in the Nordic system, is handled by taking in regulating bids from the electricity market. Each bid includes a price and a volume, and must be possible to activate within ten minutes from acceptance. The bids are typically accepted according to the cost, but transmission limits must also be considered, which can have an impact on the desired location of the change in generation. When necessary, secondary control is handled by accepting a bid of regulating power. The change in the generation forces the primary control reserves to revert to their initial state and the frequency is then stable at the nominal level again.

In many other systems, for example in UCTE [3], the secondary control is instead handled automatically by Automatic Generation Control (AGC) [4]. With AGC the change in power production is divided among all generators available for secondary control instead of choosing one bid at a time. When the secondary control is handled automatically, the frequency control can include tertiary control working like the Nordic secondary control, allowing the system operator to reschedule the production in the system to achieve more economic operation.

1.2 Power system modeling

The Transmission System Operator (TSO) in a deregulated electricity market needs to be able to simulate the frequency control. The existing methods for simulation can in most cases be divided into three categories. The first category consists of static methods ignoring many of the physical properties of the power system, primarily focusing on the economic management. One such method, where transmission capacity limits are included, is described in [5]. Network flow optimization is used to minimize the cost for operating the system, but the network flow model does not compute the actual power transfer between areas. Thus, methods of this kind are not sufficient in applications where it is necessary to model the system more accurately.

The second category consists of dynamic methods including transient effects and detailed models of all the components in the power system. Dynamic simulations are necessary to model a power system and the variations in generation, consumption and frequency accurately, but this modeling requires a large amount of input, and solving a large system of differential equations for each time step of the simulation is very time consuming. Therefore, dynamic simulations are mainly used to study stability properties in the range of seconds rather than for long-term simulations, since this gives algorithms too complex to compute. In [6] a very detailed simulation method is described, but it is too time consuming to use for long frequency control simulations. It is also impossible to use too detailed models when dimensioning faults are calculated, since this demands several repeated simulations, which will be even more time consuming.

The third possibility is to use load flow analysis, more accurate than the economic models and more efficient than the dynamic. Another advantage with a load flow is that from a given generation and consumption in a meshed system, it is easy to determine the transmission in each line. In addition, the losses of each line can be calculated, which can be of interest when discussing secondary control. However, the calculations are still very time consuming for large systems or if many possible scenarios are to be considered. Other problems are that a load flow does not consider transmission limits, derived from stability margins of dimensioning faults, and reserve capacity for dimensioning faults.

1.3 Multi-area modeling

One way to simplify the calculations, without excluding the most important physics of the system, is to introduce a multi-area model, so that all nodes in the system are aggregated into fewer areas. Several methods to aggregate nodes are described in [7] and, although they are all detailed enough to be used with dynamic simulations, they will not be used here, since they include more information than is of interest for this paper. A multi-area frequency control simulation was done for the Norwegian power system in [8], using a simulation software to run load flows, but without describing how the aggregation can be realized for a general system. Hence, there is still a need for an efficient method that can be used to minimize the costs of frequency control in a multi-area market when many possible situations are to be simulated.

This paper outlines such a method. Optimizing the frequency control means minimizing the regulation costs, without exceeding frequency limits or transmission capacity. The optimal solution is achieved by making the best possible decisions on bid acceptance: when to accept a bid, which bid and which volume. Both price and location can affect the decision. The optimization will be applied to a numerical example to show how these problems can be solved.

1.4 Organization of the paper

In section 2 the mathematical notation is defined and in section 3 the node aggregation model is described, followed by a small illustrative example. In section 4 the optimization problem is formulated and in section 5 it is applied to a larger example.

