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Coordinating Commercial and Technical Decision-Making within a Restructured Electricity Industry

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***Abstract*— This paper explores the implications of a decision-making framework that adopts energy as the commodity on which commercial transactions are based and which solves the commercial and technical operation of the industry as separate processes that are formally linked through a bidirectional interface. Under these assumptions technical decision-makers gain some flexibility in terms of implementing the commercial transactions which in turn assists in overcoming different types of disturbances. The technical operation of the power system is accomplished through the use of model predictive control which has the benefit of continuously transitioning the system toward a future state that is consistent with both the agreed commercial solution as well as taking into account known technical issues that arise on short time-horizons. The method is illustrated for several examples.**

I. Introduction

An important issue that must be addressed in the electricity industry restructuring process is the design and implementation of frameworks that constrain, inform and coordinate commercial and technical decision-makers over a range of time-horizons [1], [2], [3]. This is generally achieved through the use of optimization models that represent the underlying energy conversion process Fundamental to such models is the specification of the commodity on which commercial transactions are based and the degree of coupling between commercial and technical decision-making processes.

This paper explores the implications of a decision-making framework that adopts energy as the commodity on which commercial transactions are based and which solves the commercial and technical operation of the industry as separate processes that are formally linked through a bidirectional interface. The approach suggested in the paper is novel in that in provides a way of formally coordinating technical and commercial decisions in a restructured electricity industry. The technical operation is informed by a slower-acting commercial process and is accomplished using a model predictive control (MPC) strategy similar to that explored in [5] and [6].

II. General Framework

The framework adopted in this paper is to solve a simple electricity spot market model (commercial process) and assign the management of security/technical issues to a centralized intermediate process which is adjusts generator set-points and invokes security constraints as the need arises. This is illustrated in a conceptual manner in Fig. 1 which shows the key processes and interactions between them, as follows:

- a *commercial decision-making process* which has the objective of pricing the commodity of energy;
- an *intermediate technical decision-making process* implements the electricity spot market solution subject to technical information that more closely resembles the present very short-term physical state of the power system; and
- the *physical energy conversion chain* which encompasses the physical industry including fast-acting control loops, protection schemes and other very short-term phenomena. The industry is subject to a range of exogenous parametric and structural disturbances.

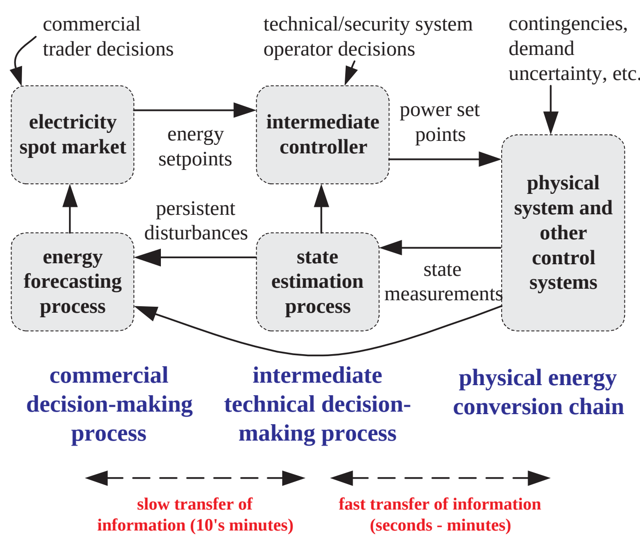

Fig. 1. conceptual diagram of processes and information flows

III. Scheme Definitions and Implementation

The electricity spot market is solved separately to the MPC-based intermediate process however the two processes interact. The overall scheme is depicted in Fig. 2 and Fig. 3 which show the processes, their periodicities and the flow of information. This following describes the processes in detail.

A. Commercial decision-making process

The electricity spot market process is shown in Fig. 2 with the key information flows between the intermediate process and time period definitions.

