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

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***Abstract*— 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 industry decision-makers over a range of time-horizons. 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 case studies including the scheme's general operation, the impact of demand forecast errors, management of a generator with specific start-up and shut-down constraints and the invocation of security constraints at short notice.**

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 industry decision-makers over a range of time-horizons [1], [2]. Because the industry must be maintained in a state where electricity continuously flows to its end-uses, coordination between decentralized commercial decision-makers and centralized technical/security oriented decision-makers is required [3]. This is generally achieved through the use of optimization models that represent the underlying energy conversion process in sufficient detail to enable the required degree of coordination to occur. 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.

The commercial commodity could be specified as energy or as a power set-point service. The former enables the commercial decision-makers to trade in terms of parcels of energy, and allocates the responsibility of instantaneous delivery (by setting generator/demand set-points) to centralized technical decision-makers. This provides flexibility in terms of the timing of power injections which assists in overcoming certain types of security issues or system disturbances, particularly those arising on short timescales that can only readily be detected and managed by centralized decision-makers. The latter approach assigns the responsibility of nominating preferred set-points to commercial decision-makers while technical decision-makers would be required to constrain, ahead of time, the space of possible power set-points to lie within an acceptable security envelope.

The coupling between the commercial and technical forms of decision-making is also a design choice. At one extreme, the commercial decision-making could occur in an environment that is not at all informed or constrained by technical issues which introduces the need for technical decision-makers to take actions that are inconsistent with commercial preferences ultimately giving rise to inefficient market behavior and/or inefficient operation of the power system. At the other extreme, the commercial decision-making process could be highly constrained and informed by an extensive set of technical issues to the extent that the complexity arising from the physics of the underlying energy conversion chain, system control and security issues overcomplicates the task of energy trading, reducing the ability of humans to make informed commercial decisions. Thus a balance between these two extremes is required.

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 of the power system is accomplished through the use of model predictive control (MPC) (see, for example [4]) using the models and approach initially considered in [5] and [6] and similar to the more recent work reported in [7], [8], [9] and [10]. The MPC process is guided by a slower-acting commercial decision-making process that is implemented as a forward-looking energy-based linear program.

This paper is structured as follows. Section II discusses the general philosophy of the decision-making framework, then section III provides a detailed description of the scheme, section IV examines the outcomes for a number of case studies to consider how the scheme operates under both technical and commercial disturbances. Finally, section V evaluates benefits of the approach and draws conclusions.

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. The intermediate process acts on a faster timescale and is informed by both measurements of the present physical state of the power system as well as by the views of technical decision-makers (system operators). In this way, a formal interface is established between commercial and technical operations in the industry. 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 using a model that abstracts away all but the key aspects of the physical energy conversion chain. Energy targets are communicated to the intermediate process for physical delivery. This gives rise to a simple trading interface and transparent market process;
- 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. In this paper, the intermediate process is implemented using MPC where the main emphasis is on ramping generators between spot market energy solutions subject to technical constraints over the controller's horizon and demand uncertainty. 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.

Within this framework, a variety of technical issues can be resolved by the intermediate process in a way that aims to minimize the impact on commercial outcomes. Since the intermediate process is implemented using MPC, it is able to coordinate technical and commercial decision-makers over a finite horizon into the future. This provides a way of enabling technical and commercial risks to be jointly managed by the corresponding industry decision-makers.

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. The following describes the key processes in more detail.

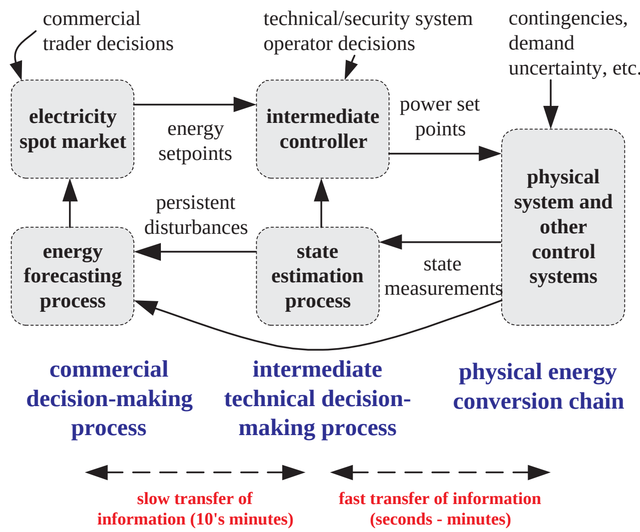

Fig. 1. conceptual diagram of processes and information flows

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.