2 NOTATION

2.1 Sets

$\mathcal{I} = \{1 \dots i, j \dots I\}$	areas
$\mathcal{N} = \{1 \dots m, n \dots N\}$	nodes
$\mathcal{N}_i$	nodes located in area i
$\mathcal{L} = \{1 \dots \ell \dots L\}$	area lines (i, j), $i < j$
$\mathcal{L}^*$	area lines (i, j), $i > j$
$\mathcal{K} = \{1 \dots k \dots K\}$	node lines (m, n), $m < n$
$\mathcal{T} = \{1 \dots t \dots T\}$	time steps
$\mathcal{H} = \{1 \dots h \dots H\}$	hours
$\mathcal{T}_h$	time steps in hour h
$\mathcal{B} = \{1 \dots b \dots B\}$	bids
$\mathcal{B}_h$	bids available in hour h
$\mathcal{B}_f$	bids activated in 5 minutes
$\mathcal{B}_s$	bids activated in 10 minutes
$\mathcal{B}_u$	up-regulation bids
$\mathcal{B}_d$	down-regulation bids
$\mathcal{B}_n$	bids located in node n

2.2 Parameters

D_{nt}	load change in node n at time t
P_{nt}^{plan}	scheduled change in production in node n at time t
$F_{\ell 0}$	total transmission in line ℓ at time $t = 0$
V_b	available volume of bid b
c_b	regulation price for bid b
t_b^{act}	activation time for bid b [no of time steps]
δ_n	droop in node n
$u_\ell^{\min}$	min transmission limit between area i and j
$u_\ell^{\max}$	max transmission limit between area i and j
T_h^{final}	the last time step in hour h

2.3 Constants

f_0	nominal frequency
f_{dev}	maximal deviation from nominal frequency
$d_{\max}$	maximal time deviation
t_{step}	length of each time step [seconds]
t_{new}	time step when a new hour begins and all activated bids are de-activated

2.4 Variables

P_{nt}	sum of activated bids minus change in load in node n at time t, i.e. the net generation in node n at time t except changes of primary reserves
G_{nt}	change in activated primary reserve in node n at time t
f_t	frequency at time t
$F_{\ell t}$	change in transmission in line ℓ at time t
$F_{\ell t}^{\text{tot}}$	total transmission in line ℓ at time t
y_{bt}	accepted volume of bid b at time t
d_t	time deviation at time t
z	total cost

3 NODE AGGREGATION

The first step is to develop a general method for multi-area modeling. Node aggregation is used to reduce the numbers of constraints in the optimization problem, the calculation time and the amount of necessary input. For example, transmission limits are usually set between areas and not for all lines between the nodes. On the other hand, too much information can be lost if all calculations are made on an area basis. An important aspect when transferring the node system to the area system is to ensure that the transmission between areas is as close as possible to the transmission from a load flow of the node system. Here a DC load flow [4] is used to simplify the calculations. To include variations in generation in different nodes in the same area, and to show how this affects the transmission in the system, the production and the consumption are modeled per node, and data for all node lines are used when the constraints are determined.

3.1 Mathematical formulation

Assume a system with N nodes that will be divided into I areas. The areas are connected with L fictive lines. To include the internal reactances of each area the matrix

$\mathbb{M}$ is determined, defined by

$$F^{\text{area}} = \mathbb{M}\, P \tag{1}$$

where F^{area} is a matrix of dimension $L \times 1$ containing the L flows F_{ij} between area i and j. Each ℓ corresponds to a pair (i, j). P is a matrix of dimension $N \times 1$ containing the net generation P_n of each node n. The matrix $\mathbb{M}$ of dimension $L \times N$ must then be identified. This is possible using a DC load flow if all reactances in the node system are known, and it is also known how the nodes are grouped into areas.

The net generation P_m in node m equals the sum of all flows F^{node}_{mn} to and from the node, as

$$P_m = \sum_n F^{\text{node}}_{mn} \tag{2}$$

and the flows F^{node}_{mn} are determined from

$$F^{\text{node}}_{mn} = \frac{(\theta_m - \theta_n)}{x_{mn}} \tag{3}$$

where θ_n are the phase angle in node n and x_{mn} the reactance between nodes m and n.

With Equations (2) and (3) expressed as

$$P = \mathbb{C}\, F^{\text{node}} \tag{4}$$

and

$$F^{\text{node}} = \mathbb{A}\, \theta \tag{5}$$

the matrix $\mathbb{B}$ can be defined as

$$B = \mathbb{C}\mathbb{A} \tag{6}$$

Defining node s as the slack node means that θ_s equals 0 and the other elements of θ can be determined from

$$\theta' = \mathbb{B}'^{-1}\, P' \tag{7}$$

with $'$ meaning that the sth row, and for $\mathbb{B}$ the sth column, are excluded. Using Equation (7) in Equation (5) then determines the transmission F.