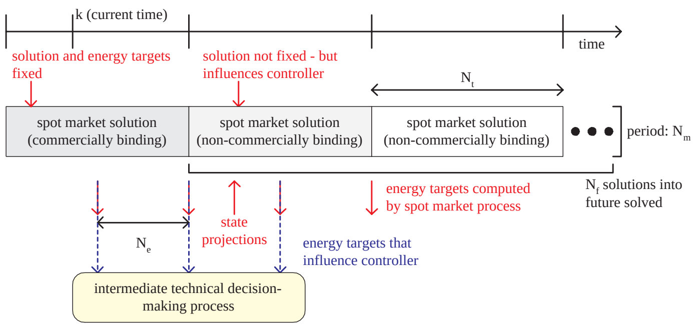

Fig. 2. time period definitions and key information flows for the electricity spot market

Define the following symbols:

- T_s is the fundamental sampling period used by the intermeddiate process controller and for convenience we assume that time is an integer multiple of T_s, that is, $t = kT_s$ where $k \in \mathbb{Z}$.
- $N_t > 1$ is the spot trading period;
- $N_f \in \mathbb{Z}^+$ is the number of electricity spot market trading intervals solved into the future;
- N_m is the periodicity with which the N_f spot market solutions are computed; and
- $1 < N_e \leq N_t$ is the periodicity with which energy targets from the spot market solutions over the MPC horizon are computed and fed forward to the controller for tracking purposes (irrespective of whether the spot market solutions is commercially binding or not).

The electricity spot market solution is computed for N_f periods into the futureon a period of N_m starting with the spot market trading period commencing immediately after the last commercially binding spot market solution. The spot market solutions that overlap with the intermediate process controller horizon, are used to compute shorter-term energy targets (periodicity N_e) for tracking purposes.

The commercial model is implemented as a simple linear program which is computed whenever $\text{mod}(k, N_m) = 0$ Define $\mathcal{G} = \{1, \ldots, N_g\}$ as the set of generators and $m \in \mathcal{M}$ as the set of N_f spot trading periods over which solutions are to be computed (refer to equation (14) in the appendix).

$$\textbf{minimize:} \quad \sum_{g \in \mathcal{G}} ET_g(m) OP_g(m) \tag{1}$$

$$\textbf{subject to:} \quad 0 \leq ET_g(m) \leq \overline{ET}_g(m)$$
$$\sum_{g \in \mathcal{G}} ET_g(m) = EF(m) \tag{2}$$

where $ET_g(m)$ is the quantity of energy offered (MWh) by generator g, $OP_g(m)$ is the offer price at which the energy offered (\$/MWh), $\overline{ET}_g(m)$ is the maximum amount of energy that a participant offers and $EF(m)$ is the centralized energy forecast (MWh).

B. Computation of energy targets

The spot energy targets, $ET_g(m)$ are used to compute shorter-term targets over the MPC horizon at times $n \in \mathcal{N}$. The set $\mathcal{N}$ is the set of time periods that are allowed to influence the tracking-behavior of the controller (refer to equation (15) in the appendix). Define the following:

$$\Phi_n \triangleq N_t + (n-1) - \text{mod}(n-1, N_t) \tag{3}$$
$$\Gamma_n \triangleq n - N_t - \text{mod}(n, N_t) \tag{4}$$

where $\Phi_n : \mathcal{N} \rightarrow \mathcal{M}$ maps n to the relevant spot trading interval m that should be used for computation of the shorter-term targets and $\Gamma_n : \mathcal{N} \rightarrow \mathcal{M}$ corresponds to the time at which the spot trading period immediately preceding spot interval Φ_n commences.

The energy targets for each generator that are provided to the intermediate process are:

$$E_g(n) = \begin{cases} \alpha(n) ET_g(\Phi_n) + \Delta E_g(\Gamma_n) & , \ n = \min(\mathcal{N}) \\ E_g(n - N_e) + \frac{N_e}{N_t} ET_g(\Phi_n) & , \ \text{otherwise} \end{cases} \tag{5}$$

where $\Delta E_g(\Gamma_n)$ is the difference between the metered energy of generator g and that expected to be delivered in the spot market at time Γ_n and $\alpha(n)$ is:

$$\alpha(n) = \frac{N_e - \text{mod}(n - N_e, N_t)}{N_t} \tag{6}$$

which describes the fraction of energy apportioned across each short-term target from the corresponding spot trading period.

C. Intermediate technical decision-making process

Fig. 3 shows the intermediate process to illustrate the main information flows and time period definitions. The scheme operates under the MPC framework of [4]. Define the following symbols:

- N_r is the periodicity with which the intermediate process controller's MPC optimization solution is computed;
- $N_h \geq 1$ is the finite horizon of the intermediate process controller's MPC algorithm;
- N_c is the number of periods commencing from k (current time) into the future for which the corresponding electricity spot market solutions are declared to be commercially binding and hence remain fixed - the purpose is to assist the controller in achieving a level of stability; and
- $N_u \geq 1$ is the number of controls computed by the MPC algorithm that are issued to the generators.

