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A. M. Shehata
Department of Mathematics, Faculty of Science, Bisha University, P. O. Box 551, Bisha, 61922, Saudi Arabia.\\ Department of Mathematics, Faculty of Science, Al-Azhar University, Assiut 71511, Egypt., ah_moukh81@yahoo.com

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Model Predictive Control for Energy Optimization Problems

A. M. Shehata [1,2,*]

[1] Department of Mathematics, College of Science, Bisha University, P. O. Box 551, Bisha, 61922, Saudi Arabia.
[2] Department of Mathematics, Faculty of Science, Al-Azhar University, Assiut 71511, Egypt.

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Abstract: Since the fuel cost of electric power generation from thermal plants is very high, several researchers have devoted their efforts to offer new strategies to minimize such cost. But reducing the fuel cost will increase the emission of gaseous pollutants such as CO2, CO, NOx and SO2. Therefore, the dynamic economic emission dispatch problem (DEED) is formulated with the objective of simultaneously minimizing the fuel cost and emission so as to meet the predicted demand over a certain period under ramp rate limits and other operational and system constraints. Spinning reserve plays a crucial role in maintaining the power system reliability and security against sudden load changes and generation outages. To consider the spinning reserve into the DEED, we formulate dynamic economic emission and spinning reserve dispatch (DEESRD) problem which integrates the spinning reserve into the DEED problem. DEESRD determines the optimal power and spinning reserve schedule by simultaneously minimizing the power and spinning reserve costs, and the amount of emission under some constraints. The optimal solutions of the DEESRD problem are open loop. The open-loop nature cannot deals with inaccuracies, modeling uncertainties and unexpected external disturbances where the power system components suffer from. To overcome this problem we designed closed-loop solutions using a suitable version of MPC approach. The performance of the MPC has been investigated by applying the MPC strategy to the DEESRD problem with test system consisting of five generating units and five customers.

Keywords: Dynamic economic dispatch, Emission dispatch, Optimization, Model predictive control, Spinning reserve.

1 Introduction

One of the most important tasks of the electric power generation utilities and companies is to satisfy the customer's load demand in an optimal and secure way. To achieve such task, dynamic economic dispatch (DED) problem has to be applied. In the DED problem we aim to satisfy the predicted load customer's demand over a certain period (e.g. 24 hours) at minimum generation cost taking into consideration the ramp rate limits of the thermal generating units [1-14]. Several researchers have devoted their efforts to propose optimization methods and techniques for solving the DED problem with different objectives and constraints such as linear programming [15]; Lagrangian relaxation [16]; quadratic programming [17]; dynamic programming [18]; evolutionary programming [19]; particle swarm optimization [20]; artificial bee colony algorithm [21]; genetic algorithm [22]; simulated annealing [23]; artificial immune system [24]; differential evolution [25]; enhanced cross-entropy [26]; imperialist competitive algorithm [27]; harmony search [6,28]; Quasi-oppositional group search optimization [9]; Crisscross optimization algorithm [1], hybrid evolutionary programming and SQP [19]; hybrid particle swarm optimization and SQP [29]; hybrid differential evolution and SQP [29]; hybrid bare-bones particle swarm optimization [30]; hybrid genetic algorithm and bacterial foraging approach [31]; hybrid weighted probabilistic neural network and biogeography based optimization [32].

The thermal units produce gaseous pollutants which effects on the health of the human, animal and plant. As a result, generation companies (GENCOs) and utilities are obliged to minimize the emission from these units. The emission of gaseous pollutants can be taken in the dynamic dispatching by formulating three problems (see e.g. [33-47]): (1) emission constrained dynamic economic dispatch (ECDED), where the emission is added as a constraint in the optimization, (2) pure dynamic emission dispatch (PDED), where the emission is minimized under ramp rate constraints and other constraints, (3) dynamic economic emission dispatch (DEED) with the purpose to minimize

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[*] Corresponding author e-mail: ah_moukh81@yahoo.com

both fuel cost and the amount of emission and satisfy the system constraints. The emission of gaseous pollutants have been included into the optimal dynamic dispatch problem in several papers (see e.g. [33-47].