The transfer matrix $\mathbb{R}$, of dimension $L \times K$ with elements r_{lk}, between the node system and the area system is defined as

$$F^{\text{area}} = \mathbb{R} F^{\text{node}} \tag{8}$$

or

$$F^{\text{area}}_{\ell} = \sum_k r_{\ell k} F^{\text{node}}_k \tag{9}$$

with

$$r_{\ell k} = \begin{cases} 1 & \text{if } F^{\text{node}}_k \text{ increases } F^{\text{area}}_{\ell} \\ -1 & \text{if } F^{\text{node}}_k \text{ decreases } F^{\text{area}}_{\ell} \\ 0 & \text{otherwise} \end{cases} \tag{10}$$

Altogether, Equations (2) to (9) give that the matrix $\mathbb{M}$ is

$$\mathbb{M} = \mathbb{R}\, \mathbb{A}\, \mathbb{B}^* \tag{11}$$

where the matrix $\mathbb{B}^*_{N\times N}$ consists of the elements of $\mathbb{B}'^{-1}_{N-1\times N-1}$ combined with zeros in the sth row and sth column. Thereafter Equation (1) can be used to determine the area flows F_{ij} in the system when the net generation P_n in each node is known.

Using the matrix $\mathbb{M}$ in the optimization problem formulation ensures that the transmission between the areas will be comparable with the results of a load flow.

3.2 Small example

The system in Figure 1 consists of four nodes, n = 1, 2, 3, 4, divided into three areas, i = I, II, III. The node system consists of five lines, mn = 12, 13, 14, 23, 34, and the area system consists of three lines, ij = I-II, I-III, II-III.

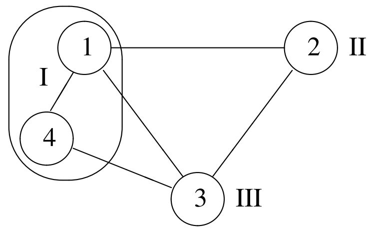

Figure 1: A system with 4 nodes divided into 3 areas.

From Equation (2), the net generation of each node is

$$\begin{aligned} P_1 &= F_{12} + F_{13} + F_{14} \\ P_2 &= -F_{12} + F_{23} \\ P_3 &= -F_{13} - F_{23} + F_{34} \\ P_4 &= -F_{14} - F_{34} \end{aligned} \tag{12}$$

which gives the matrix $\mathbb{C}$ in Equation (4) as

$$\mathbb{C} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ -1 & 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & -1 & 1 \\ 0 & 0 & -1 & 0 & -1 \end{bmatrix} \tag{13}$$

The area flows and the node flows are connected as

$$\begin{aligned} F_{\text{I-II}} &= F_{12} \\ F_{\text{I-III}} &= F_{13} - F_{34} \\ F_{\text{II-III}} &= F_{23} \end{aligned} \tag{14}$$

which gives the matrix $\mathbb{R}$ in Equation (8) as

$$\mathbb{R} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{15}$$

With all x_{mn} equal and node 4 as slack node, this gives the matrix $\mathbb{M}$ as

$$\mathbb{M} = \begin{bmatrix} 0.125 & -0.5 & -0.125 & 0 \\ -0.125 & -0.5 & -0.875 & 0 \\ 0.125 & 0.5 & -0.125 & 0 \end{bmatrix} \tag{16}$$

which can be used to calculate the area flows when the net generation of all nodes is known as in Equation (1).

4 OPTIMIZATION PROBLEM FORMULATION

A challenging problem for the TSO is how to manage the frequency control at the end of an hour, for example in the morning, when the load is increasing and the new scheduled generation will start at the change of hour. This will probably cause up-regulation at the end of the hour, with the standard approach to accept the bids in price order, but it can also be necessary to use down-regulation in some areas to avoid exceeding the transmission limits. It is also a challenge to determine when and at which volume it is optimal to activate the regulating power to minimize the cost. A bid can only be accepted once, and is then active until end of hour. All activated bids are de-activated at the change of hour, and a new bid list is available for the new hour.