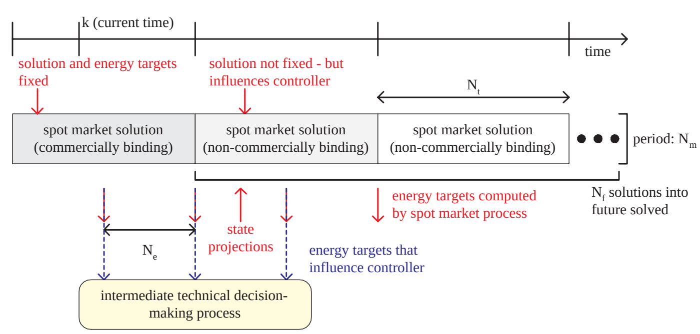

Fig. 2. time period definitions and key information flows for the electricity spot market

Before describing its operation, it is useful to firstly define the following concepts:

- a *spot market solution* is the set of energy targets and energy prices which satisfy forecast energy requirements at least cost. Numerous spot market solutions into the future are comptued to assist decentralized decision-making;
- a *commercially binding spot market solution* is a spot market solution that can no longer change and the prices along with the energy targets form the basis of commercial transactions or cashflows; and
- a *commercially non-binding spot market solution* is a spot market solution in the future that can change as time progresses as a consequence of decentralized participants revising their energy offers or a centralized decision-maker revising energy forecasts.

and to 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 $k \in \mathbb{Z}$. All time periods defined hereafter are integer multiples of T_s and k is used as a surrogate for time;
- $N_t > 1$ is the spot trading period;
- $N_f \in \mathbb{Z}^+$ is the number of electricity spot market trading intervals solved into the future starting with the first commercially non-binding spot trading period;
- 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 future based on participants' forward-estimates of energy bids and offers and on a centralized projection of energy requirements for the industry. This process occurs on a period of N_m and starts with the spot market trading period commencing immediately after the last commercially binding spot market solution. For the spot market solutions that overlap with the intermediate process controller horizon, the spot market solution is turned into shorter-term energy targets (with a periodicity of N_e) for tracking purposes. The process for turning a non-commercially binding solution into a commercially binding one arises from technical considerations and is described in the following section.

The commercial model is implemented as a simple linear program (which for clarity does not include demand-side bidding) which is computed whenever $\mathrm{mod}(k, N_m) = 0$ (k is the current time). 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 (an expression for this is given in equation (14) of the appendix).

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

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

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 (an expression for this set is provided in equation (15) of the appendix). Define the following:

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

$$\Gamma_n \triangleq n - N_t - \mathrm{mod}(n, N_t) \tag{4}$$

where $\Phi_n : \mathcal{N} \to \mathcal{M}$ maps n to the relevant spot trading interval m that should be used for computation of the shorter-term targets and $\Gamma_n : \mathcal{N} \to \mathcal{M}$ 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 therefore given by the following recursive formula:

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

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:

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

which describes the fraction of energy apportioned across each short-term target from the corresponding spot trading period. Equation (5) simply says that any energy that was not delivered in the previous spot market trading interval can nolonger be delivered and that the energy targets from the spot market are to be delivered in linearly across the interval. The larger the value N_e the less specific the delivery strategy.

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 $\mathrm{mod}(k, N_r) = 0$ and is

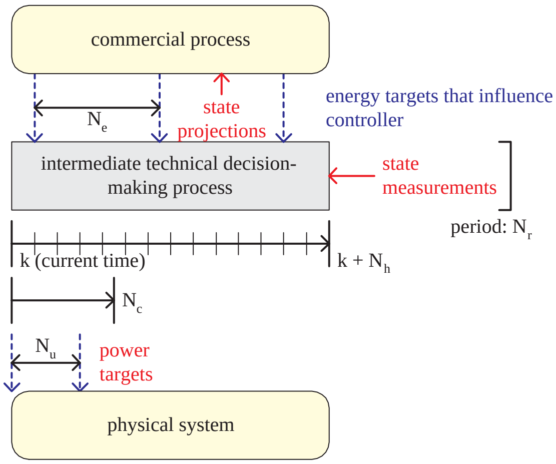

Fig. 3. time period definitions and key information flows for the intermediate technical decision-making process

formulated as follow:

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

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

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, constraints to reflect certain aspects of the operational characteristics of generators and constraints to reflect the transmission system. Examples of such constraints are illustrated in the following section.