In regulated and deregulated power systems, spinning reserve plays an important role in maintaining the power system reliability and security against sudden load changes and generation outages. In regulated systems, the spinning reserve is taken in the static or dynamic dispatch problems as a constraint. In contrast, in deregulated environment it is important to find the optimal spinning reserve requirement. In this case, both the energy and spinning reserve costs are minimized under a set of constraints. In [48-53], the spinning reserve constraint is included into the static and dynamic dispatch problems. Joint generation and spinning reserve dispatch has been studied in [54-59], where the spinning reserve is inserted in the objective function as another optimization variable in addition to the power output variable.

To incorporate the spinning reserve into the dynamic dispatch problem, we have formulated three problems:

(a) Dynamic economic and spinning reserve dispatch (DESRD). In the DESRD we aim to minimize the energy and reserve costs, satisfy the predicted power and spinning reserve load demands over a certain period and satisfy the ramp rate limits and other constraints. In this case, the emission is neglected.

(b) Pure dynamic emission and spinning reserve dispatch (PDESRD). The objective of the PDESRD is to minimize the emission (regardless of energy and reserve costs) so as to meet the predicted power and spinning reserve load demands over a certain period under ramp rate limits and other constraints.

(c) Dynamic economic emission and spinning reserve dispatch (DEESRD). DEESRD is a multi-objective optimization problem which simultaneously minimize the energy and reserve costs and the amount of emission while satisfying the load demand balance form both power and spinning reserve, ramp rate constraints and other constraints.

All the DESRD, PDESRD and DEESRD problems provide open-loop solutions. The open-loop nature cannot deals with inaccuracies, modeling uncertainties and unexpected external disturbances where the power system components suffer from. A good solution of such deficiency is to design a feedback control strategy using model predictive control (MPC) method. MPC provides closed-loop solutions which has the ability to deal with disturbances that arise from real systems. MPC has been applied in power system in [47, 60-64, 66]. In these papers, the MPC has been applied for the optimal dynamic dispatch problems without taking into consideration the spinning reserve.

The objective of the paper is to introduce optimality in generation side, such that the energy and spinning reserve costs as well as the amount of emission are minimized. To apply the optimal solution practically, MPC strategy will be used. In this paper, we first formulate the DESRD, PDESRD and DEESRD problems, then we construct a feedback control by using the MPC strategy. The performance of MPC algorithm including convergence and robustness have been shown and the controller has been tested with test system consisting of five units.

2 Problem Formulation

We devote this section to introduce the mathematical formulation of the DEED problem incorporated with the spinning reserve with the aim to determine the optimal power and spinning reserve schedule of the committed generating units. To do this we formulate the DEESRD problem. DEESRD is a multi-objective optimization which simultaneously minimize the energy and reserve costs and the amount of emission so as to meet the predicted power and spinning reserve load demands over a certain period under ramp rate limits and other constraints. Let p_i^t and s_i^t be the power output and spinning reserve contribution of unit i at time t (during the time interval $[t-1,t)$), respectively. The cost and emission functions of unit i are given, respectively, as [2, 43, 44, 65]:

$$C_i(p_i^t) = a_i + b_i p_i^t + c_i (p_i^t)^2,$$
$$E_i(P_i^t) = \alpha_i + \beta_i p_i^t + \gamma_i (p_i^t)^2,$$

where, $a_i, b_i, c_i, \alpha_i, \beta_i$ and γ_i are constants. Other forms for the fuel cost and emission functions are given in [2]. Let us define the following: N_G and N_T be the number of committed generating units and number of intervals in the dispatch period, respectively; $P^t = \left\{p_1^t, ..., p_{N_G}^t\right\}$, $S^t = \left\{s_1^t, ..., s_{N_G}^t\right\}$, $PS^t = (P^t, S^t)$, $PS = (PS^1, PS^2, ..., PS^{N_T})$; r is forecasted probability that the reserve is actually called up; B_{ij} is ijth element of the transmission line loss coefficient matrix; UL_i and DL_i are the maximum ramp rate of unit i; D^t and SR_D^t are the power and spinning reserve demands at time t; $p_i^{\min}, p_i^{\max}$ are the limits of power capacity of unit i. We assume that the power and spinning reserve demands are periodic with period N_T, then $D^t = D^{t+N_T}$, $SR^t = SR^{t+N_T}$

There are two methods for solving the multi-objective problem. The first method is by finding the Pareto solutions and the second one is by combining the objectives into a single-objective function. The advantages of the second method include (i) it makes the multi-objective problem easy to solve; (ii) it gives the decision maker the ability to change the weighting factor according to the importance of each objective. The second method will be used in this project. Let $\omega \in [0,1]$ be a weighting factor, and h_i^t be the price penalty factor at time t, which blends the emission cost with the normal fuel cost. Let us define

$$CE_i(p_i^t) = \omega C_i(p_i^t) + (1-\omega)h_i^t E_i(p_i^t)$$

The price penalty factor h^t can be determined for a particular demand D^t as follows [63]:

(i) Evaluate the ratio between the maximum fuel cost and maximum emission for each unit as: $h_i^t = \dfrac{C_i(p_i^{\max})}{E_i(p_i^{\max})}, \quad i = 1,2,\ldots,N_G,$

(ii) Arrange $h_i^t, \quad i = 1,2,\ldots,N_G$ in ascending order.,

(iii) Add the maximum capacity of each unit, $(P_i^{\max})$ one at a time, starting from unit having smallest h_i^t until the demand is met as shown below:

$$\sum p_i^{\max} > D^t,$$

(iv) At this stage, h_i^t associated with the last unit in the process is the price penalty factor, h_i^t for the given demand D^t.

We formulate the DEESRD problem over dispatch interval $[0, N_T]$ as:

$$\min_{PS} TC(PS) = \sum_{t=1}^{N_T}\sum_{i=1}^{N_G}(1-r)CE_i(p_i^t) + rCE_i(p_i^t + s_i^t) \quad (1)$$

Subject to:

Load-generation balance

$$\sum_{i=1}^{N_G} p_i^t = D^t + Loss^t, \qquad t = 1,\ldots,N_T, \qquad (2)$$

where $Loss^t = \sum_{i=1}^{N_G}\sum_{j=1}^{N_G} p_i^t B_{ij} p_i^t$.

Spinning reserve and demand balance

$$\sum_{i=1}^{N_G} s_i^t = SR_D^t \qquad t = 1,\ldots,N_T, \qquad (3)$$

Generating unit capacity limits

$$p_i^{\min} \le p_i^t \le p_i^{\max}, \quad t = 1,\ldots,N_T,\ i = 1,\ldots,N_G. \qquad (4)$$

Ramp rate limits

$$-DL_i \le p_i^{t+1} - p_i^t \le -UL_i, \ \ t = 1,\ldots,N_T - 1, \ \ i = 1,\ldots,N_G,$$
$$-DL_i \le p_i^1 - p_i^N \le -UL_i, \quad i = 1,\ldots,N_G, \qquad (5)$$

Generating spinning reserve capacity limits

$$0 \le s_i^t \le UL_i, \quad t = 1,\ldots,N_T, \qquad i = 1,\ldots,N_G, \qquad (6)$$

Unit power and spinning reserve coupling capacity limits

$$s_i^t + p_i^t \le p_i^{\max}, \quad t = 1,\ldots,N_T, \qquad i = 1,\ldots,N_G. \qquad (7)$$

In this case, we assume that the spinning reserve demand is 10% of the power demand. This means that $SR_D^t = 0.1D^t, \quad t = 1,\ldots,N_T$.

We note that, problem (1) generalizes the following problems

i. $\omega = 1,\ r = 0$, dynamic economic dispatch (DED) [2],
ii. $\omega = 0,\ r = 0$, pure dynamic emission dispatch (PDED) [35],
iii. $0 < \omega < 1,\ r = 0$, dynamic economic emission dispatch (DEED) [29],
iv. $\omega = 1,\ 0 < r < 1$, dynamic economic and spinning reserve dispatch (DESRD) [58],
v. $\omega = 0,\ 0 < r < 1$, pure dynamic emission and spinning reserve dispatch (PDESRD).

The function TC is quadratic and then this optimization problem (1) can be solved by e.g., quadratic programming.

Now instead of solving DEESRD problem over the interval $[0, N_T]$, we solve the problem over an arbitrary interval $[k, k+N_T]$ for any $k \ge 0$. Let $\overline{PS}^k = (PS^{1+k}, PS^{2+k}, \ldots, PS^{N_T+k})$. Thus the mathematical model for DEESRD problem is given by

$$\min_{\overline{PS}^k} F(\overline{PS}^k)$$

Subject to $PS^t \in \Gamma(\overline{PS}^k), \qquad t = k+1, k+2, \ldots, k+N_T$