The optimization problem is formulated to capture these conditions, and the calculation will be done for two hours starting at 0X:00 and ending at 0Z:00. A list of bids is available for up-regulation or down-regulation for each hour. At $t = t_{\text{new}}$ the time is 0Y:00 and all activated bids are de-activated. This can be formulated as a Linear Programming problem (LP-problem).

The constraints will keep the frequency within its limits, keep the transmission lower than the capacity of the area lines, control the primary (and secondary) reserves and distribute the flows in the system with a DC load flow. In this model the price of primary control has been assumed to be constant, by forcing the time deviation to be zero after a certain period. This means that the primary control has been used as much for up-regulation as for down-regulation.

4.1 Objective

The main objective of the optimization is to minimize the cost of all bids for the TSO. The objective function is then

$$\min z = \frac{H}{T} \sum_{\substack{b \in \mathcal{B}_h \\ t \in \mathcal{T}, h \in \mathcal{H}}} y_{bt}\, c_b\, (T_h^{\text{final}} - t - t_b^{\text{act}}) \tag{17}$$

4.2 Constraints on generation

As definition, the change in net generation P_{nt} in node n at time t is the sum of accepted bids plus scheduled change in generation minus load change. A bid y_{bt} is assumed to be accepted at time t but the activation time of the power gives that the power is available at $t + t_b^{\text{act}}$. The net generation is then

$$P_{nt} = \sum_{b \in \mathcal{B}_n \cup \mathcal{B}_h} y_{b\, t - t_b^{\text{act}}} + P_{nt}^{\text{plan}} - D_{nt} \qquad \forall\, n \in \mathcal{N}, t \in \mathcal{T}_h : t \neq t_{\text{new}} \tag{18}$$

A special case occurs at the change of hour when all activated bids are de-activated:

$$\begin{aligned} P_{nt} = &\sum_{b \in \mathcal{B}_n \cup \mathcal{B}_{h=2}} y_{b\, t - t_b^{\text{act}}} + P_{nt}^{\text{plan}} - D_{nt} \\ &- \sum_{\substack{b \in \mathcal{B}_n \cup \mathcal{B}_{h=1} \\ s \in \mathcal{T} : s < t}} y_{bs} \quad \forall\, n \in \mathcal{N}, t = t_{\text{new}} \end{aligned} \tag{19}$$

The change in generation to or from the primary reserve G_{nt} in node n at time t changes in proportion to the droop δ_n in node n as

$$G_{nt} = \delta_n \frac{\sum_{m \in \mathcal{N}} G_{mt}}{\sum_{m \in \mathcal{N}} \delta_m} \qquad \forall\, n \in \mathcal{N}, t \in \mathcal{T} \tag{20}$$

4.3 Constraints on flow

The flow in one direction is defined as being equal to the negative flow in the other direction:

$$F_{ijt} = -F_{jit} \quad \forall\, (i,j) \in \mathcal{L}, t \in \mathcal{T} \tag{21}$$

To ensure that energy does not disappear in the system, the sum of the changes in generation in node n and the change in transmission to and from node n at time t must be equal to zero:

$$\sum_{j \in \mathcal{L} \cup \mathcal{L}^*} F_{ijt} = \sum_{n \in \mathcal{N}_i} (P_{nt} + G_{nt}) \quad \forall\, i \in \mathcal{I}, t \in \mathcal{T} \tag{22}$$

To obtain flows corresponding to a DC load flow, the elements $\mu_{\ell n}$ of the matrix $\mathbb{M}$ is used. The change in the flow in line ℓ at time t is given by

$$F_{\ell t} = \sum_{n \in \mathcal{N}} \mu_{\ell n} (P_{nt} + G_{nt}) \quad \forall\, \ell \in \mathcal{L}, t \in \mathcal{T} \tag{23}$$

and the total flow in line ℓ at time t is given by

$$F_{\ell t}^{\text{tot}} = F_{\ell 0} + \sum_{s \in \mathcal{T} : s \leq t} F_{\ell s} \tag{24}$$