IV. Examples

A. Parameters

All of the examples 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). The examples were implemented using the optimization tools provided in SCILAB [11].

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

In order 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. There will be a corresponding set of energy prices that will minimize the cost of energy provision; however the specific set of prices are not of interest here so we omit them. It is assumed in this case that the scheduled energy quantities are fixed and don't vary with time.

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
Total	137.50	110.00	52.50	0.00

The power targets computed by the intermediate process controller for each generator are shown in Fig. 4, the key observation is that the targets are chosen so that the energy schedule of the spot market in table II is adhered to. 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 over the simulation period is consistent with the energy schedule of table II, which is expected given the absence of demand uncertainty and the absence of any significant technical actions being required. Fig. 6 shows that energy deviations between the commercial and technical models does in fact vary across the simulation period but that they tend to zero. The variations are needed in order to transition from one set of commercial energy quantities to the next. Finally, Fig. 7 shows the ramping signals used to control each generator, the key point to observe is that they anticipate the future commercial solutions and accordingly most of the ramping occurs prior to the commencement of each commercial period.

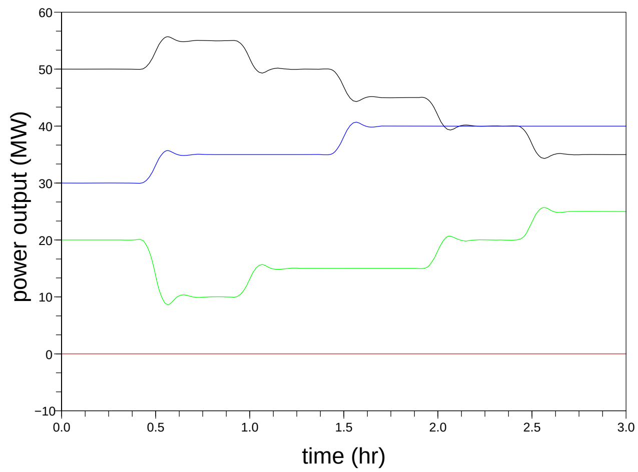

Fig. 4. Case A: power targets for each generator

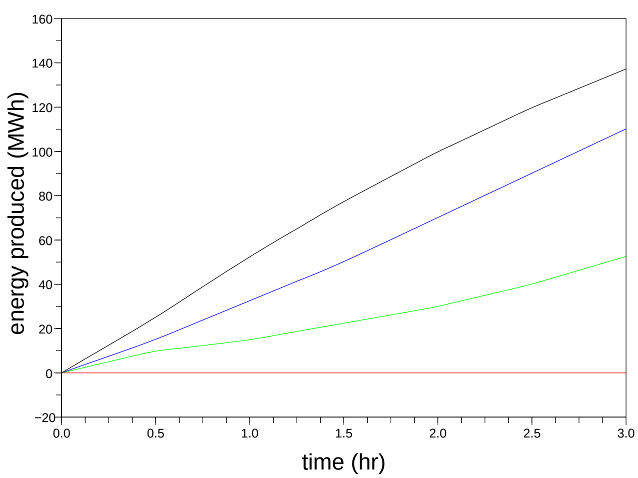

Fig. 5. Case A: accumulated energy provision for each generator

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. 8 while the

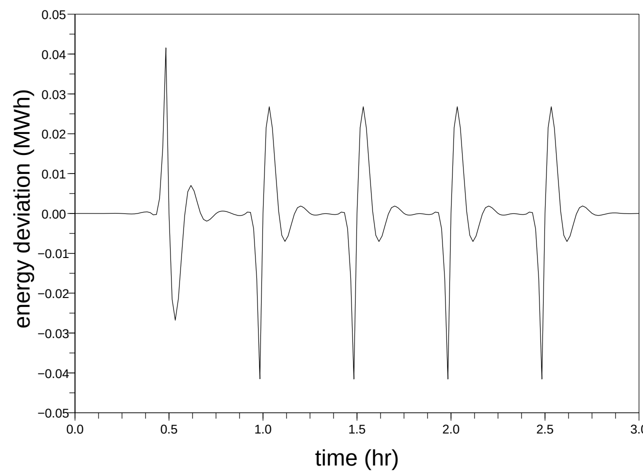

Fig. 6. Case A: generator 1's energy oversupply between the commercial model and the intermediate process controller (technical model)