Usually the following will hold: $N_e \geq N_r$, $N_r \geq 1$ and $N_h \geq N_c$, although this is not necessary.

The intermediate process controller is a repeated optimization problem that is primarily concerned with tracking the energy targets, $E_g(n)$ for $n \in \mathcal{N}$ while also resolving structural and/or parametric uncertainties. The optimization formulation computes N_h discrete-time controls over the horizon $k \in \mathcal{K} = \{k_0, \ldots, k_0 + N_h\}$ whenever $\text{mod}(k, N_r) = 0$ and is

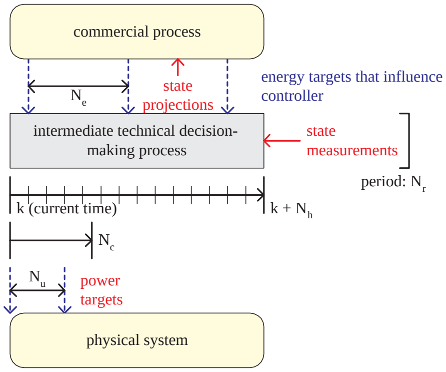

Fig. 3. time period definitions and key information flows for the intermediate technical decision-making process

formulated as follow:

$$\begin{aligned}\textbf{minimize:}\quad & W_t \sum_{g\in\mathcal{G}} \sum_{n\in\mathcal{N}} \left(e_g(n) - E_g(n)\right)^2 \\ & + W_r \sum_{g\in\mathcal{G}} \sum_{k\in\mathcal{K}} r_g(k)^2\end{aligned} \tag{7}$$

$$\begin{aligned}\textbf{subject to:}\quad & \mathbf{x}(k+1) = A\mathbf{x}(k) + B\mathbf{r}(k) \\ & \mathbf{x}(k_0) = \mathbf{x}_0 \\ & \sum_{g\in\mathcal{G}} p_g(k) = d(k) \\ & |r_g(k)| \le \overline{r}_g \\ & 0 \le p_g(k) \le \overline{p}_g\end{aligned} \tag{8}$$

where W_t and W_r are weigthing coefficients, for generator g we define $e_g(k)$ to be its energy production (MWs), $p_g(k)$ to be its power output level (MW), $r_g(k)$ to be the ramping control signal (MW/s), $\overline{r}_g$ to be its maximum ramp rate (MW/s) and $\overline{p}_g(k)$ to be the maximum output power level (MW), the vector $\mathbf{x}(k)$ comprises the system states:

$$\mathbf{x}(k) = \left[p_1(k), \ldots, p_{N_g}(k), e_1(k), \ldots, e_{N_g}(k)\right]^T \tag{9}$$

and $\mathbf{r}(K)$ is the control vector, given by:

$$\mathbf{r}(k) = \left[r_1(k), \ldots, r_{N_g}(k)\right]^T \tag{10}$$

finally A and B are matrices determined through the discretization of a continuous linear time invariant state-space system (with sampling period T_s). The particular model considered in this paper is given by $\dot{\mathbf{x}}(t) = A_c\mathbf{x}(t) + B_c\mathbf{r}(t)$, where

$$A_c = \begin{pmatrix} 0 & 0 \\ I & 0 \end{pmatrix}, \quad B_c = \begin{pmatrix} I \\ 0 \end{pmatrix} \tag{11}$$

The set of constraints in (8) only encompass the basic operation of the intermediate process controller; in general, the set of constraints would include security limits and the effect of the transmission system.

IV. Examples

A. Parameters

All of the examples[1] will adopt the following values of parameters: $T_s = 60s$, $N_h = 90$, $N_t = 30$, $N_r = 5$, $N_e = 5$ and $N_u = 5$. These correspond to a 30-minute electricity spot market, with a 5-minute intermediate process controller which implements control actions over a finite-horizon of 90 minutes. The weighting factors for the intermediate process controller are $W_r = 10^6$ and $W_t = 1$. Table I contains the parameters of generators used in the simplistic system for the examples (p_g^0 denotes the initial output of generator g).

[1]The examples were implemented using SCILAB [7].