where the feasible domain $\Gamma(\overline{PS}^k)$ is defined to be the set of $(p_i^t, s_i^t : i = 1,\ldots,N_G, t = k+1,\ldots,k+N_T)$ satisfying constraints (2)-(7). Since both the power and spinning reserve demands are periodic and all the parameters of the problem do not change over time, then $PS^{1+k} = PS^{1+k+N_T}$ and

$$\begin{aligned}\Gamma(\overline{PS}^{k+1}) &= \Gamma(PS^{2+k}, PS^{3+k}, \ldots, PS^{N_T+k}, PS^{N_T+1+k})\\ &= \Gamma(PS^{2+k}, PS^{3+k}, \ldots, PS^{N_T+k}, PS^{1+k})\\ &= \Gamma(PS^{1+k}, PS^{2+k}, \ldots, PS^{N_T+k})\\ &= \Gamma(\overline{PS}^k).\end{aligned}$$

Then $\Gamma(\overline{PS}^k)$ is shift-invariant, which is required for applying the MPC method to the DEESRD problem [64].

3 Model Predictive Control Method For DEESRD

In this part, we show how to apply MPC strategy to the DEESRD problem. Consider the linear discrete time control system [61]

$$p_i^{t+1} = p_i^t + x_i^t, \quad s_i^{t+1} = s_i^t + y_i^t,$$
$$i = 1,\ldots,N_G,\ j = 1,\ldots,N_C,\ t = 1,\ldots,N_T - 1, \qquad (8)$$

where, $(p_i^t, s_i^t,\ i = 1,\ldots,N_G,\ j = 1,\ldots,N_C,\ t = 1,\ldots,N_T)$, are the state variables and

$(x_i^t, y_i^t,\ i=1,\dots,N_G,\ j=1,\dots,N_C,\ t=1,\dots,N_T-1)$ are the control inputs. Then, we have the following transformation

$$p_i^t = p_i^1 + \sum_{m=1}^{t-1} x_i^m, \qquad s_i^t = s_i^1 + \sum_{m=1}^{t-1} y_i^m, \tag{9}$$
$$i=1,\dots,N_G,\ j=1,\dots,N_C,\ t=2,\dots,N_T.$$

Substituting transformations (9) into the optimization problem (1)-(7), we get the control version of the dynamic economic emission and spinning reserve dispatch (DEESRD) problem. Here, the decision variables are $(p_i^1, s_i^1, x_i^t, y_i^t,, i=1,\dots,N_G,\ j=1,\dots,N_C,\ t=1,\dots,N_T-1)$.

Assume that $(p_i^1, s_i^1, i=1,\dots,N_G j=1,\dots,N_C)$ are given. Then, the decision variables of the DEESRD will be $(x_i^t, y_i^t, i=1,\dots,N_G,\ j=1,\dots,N_C,\ t=1,\dots,N_T-1)$.

The idea of the MPC is that, at time $t=1$ we measure the current state of the system $(p_i^1, s_i^1, i=1,\dots,N_G j=1,\dots,N_C)$ and then solve the optimization problem DEESRD over the interval $[0, N_T-1]$, we get the optimal controller as $(\bar{x}_i^t, \bar{y}_i^t, i=1,\dots,N_G,\ j=1,\dots,N_C,\ t=1,\dots,N_T-1)$.

Then the first part of the optimal controller $(\bar{x}_i^1, \bar{y}_i^1, \bar{z}_j^1, \bar{d}_j^1, i=1,\dots,N_G j=1,\dots,N_C)$ is applied for the system on the interval $[1,2)$.

$$p_i^2 = p_i^1 + \bar{x}_i^1, \qquad s_i^2 = s_i^1 + \bar{y}_i^1, \tag{10}$$
$$i=1,\dots,N_G,\ j=1,\dots,N_C,$$

At the time instant $t=2$ the whole procedure is repeated.

The objective function of the DEESRD are differentiable and quadratic, and $\Theta(\bar{Q}^k)$ is shift-invariant the constraints. Then, using Theorems 1-2 of [62], we obtain that, the solution of MPC algorithm converges to the solution of the DEESRD problem. Moreover, MPC is robust against the disturbances and uncertainties happen in the execution of the controller. In this case, the system actually executes

$$p_i^2 = p_i^1 + \bar{x}_i^1 + b_{p,i}^1, \qquad s_i^2 = s_i^1 + \bar{y}_i^1 + b_{s,i}^1, \tag{11}$$
$$i=1,\dots,N_G,\ j=1,\dots,N_C,$$

where, the disturbances $(b_{p,i}^t, b_{s,i}^t, b_{v,j}^t, b_{u,j}^t, i=1,\dots,N_G,\ j=1,\dots,N_C,\ t=1,\dots,N_T-1)$ satisfy the following bound $\|b_{p,i}^t\| \le \varepsilon_{p,i}$, $\|b_{s,i}^t\| \le \varepsilon_{s,i}$, $\|b_{v,i}^t\| \le \varepsilon_{v,i}$ $\|b_{u,i}^t\| \le \varepsilon_{p,i}$.