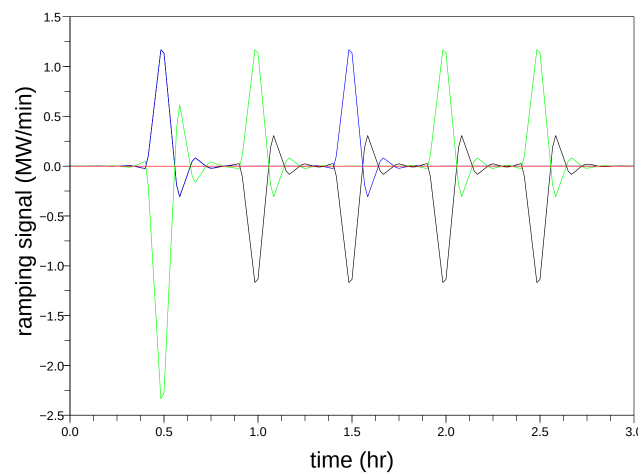

Fig. 7. Case A: ramping signals for each generator

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. 9 shows the resulting power trajectories for each plant which demonstrates that, as might be expected, the plant are shifted to satisfy the demand profile of the intermediate process. This is in line with the concept of the intermediate process operating the system subject to less uncertainty. Fig. 10 shows the corresponding energy deviations between the commercial and intermediate processeses. The errors are larger for higher forecast errors (positive for -10% and -20% and negative for 10% and 20%) and would proceed to accumulate if not for correcting the accumulated energy schedule of the commercial process as suggested in equation (5) at the commencement of each spot trading interval. Fig. 11 illustrates the energy correction process and accumulation of errors for generator 3 in the case of a -20% demand forecast error; the demand forecast is consistently below the energy that the intermediate process deems necessary to deliver. In general this example simply confirms that the intermediate process can implement an alternative set of assumptions about demand compared to that used in the commercial model which offers flexibility in system operations.

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
Total	132.53	93.60	64.13	0.00

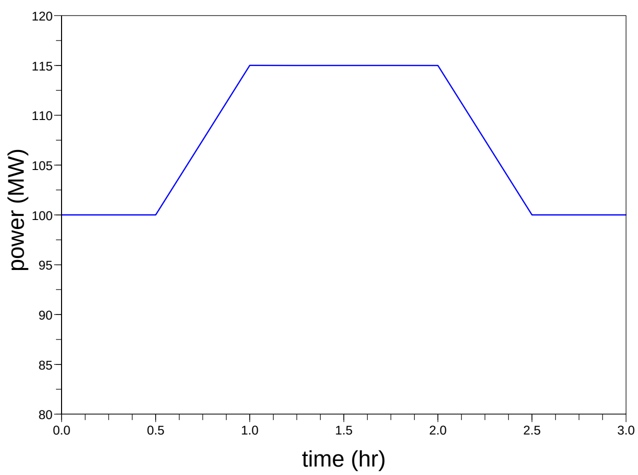

Fig. 8. Case B: demand profile used by intermediate process

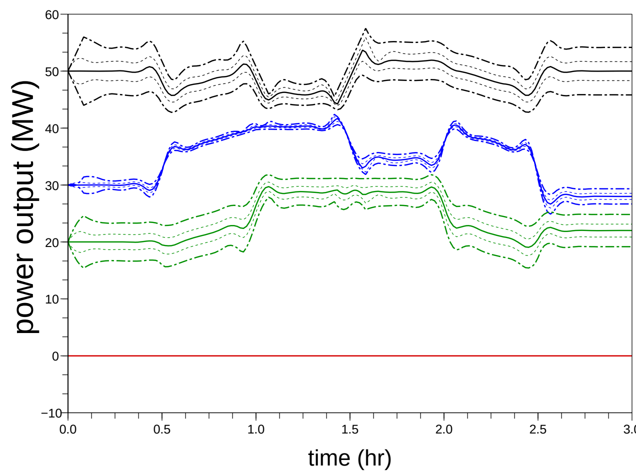

Fig. 9. Case B: power targets with 0% forecast error shown in solid lines and others ($\pm10\%$, $\pm20\%$) in dashed lines