TABLE I
Generator data

Generator	Technology	$\overline{p}_g$ (MW)	$\overline{r}_g$ (MW/min)	p_g^0 (MW)
1	Baseload	220	1.2	60
2	Baseload	120	3.0	30
3	Intermediate	100	4.8	10
4	Peaking	50	6.0	0

B. Case A: basic operation

To illustrate the general operation of the scheme, we consider a fictitious situation where the demand is fixed at 100MW and generators compete for the provision of energy services to satisfy demand. We assume that the commercial energy-based spot market of equations (1) and (2) results in the quantities shown in table II. The power targets computed by the intermediate process controller for each generator are shown in Fig. 4, The power targets also anticipate future spot market solutions and so the system is continuously being pushed toward the state anticipated by both the commercial process subject to the technical limits that are not explicitly modelled in the commercial process. Fig. 5 shows that the accumulated energy delivered by each generator is consistent with the energy schedule of table II and Fig. 6 shows for a single generator how the energy deviations vary between the commercial and technical models over the simulation and that in in general they tend toward zero.

TABLE II
Case A Commercial Energy Schedule

Time (hr)	Gen 1 (MWh)	Gen 2 (MWh)	Gen 3 (MWh)	Gen 4 (MWh)
0.50	25.00	15.00	10.00	0.00
1.00	27.50	17.50	5.00	0.00
1.50	25.00	17.50	7.50	0.00
2.00	22.50	20.00	7.50	0.00
2.50	20.00	20.00	10.00	0.00
3.00	17.50	20.00	12.50	0.00

C. Case B: energy demand forecast error

This example considers the implications of the commercial model's energy demand energy forecast being different to that used in the technical model. The demand profile used in the intermediate process is as shown in Fig. 7 while the commercial energy schedule in the absence of a forecast error is provided in table IV. The simulation is run for forecast errors of $\pm 10\%$ and $\pm 20\%$ being introduced into the commercial process. Fig. 8 demonstrates how the plant targets change in order to satisfy the demand profile of the intermediate process, Fig. 9 shows

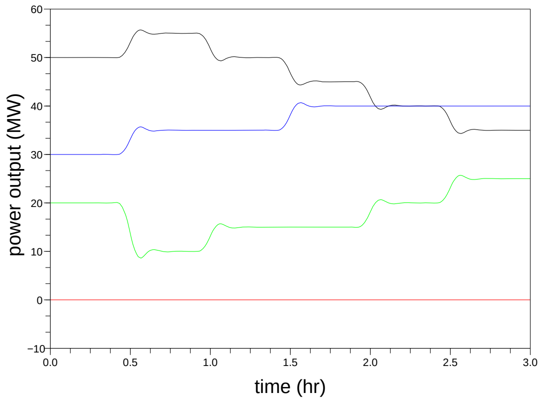

Fig. 4. Case A: power targets for each generator

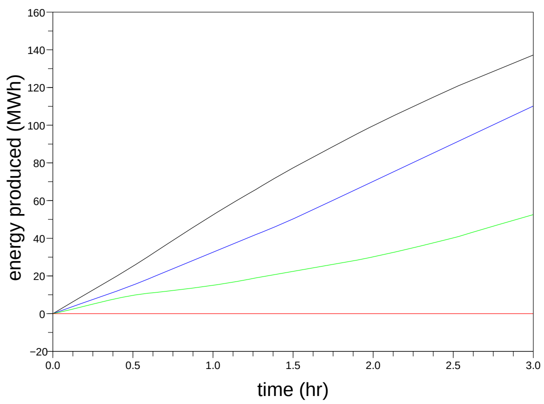

Fig. 5. Case A: accumulated energy provision for each generator

the corresponding energy deviations between the commercial and intermediate processeses.

TABLE III
CASE B (FORECAST ERROR) COMMERCIAL ENERGY SCHEDULE

Time (hr)	Gen 1 (MWh)	Gen 2 (MWh)	Gen 3 (MWh)	Gen 4 (MWh)
0.50	22.50	13.50	9.00	0.00
1.00	21.77	16.93	9.68	0.00
1.50	20.70	18.11	12.94	0.00
2.00	23.29	15.53	12.94	0.00
2.50	21.77	16.93	9.68	0.00
3.00	22.50	12.60	9.90	0.00

D. *Case C: Generation start-up and shut-down profiles*

The energy-based spot market formulation of equations (7) and (8) doesn't require the transactions of the energy-based spot market to be delivered at specific points in time This provides flexibility in the precise timing associated with the delivery of energy throughout a spot trading interval and is useful in situations where generators are subject to specific technical constraints such as a start-up and/or shut-down profiles and uncertainty about the exact point within a spot trading interval that it commences or ceases operation.