Since the demand is forecasted then, it may have some disturbances or uncertainties. Then the actual (disturbed) demand will be $\tilde{D}^t$. It has been shown in [2] that if $\|D^t - \tilde{D}^t\|$ is small enough, then the demand disturbances can take the form of (11). Since we assumed that the forecasted spinning reserve demand is 10% of the power demand, therefore Theorem 2 of [62] is still valid for this case.

4 Results and Discussion

The above optimization problem DEESRD can be put in the following general form

$$\begin{array}{l} \min\limits_{x} f(x) \\ subject\,to \\ A_{eq}x = b_{eq} \\ Ax \le b \\ c(x) \le 0 \\ c_{eq}(x) = 0 \\ lb \le x \le ub \end{array} \tag{12}$$

Where x, b, b_{eq}, lb and ub are vectors; A and A_{eq} are matrices; $f(x)$, $c(x)$ and $c_{eq}(x)$ are nonlinear functions. Problem (12) can be solved by several optimization methods. In this paper, we will use Sequential Quadratic Programming (SQP) for solving the above problem. We use fmincon code of MATLAB optimization Toolbox

4.1 Effectiveness of the SQP Method

In order to show the effectiveness of the SQP method we make a comparison between SQP and other optimization methods through solving DED problem ten generating units and 12 hours dispatch period without transmission line losses. The technical data of the units and the power demand are taken from [65], which are given in Tables 1-2. We make a comparison between the SQP and hybrid approach of Hopfield neural network (HNN) and quadratic programming (QP) HNN-QP [65], which is given in Table 3. From these results, it is observed that the SQP is efficient, giving a cheaper total generating cost and minimize the emission than the other methods. For the DED problem, the total cost over 12 hours obtained by [65] is 2196210 $ and by SQP is 2185400 $; therefore, SQP can save 10810 $ over 12 hours or about 10810×2 = 21620 $ over one day. It means that, over one year SQP can save about 21620×30×12 = 7783200$: These results encourage us to use the SQP method for solving the optimization problems presented in this paper.

4.2 Simulation Results for DEESRD

In this part, we first solve the DEESRD problem. We present two test systems. The first for the DEESRD problem and consists of five generating units. The data of this system is taken from [36] and is given in Tables 4-5.

Table 1. Data of the ten-unit system

Unit	1	2	3	4	5	6	7	8	9	10
a_i	180	275	352	792	440	348	588	984	1260	1200
b_i	26.4408	21.0771	18.6626	16.8894	17.3998	21.6180	15.1716	14.5632	14.3448	13.5420
c_i	0.0372	0.03256	0.03102	0.02871	0.03223	0.02064	0.02268	0.01776	0.01644	0.01620
P_i^{min}	155	320	323	275	230	350	220	225	350	450
P_i^{max}	360	680	718	680	600	748	620	643	920	1050
DL_i	25	25	50	50	50	50	100	150	150	150
UL_i	20	20	50	50	50	50	100	100	100	100

Table 2: Power demand of the ten-unit system for 12 hours

Time (h)	1	2	3	4	5	6	7	8	9	10	11	12
Power Demand (MW)	5560	5620	5800	5560	5990	6041	6001	5790	5680	5540	5690	5750

Table 3: Comparison results for the DED problem without loss.

	Cost	
Time	HNN-QP [65]	SQP
1	174460	173400
2	177090	176060
3	185110	184200
4	174460	173510
5	193730	193070
6	196070	195480
7	194240	193580
8	184660	183740
9	179750	178740
10	173580	172510
11	180190	179200
12	182870	181910
Total	2196210	2185400

Table 4: Data of the five-unit system

Unit	1	2	3	4	5
a_i	25	60	100	120	40
b_i	2	1.8	2.1	2	1.8
c_i	0.008	0.003	0.0012	0.001	0.0015
α_i	80	50	60	45	30
β_i	-0.805	-0.555	-1.355	-0.600	-0.555
γ_i	0.0180	0.0150	0.0105	0.0080	0.0120
P_i^{min}	10	20	30	40	50
P_i^{max}	75	125	175	250	300
DL_i	30	30	40	50	50

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* Corresponding author e-mail: ah_moukh81@yahoo.com

UL_i	30	30	40	50	50

Table 5: Power demand of the five-unit system for 24 hours.