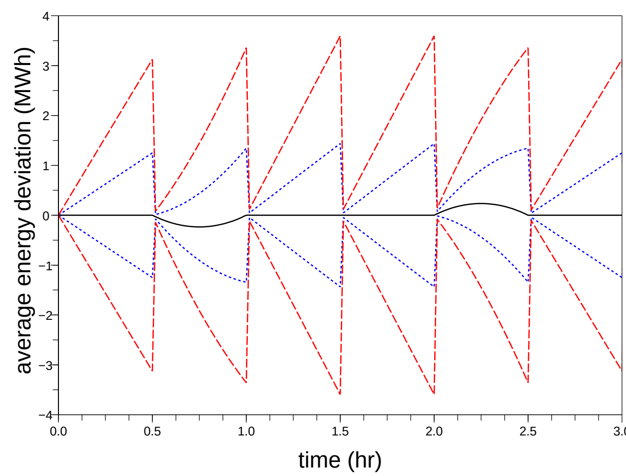

Fig. 10. Case B: energy deviations 0% forecast error shown in solid lines and others ($\pm10\%$, $\pm20\%$) in dashed lines

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, instead soft contraints are implemented to reduce difference between the commercial and technical delivery of energy. This provides a degree of flexibility in the 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 generating.

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:

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

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.

The power output targets for each generator are shown in Fig. 12. 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. 13 shows the profile of Generator 4 and its corresponding targets within the feasible space they define. Due to the operation of this generator and the way in which energy targets are constructed for the generators, there are significant energy deviations within the interval for all units, as shown in Fig. 14. However, as shown they generally tend toward zero by the end of each spot trading period.

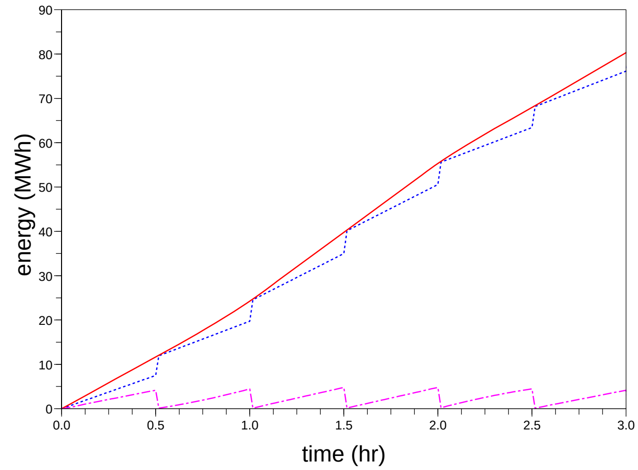

Fig. 11. Case B: example of corections made to energy forecast for generator 3 (-20% forecast error case), the solid line is the accumulated energy delivered by the generator, the dashed line below it is the forecast which is updated every 30-minutes and the remaining line is the forecast error

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
Total	135.00	95.00	51.00	24.00

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. In order to exemplify the impact of the security limit, we again restrict attention to the simplistic energy schedule of table V and set the demand to 100MW. The security limit is implemented through the introduction of the constraints of the following form:

$$\sum_{g \in \mathcal{G}} c_g p_g(k) \leq L(k) \tag{13}$$

which are added to the optimization of (7) or (8). Where c_g are generator-term coefficients and $L(k)$ is the constraint upper bound. Assume that the security limit imposes an upper bound on the combined power output of generators 2 and 3 of $L(k)$ so that $c_1 = c_4 = 0$, $c_2 = c_3 = 1$. $L(k)$ will vary as a function of system conditions over the simulation period; in particular, 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; $L(k)$ will be initially set to 55MW and later relaxed to 58MW.