The transmission between the areas must not exceed the capacity of the lines. Thus,

$$u_\ell^{\min} \leq F_{\ell t}^{\text{tot}} \leq u_\ell^{\max} \qquad \forall\, \ell \in \mathcal{L}, t \in \mathcal{T} \tag{25}$$

4.4 Constraints on frequency

The frequency at time t differs from the previous frequency at time $t-1$ with the total change in net production at time t divided by the total droop of the system:

$$f_t = f_{t-1} + \frac{\sum_{n \in \mathcal{N}} P_{nt}}{\sum_{n \in \mathcal{N}} \delta_n} \quad \forall\, t \in \mathcal{T} \tag{26}$$

The frequency must stay within its limits:

$$f_0 - f_{\text{dev}} \leq f_t \leq f_0 + f_{\text{dev}} \qquad \forall\, t \in \mathcal{T} \tag{27}$$

The time deviation is the time difference between a clock driven by the nominal frequency and a clock driven by the actual frequency. It is defined by an integral and is here calculated as

$$d_t = \frac{t_{\text{step}}}{f_0} \sum_{s \in \mathcal{T}: s \leq t} (f_s - f_0) \tag{28}$$

The time deviation must stay within its limits:

$$-d_{\max} \leq d_t \leq d_{\max} \qquad \forall\, t \in \mathcal{T} \tag{29}$$

Here the time deviation is assumed to be zero after each hour:

$$d_t = 0 \qquad \text{for } t = T_h^{\text{final}} \tag{30}$$

4.5 Constraints on limitations on bids

As convention, only positive volumes y_{bt} of a bid b can be accepted for up-regulation and only negative volumes can be accepted for down-regulation, which gives

$$y_{bt} \geq 0 \qquad \forall\, b \in \mathcal{B}_u, t \in \mathcal{T} \tag{31}$$

$$y_{bt} \leq 0 \qquad \forall\, b \in \mathcal{B}_d, t \in \mathcal{T} \tag{32}$$

The accepted values y_{bt} must not exceed the available volume of each bid b:

$$\sum_{t \in \mathcal{T}} y_{bt} \leq V_b \qquad \forall\, b \in \mathcal{B}_u \tag{33}$$

$$\sum_{t \in \mathcal{T}} y_{bt} \geq -V_b \qquad \forall\, b \in \mathcal{B}_d \tag{34}$$

A bid can only be accepted the hour it is available. Bids not available are equal to zero:

$$y_{bt} = 0 \qquad \forall\, b \in \mathcal{B}_h, t \notin \mathcal{T}_h, h \in \mathcal{H} \tag{35}$$

A bid cannot be accepted closer to the end of an hour than the activation time since it is impossible to activate the bid within the hour.

$$y_{bt} = 0 \qquad \forall b \in \mathcal{B}, t \in \mathcal{T} : t \geq T_h^{\text{final}} - t_b^{\text{act}}, h \in \mathcal{H} \tag{36}$$

These equations have been implemented in GAMS [9] and can be solved using an LP-solver.

5 CASE STUDY

The optimization problem has been applied to the Nordic system, described by 41 nodes divided into 9 areas connected with 11 lines, as shown in Figure 2. Area 1, 2 and 3 represent Sweden, area 4 and 5 represent Norway, area 6 represents Finland, area 7 and 8 represent Denmark and area 9 represents the northern part of Germany. The capacities of the area lines [10] are also shown in Figure 2.

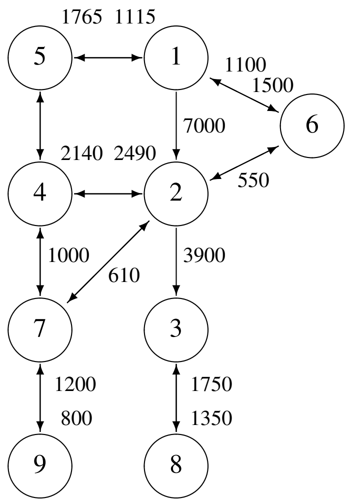

Figure 2: Areas and capacities.