Time (h)	Power Demand (MW)	Time (h)	Power Demand (MW)
1	410	13	704
2	135	14	690
3	475	15	654
4	530	16	580
5	558	17	558
6	608	18	608
7	626	19	654
8	654	20	704
9	690	21	680
10	704	22	605
11	720	23	527
12	740	24	463
Time (h)	Power Demand (MW)	Time (h)	Power Demand (MW)

The transmission loss formula coefficient of the five-unit .

$$B_{ij} = 10^{-4} \times \begin{bmatrix} 0.49 & 0.14 & 0.15 & 0.15 & 0.20 \\ 0.14 & 0.45 & 0.16 & 0.20 & 0.18 \\ 0.15 & 0.16 & 0.39 & 0.10 & 0.12 \\ 0.15 & 0.20 & 0.10 & 0.40 & 0.14 \\ 0.20 & 0.18 & 0.12 & 0.14 & 0.35 \end{bmatrix} \text{ per MW}$$

First we present the optimal solutions of the DESRD, DEESRD and PDESRD problems, which correspond three values of the weighting factor $\omega = 1$, $\omega = 0.5$ and $\omega = 0$, respectively. The optimal solutions of these problems are given by Tables 6-8, respectively. Table 6 present the optimal power and spinning reserve schedule obtained from the solution of the DESRD problem. Table 7 summarizes hourly power and spinning reserve schedule obtained from DEESRD problem. Table 8 shows hourly power and spinning reserve schedule obtained from PDESRD problem

From these tables we can show that that, all constraints are satisfied and our results are accurate. In Table 9 we present a comparison between the three problems DED, DESRD, DEESRD, PDED and PDESRD problems in view of the cost, emission and transmission losses. We note that, the cost obtained from the DEESRD is 42486$ which is bigger than 41875$ obtained by DESRD and smaller than 42573$ obtained by PDESRD. Moreover, the emission obtained from the DEESRD is 18393lb which is bigger than 18367 obtained by PDESRD and smaller than 22222lb obtained by DESRD. Moreover, we can see that, both the cost and emission are higher, while the transmission line losses are lower in case of DESRD problem than that of the DED problem. The reason of this is due to that, the DESRD problem contains more constraints than the DED problem, that are constraints (3), (6) and (7). We also observe that, taking into account the spinning reserve in the dynamic dispatch problem will reduce the transmission line losses. Therefore, incorporating the spinning reserve into the DED problem maintains the security of the electrical power system but it increases both fuel cost and the amount of emission.

Our second target in this section is to show that the solution of the MPC converge to the optimal solutions of the DESRD, DEESRD and PDESRD problems. The initial power and spinning reserve are chosen such that

$$\sum_{i=1}^{N_G} p_i^1 = D^1 + Loss^1, \qquad SR_D^1 = 0.1D^1.$$

Figures 1, 6 and 11 show that the MPC solutions approach the optimal solution of the DESRD, DEESRD and PDESRD problems, respectively in a few hours.

To show the inherent robustness properties of the MPC (IRP-MPC), we consider two types of disturbances:

Table 6: Hourly power and spinning reserve schedule obtained from DESRD.