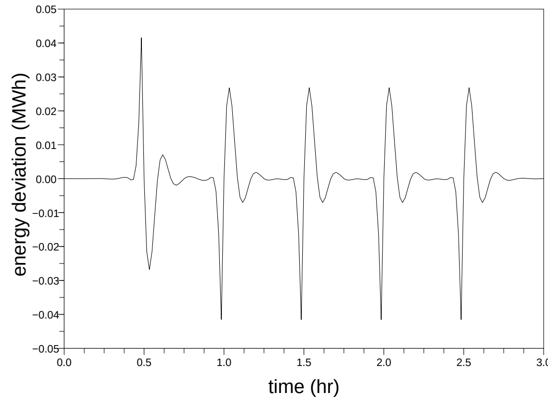

Fig. 6. Case A: generator 1's energy oversupply between the commercial model and the intermediate process controller (technical model)

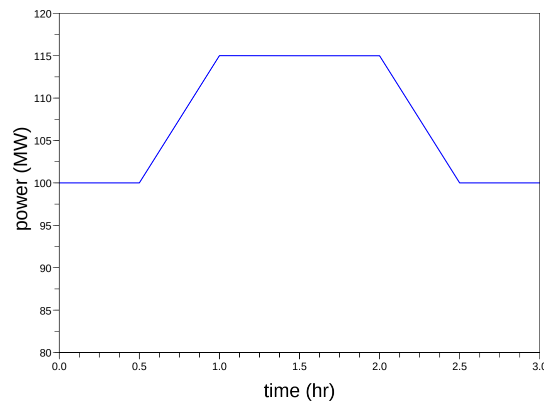

Fig. 7. Case B: demand profile used by intermediate process

As shown in table IV, generator 4 is scheduled to deliver energy over the period $t \in [1.0, 3.0]$ however, it is only able to commence operation 15 minutes into the spot trading interval $t = 1.0$ and it is subject to a generation profile for the generator's start-up, shut-down and general operation. In this example, the constraints from (8) are modified to be in the following form:

$$\underline{p}_g(k) \leq p_g(k) \leq \overline{p}_g(k) \tag{12}$$

where $\underline{p}_g(k)$ and $\overline{p}_g(k)$ corresponds to lower and upper limits that can be used to construct a profile for the generator. For simplicity we again assume that the demand is 100MW.

TABLE IV
CASE C (GENERATOR PROFILES) COMMERCIAL ENERGY SCHEDULE

Time (hr)	Gen 1 (MWh)	Gen 2 (MWh)	Gen 3 (MWh)	Gen 4 (MWh)
0.50	25.00	15.00	10.00	0.00
1.00	27.50	17.50	5.00	0.00
1.50	25.00	12.50	10.00	2.50
2.00	20.00	12.50	7.50	10.00
2.50	17.50	15.00	7.50	10.00
3.00	20.00	17.50	11.00	1.50

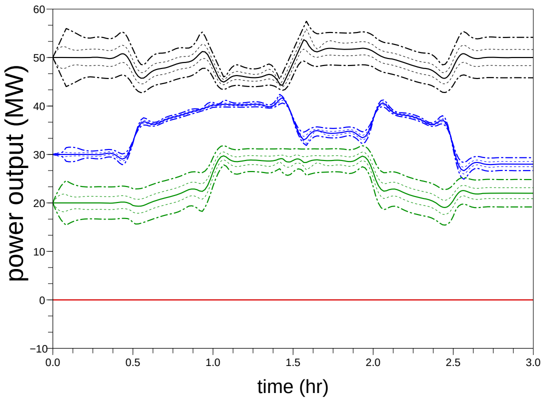

Fig. 8. Case B: power targets with 0% forecast error shown in solid lines and others (±10%, ±20%) in dashed lines