The calculation is made for two hours with 24 time steps indexed t = 1, ..., 24, starting at 0X:00 and ending at 0Z:00. At t = 12 the time is 0Y:00. There are 20 bids available for up-regulation, and 20 bids available for down-regulation, half of them available in hour 1 and the rest in hour 2. The bid list used is shown in Table 1. At t = 12 all activated bids are de-activated. The load increases equally in every time step and at t = 12 and t = 24 is a scheduled production increase, see Figure 3. The droop is assumed to be constant. Necessary data are found in [11].

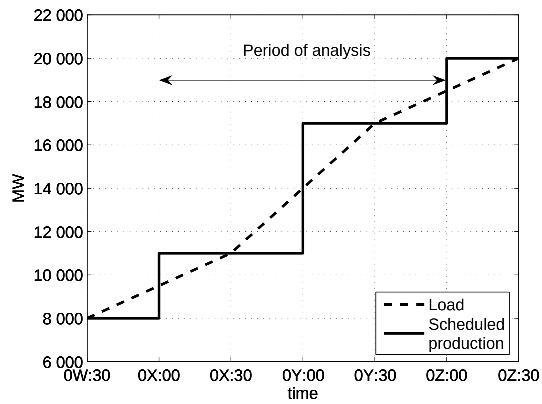

Figure 3: Load and scheduled production.

To keep the frequency and the time deviation within their limits, in the Nordic system ± 0.1 Hz and ± 30 seconds respectively, the optimization is expected to cause up-regulation to balance the load for the time steps before the change of hour and down-regulation after the change of hour. If the capacity limit of an area connection is reached, it will force additional regulation and the bids may not be accepted according to price, if another bid can better avoid overload.

By modifying constraints, different strategies for frequency control can be compared. For example, the case described above has been optimized with the constraints in Equations (18) to (36) (Case 1), but also with Equation (30) modified so the time deviation should be zero after two hours instead of after each hour (Case 2).

Bids in hour 1				Bids in hour 2			
bid	area	price	vol	bid	area	price	vol
b1u1	4	180	200	b2u1	4	190	200
b1u2	4	185	200	b2u2	4	195	200
b1u3	1	190	250	b2u3	1	200	250
b1u4	5	195	100	b2u4	5	205	100
b1u5	1	200	200	b2u5	1	210	200
b1u6	4	215	100	b2u6	4	225	100
b1u7	2	220	350	b2u7	2	230	350
b1u8	6	230	100	b2u8	6	240	100
b1u9	2	250	200	b2u9	2	260	200
b1u10	3	300	500	b2u10	3	310	500
b1d1	4	160	-200	b2d1	4	170	-200
b1d2	4	155	-200	b2d2	4	165	-200
b1d3	1	150	-250	b2d3	1	160	-250
b1d4	5	145	-100	b2d4	5	155	-100
b1d5	1	140	-200	b2d5	1	150	-200
b1d6	4	135	-100	b2d6	4	145	-100
b1d7	2	130	-350	b2d7	2	140	-350
b1d8	6	125	-100	b2d8	6	135	-100
b1d9	2	120	-200	b2d9	2	130	-200
b1d10	3	100	-500	b2d10	3	110	-500

Table 1: Bid list.

6 RESULTS AND DISCUSSION

The optimization problem is solved in 0.1 seconds. The flow between area 2 and area 3 is equal to the capacity at almost every time step in the second hour. To avoid exceeding the capacity, an expensive up-regulation bid located in area 3 is accepted at t = 10-21, and two other expensive bids are accepted at t = 22. All the other accepted bids are used to keep the frequency and time deviation within their limits. Accepted bids in Case 1 are shown in Table 2 and the resulting frequency in Case 1 is shown in Figure 4.

Accepted bids and volumes at time t									
t =	1	2	3	...	9	10	11	12	13
b1u1	25		175						
b1u2					100				
b2u1							200		
b2u2							61		
b2u10						105	36	9	9
b2d1						-200			
b2d2						-200			
b2d3						-250			
b2d4						-100			
b2d5							-155		
t =	14	15	16	17	18	19	20	21	22
b2u8								100	
b2u9								185	
b2u10	9	9	9	5	5	5	5	294	
b2d5									-45
b2d6									-43
b2d7									-350

Table 2: Accepted bids and volumes in Case 1.