Fig. 15 shows the power targets computed by the intermediate process The impact the constraint has is to pre-emptively

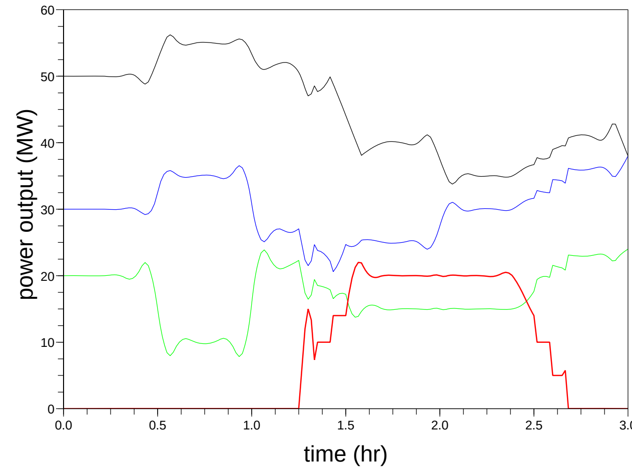

Fig. 12. Case C: power targets for each generator

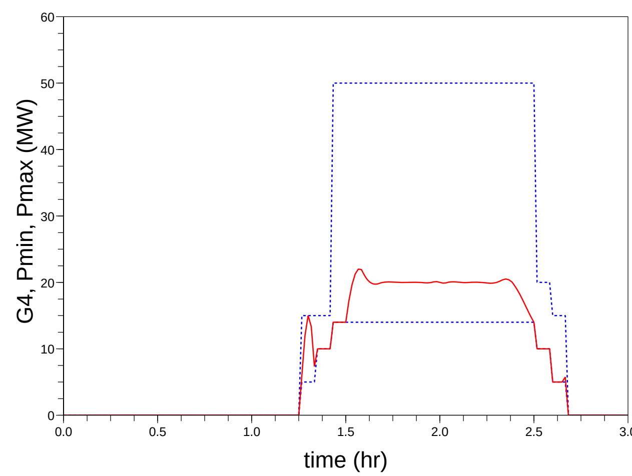

Fig. 13. Case C: generator 4 profile (upper & lower targets limits shown as dashed line) and actual targets

ramp generators 2 and 3 down to appropriate levels while ramping generator 1 up. This ensures that the security limit is satisfied and demonstrates the anticipatory nature in which the MPC algorithm works. Fig. 16 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. It also shows that there is significant ramping following the relaxation of the security constraint which occurs in an attempt to deliver the commercial energy prior to the end of the corresponding trading period. Finally Fig. 17 shows the energy deviations for all generators where again it is clear that the algorithm generally drives the deviations within a commercial period toward zero, although it is clear that in this instance the deviations within the interval are larger than for some of the

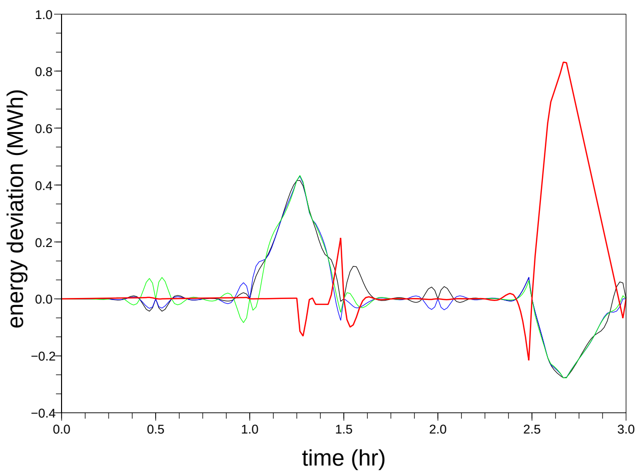

Fig. 14. Case C: energy deviations for each generator between commercial schedule and technical controller

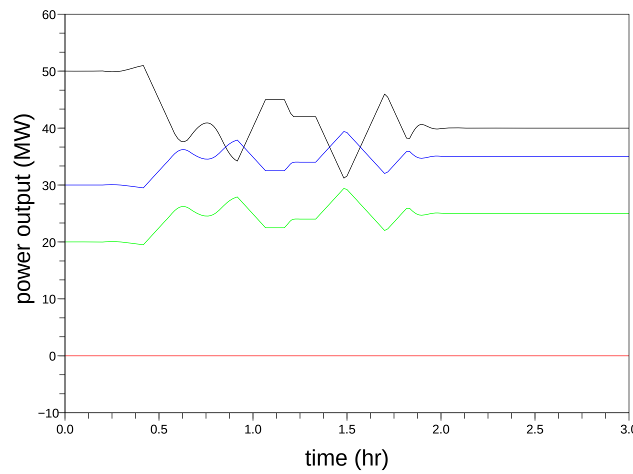

Fig. 15. Case D: power targets for each generator

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
Total	125.00	102.50	72.50	0.00