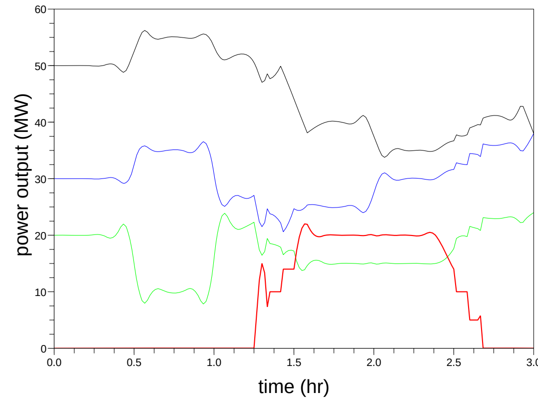

Fig. 10. Case C: power targets for each generator

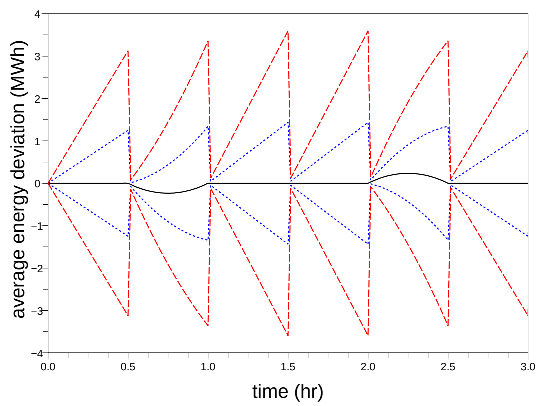

Fig. 9. Case B: energy deviations 0% forecast error shown in solid lines and others (±10%, ±20%) in dashed lines

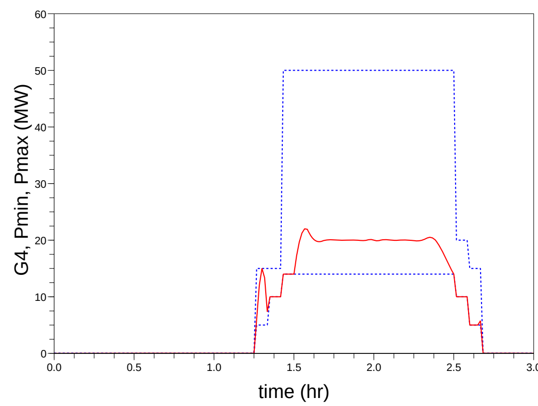

Fig. 11. Case C: generator 4 profile (upper & lower targets limits shown as dashed line) and actual targets

The power output targets for each generator are shown in Fig. 10. This shows that Generator 4 commences energy delivery at $t = 1.25$, with modifications to the targets of other generators to accommodate its start-up. Fig. 11 shows the profile of Generator 4 and its corresponding targets within the feasible space they define. In this case some significant energy deviations were experienced during the generator's start-up and shut-down; however, overall they tended toward zero by the end of each spot trading period which shows that the commercial transactions were still implemented.

E. Case D: Invocation of security constraint

In this example we consider the situation where system operators become aware of a known security limit after the corresponding commercial solution has become commercially binding. The energy schedule used for this example is in table V and security constraint that is implemented is:

$$p_2(k) + p_3(k) \le L(k) \tag{13}$$

which is added to the optimization of (7) or (8). $L(k)$ will vary as a function of system conditions over the simulation period and the security constraint is invoked at $t = 35$min to address an issue that system operators know will impact the system over the time period $t = [64, 80]$min.

TABLE V
CASE D (SECURITY CONSTRAINT) COMMERCIAL ENERGY SCHEDULE

Time (hr)	Gen 1 (MWh)	Gen 2 (MWh)	Gen 3 (MWh)	Gen 4 (MWh)
0.50	25.00	15.00	10.00	0.00
1.00	20.00	17.50	12.50	0.00
1.50	20.00	17.50	12.50	0.00
2.00	20.00	17.50	12.50	0.00
2.50	20.00	17.50	12.50	0.00
3.00	20.00	17.50	12.50	0.00

Fig. 12 shows the power targets computed by the intermediate process The impact the constraint has is to pre-emptively ramp generators 2 and 3 down to appropriate levels while ramping generator 1 up. Fig. 13 shows the combined output of generators 2 and 3 with the impact of the contraint on their combined outputs. It is clear that the algorithm ramps the generators up following the release of the constraint in order to ensure they deliver as much of the energy as agreed to in the commercial process as can be achieved and this consequently results in generator 1 being ramped down. Finally Fig. 14

shows the energy deviations for all generators where the deviations within a commercial period tend toward zero.