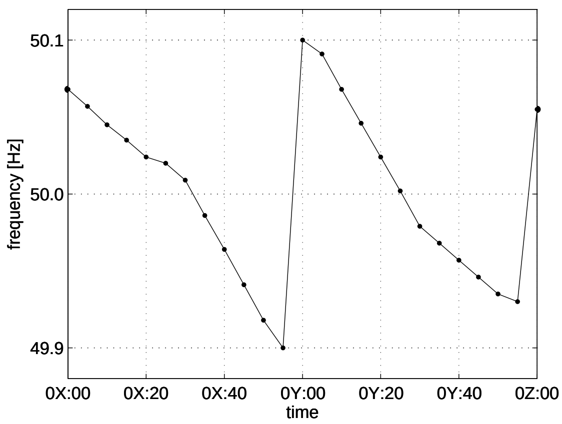

Figure 4: Frequency in Case 1.

In Case 2, with the modification of Equation (30), the result is, as expected, a cheaper solution for the TSO than in Case 1, when smaller volumes have been activated. Some of the up-regulation has also been moved to the first hour where the bids are cheaper, when the constraint at t = 12 has disappeared. The resulting frequency in Case 2 is shown in Figure 5 and the accepted bids in Case 2 are shown in Table 3.

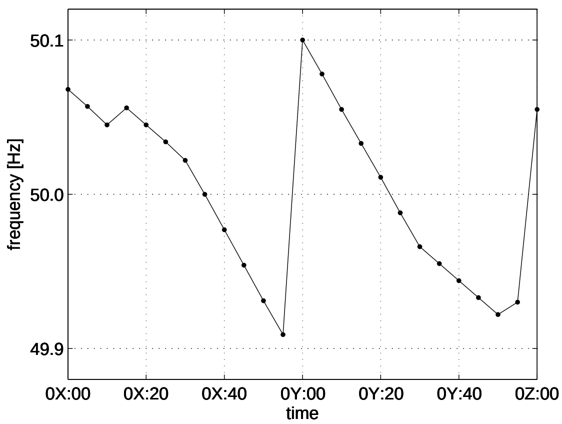

Figure 5: Frequency in Case 2.

Accepted bids and volumes at time t													
t =	1 ...	10	11	12	13	14	15	16	17	18	19	20	21	22
b1u1	200													
b1u2	200													
b1u3	92													
b2u4													98	
b2u8													100	
b2u9													200	
b2u10		105	9	9	9	9	9	9	5	5	5	5	320	
b2d1		-200												
b2d2		-200												
b2d3		-250												
b2d4		-100												
b2d5			-155											-45
b2d7														-245

Table 3: Accepted bids and volumes in Case 2.

It is a simplification that any volume of a bid can be accepted. In reality, bids are accepted of fix amounts, for example 25 or 50 MW. It is also a simplification that all changes of generation and loads are modeled as step changes. It would be more realistic to increase the number of time steps and ramp up or down all changes. These conditions can be handled by modifying the constraints.

As a consequence of using a DC load flow losses are neglected. This approximation is not a problem here since losses are ignored when determining the order of bid acceptance in the Nordic system, but it may be necessary to handle in a different way when other systems are considered.

The model has not been applied to a more meshed system, but there is no implications that this should be a problem.

7 CONCLUSIONS

This paper shows how the frequency control can be optimized using a multi-area model. The optimization is applied to a numerical example to show how these problems can be solved, and also to show how different strategies for frequency control can be compared by modifying constraints.

In this paper all data are considered deterministic, but since the method is easy to implement and fast to use it can be extended to include stochastic optimization, which is of interest to examine a situation with uncertainties. Examples of interesting situations are varying wind power production, varying load, outages and unknown bid list for the next hour.

8 ACKNOWLEDGEMENT

The contribution of knowledge from Christer Bäck at Svenska Kraftnät and the financial support from the Swedish Energy Agency (STEM) and the EU-WILMAR-project (Wind power Integration in a Liberalized electricity MARket) are highly appreciated.

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