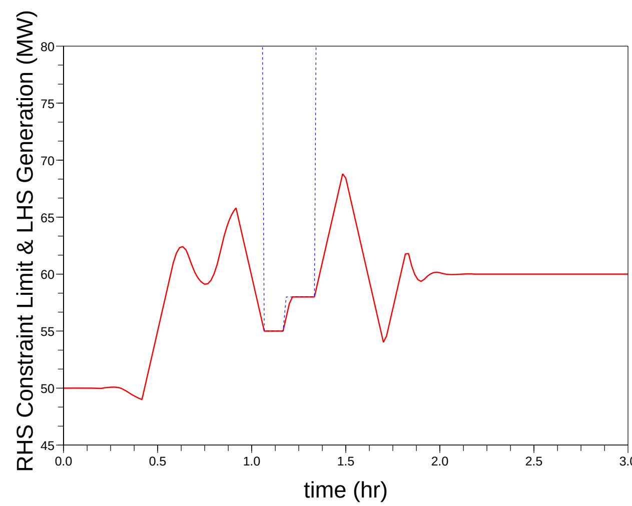

Fig. 16. Case D: $p_2(k) + p_3(k)$ and constraint upper limit, $L(k)$ shown as a dashed line

previous examples.

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 as a tool for reconciling technical decisions with commercial decisions. Both the commercial and technical models are solved over a finite horizon into the future; thus a consensus between technical and commercial issues can be formed ahead of time. Within the framework, technical issues can be managed on a shorter timescales compared to the operation of commercial model. The shorter timescale is more appropriate for the management of issues arising in a power system while the longer timescale of the commercial model is more appropriate for enabling humans to make informed commercial decisions.

The technical controller (intermediate process) computes set-points for generators (and in principle the set-points of demand-side resources) in a way that aims to implement the agreed energy transactions. This is beneficial to system operators as they will be able to implement technical actions in the knowledge that the implications for decentralized commercial decision-making will be minimized. It is also beneficial to commercial decision-makers as the operation of their equipment will generally be in alignment with commercial decisions and will, in the main, not be adversely affected by uncertain technical actions. 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 power set-points as the primary commercial service with the responsibility of centralized technical decision-makers being to constrain the set-points to lie within an acceptable security envelope.

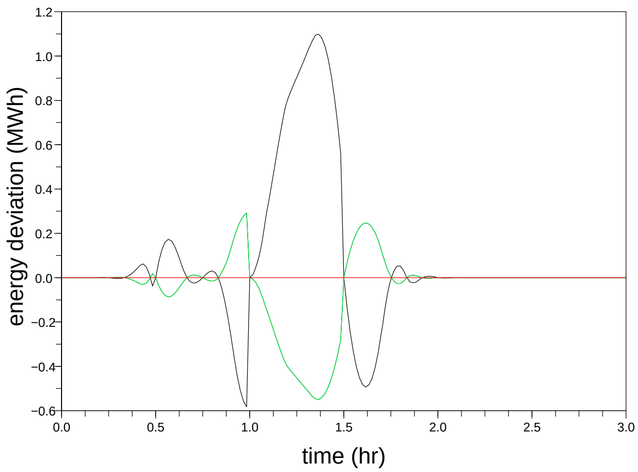

Fig. 17. Case D: energy deviations for each generator between commercial schedule and technical controller

APPENDIX

An expression for the set of non-commercially binding spot trading periods as a function of the present time and the N_c parameter of the intermediate process controller is $m \in \mathcal{M}$ where the set $\mathcal{M}$ is given by:

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

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

An expression for the set of times at which energy market targets that influence the target-tracking behavior of the intermediate process controller are computed for is given by the set $\mathcal{N}$ for current time k:

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

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

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