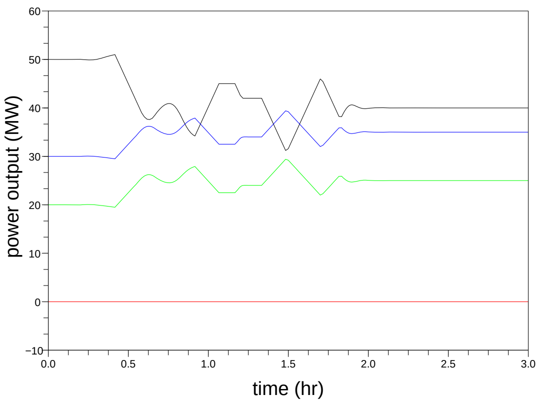

Fig. 12. Case D: power targets for each generator

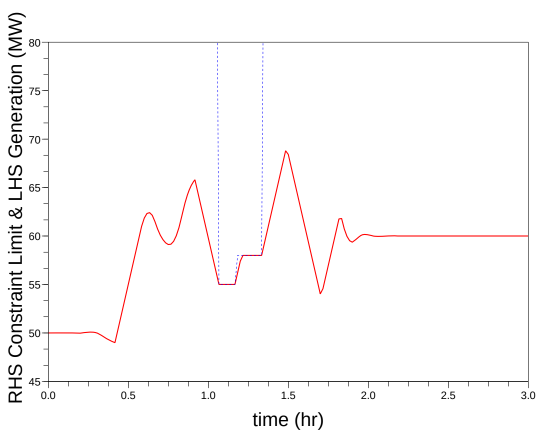

Fig. 13. Case D: $p_2(k) + p_3(k)$ and constraint upper limit, $L(k)$ shown as a dashed line

V. Conclusions

This paper has explored a decision-making framework for a restructured electricity industry that attempts to formally coordinate commercial and technical decision-making by adopting energy as the primary commodity and by solving the commercial and technical operation of the industry as separate processes that are coupled through the use of a bidirectional interface. Model predictive control was used in order to reconcile the commercial and technical models over a finite horizon into the near-term future and thus coordinate the two forms of decision-making. However to achieve this, control over set-points was assigned to centralized technical decision-makers. Consequently decentralized commercial decision-makers have reduced control over the specific power levels of their equipment which may be undesirable as their detailed understanding of the present physical capability of the equipment they own or operate could be overlooked by centralized technical decision-makers. This suggests that there is merit in comparing the appoach adopted in this paper to an alternative that treats

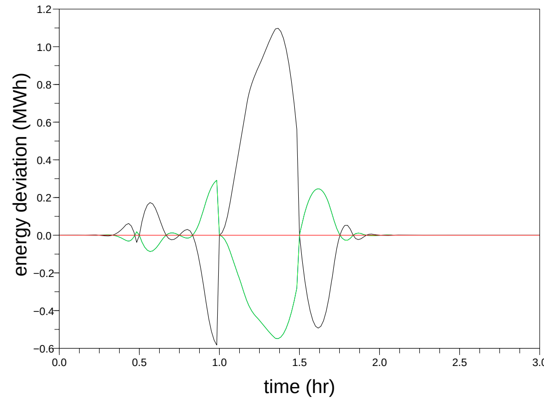

Fig. 14. Case D: energy deviations for each generator between commercial schedule and technical controller

power set-points as the primary commercial service with the responsibility of technical decision-makers being to constrain the set-points to lie within an acceptable security envelope.

Appendix

The non-commercially binding spot trading periods are given by:

$$\mathcal{M} = \{i : i \in \{m_f, \ldots, m_l\} \wedge \operatorname{mod}(i, N_t) = 0\} \quad (14)$$

where $m_f = (k + N_c + N_t) - \operatorname{mod}(k + N_c + N_t, N_t) + 1$ is the first commercially binding spot trading interval and $m_l = m_f + (N_f - 1)N_t$.

The times at which energy market targets influence the intermediate process controller are given by:

$$\mathcal{N} = \{i : i \in \{n_f, \ldots, n_l\} \wedge \operatorname{mod}(i, N_e) = 0\} \quad (15)$$

where $n_f = k + 1$ is the first time period of the spot trading interval corresponding to the present time $k$and $n_l = n_f + N_h$ is the last.

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