T	P_1	P_2	P_3	P_4	P_5	Loss	S_1	S_2	S_3	S_4	S_5
1	15.5843	71.4388	64.6857	117.1999	144.6906	3.5993	1.3829	6.8118	5.7538	15.9510	11.1004
2	16.6334	74.4170	71.8379	125.5019	150.6493	4.0394	1.3632	6.8816	5.8826	17.6570	11.7156
3	18.7373	79.7273	82.7465	138.8868	159.7033	4.8011	1.0861	6.0517	8.4046	19.1233	12.8343
4	21.0808	85.3087	99.7369	157.0939	172.7322	5.9525	1.2820	7.8003	7.8481	22.2525	13.8171
5	22.3012	88.4045	107.9975	166.5304	179.3575	6.5911	1.4121	8.3368	8.4195	23.4279	14.2037
6	24.4288	94.1452	122.7440	183.3576	191.1416	7.8173	1.7063	9.0217	9.4723	25.6295	14.9702
7	25.2505	95.9053	128.1457	189.4830	195.5001	8.2846	1.7605	9.6513	9.7402	26.3261	15.1219
8	26.5842	99.3405	136.3058	198.8323	201.9786	9.0415	1.7701	9.5660	10.5502	27.6935	15.8203
9	28.3466	103.6245	146.6082	211.3470	210.1405	10.0668	1.6975	9.8342	11.7804	28.8264	16.8615
10	28.8888	105.1597	150.7328	216.1873	213.5123	10.4809	1.9181	10.2434	12.0579	29.3325	16.8481
11	29.5572	107.1370	155.2099	221.7878	217.2744	10.9663	1.9862	10.3069	13.4076	28.2122	18.0870
12	30.3862	109.2930	161.9511	228.0759	221.8760	11.5822	2.9005	12.9045	13.0489	21.9241	23.2220
13	28.9071	105.1553	150.7284	216.1842	213.5058	10.4808	1.8873	10.2508	12.0635	29.3421	16.8562
14	28.3480	103.6240	146.6074	211.3488	210.1387	10.0668	1.6775	9.8375	11.7903	28.8289	16.8658
15	26.5870	99.3373	136.3012	198.8331	201.9829	9.0415	1.7667	9.5728	10.5549	27.6921	15.8135
16	23.1395	90.9580	114.5068	173.9667	184.5465	7.1175	1.6452	8.7578	8.8117	24.3330	14.4524
17	22.3270	88.3973	107.9861	166.5261	179.3545	6.5911	1.3892	8.3431	8.4325	23.4323	14.2029
18	24.4245	94.1452	122.7397	183.3624	191.1456	7.8174	1.6954	9.0287	9.4813	25.6257	14.9690
19	26.5732	99.3429	136.3025	198.8387	201.9842	9.0416	1.7737	9.5641	10.5579	27.6864	15.8179
20	28.8915	105.1594	150.7311	216.1902	213.5088	10.4809	1.9010	10.2516	12.0555	29.3344	16.8575
21	27.7571	102.6782	143.9685	207.4496	207.9221	9.7754	1.7376	9.2737	11.1986	29.2669	16.5233
22	24.2860	93.7773	121.8647	182.3651	190.4474	7.7407	1.6870	9.0241	9.4049	25.4769	14.9070
23	20.9663	85.0189	98.7972	156.0948	172.0091	5.8863	1.2559	7.5478	7.8997	22.1390	13.8577
24	17.9330	77.9711	79.2745	135.1779	157.2102	4.5668	1.4403	6.5292	8.0384	18.2524	12.0398
Cost=41875 \$ Emission=22222 *lb* Loss=191.8299*MW*											

Table 7: Hourly power and spinning reserve schedule obtained from DEESRD.

T	P_1	P_2	P_3	P_4	P_5	Loss	S_1	S_2	S_3	S_4	S_5
1	46.3855	59.6700	116.8015	112.1502	78.4381	3.4452	4.5579	6.4774	9.4529	12.5435	7.9683
2	50.0050	63.3498	123.0169	119.6002	82.9110	3.8828	4.9083	6.8831	9.9698	13.2964	8.4423
3	54.6588	69.5984	132.4562	131.7907	91.1343	4.6385	5.3552	7.5357	10.8442	14.5714	9.1934
4	61.0826	78.2002	145.4675	148.5713	102.4684	5.7901	5.9603	8.4375	12.0407	16.3409	10.2206
5	64.3560	82.5847	152.1075	157.1282	108.2503	6.4267	6.2679	8.9002	12.6466	17.2414	10.7438
6	70.2291	90.4248	163.9694	172.4201	118.6050	7.6484	4.7709	10.8408	11.0306	21.0522	13.1055
7	72.3507	93.2442	168.2526	177.9300	122.3374	8.1149	2.6493	12.7898	6.7474	24.8402	15.5733
8	75.0000	97.7592	174.9999	186.7942	128.3164	8.8696	0.0000	15.7051	0.0001	30.4382	19.2566
9	75.0000	106.5168	175.0000	203.7534	139.6447	9.9150	0.0000	16.5994	0.0000	32.2068	20.1937
10	75.0000	109.9189	175.0000	210.3214	144.1001	10.3404	0.0000	15.0811	0.0000	34.0098	21.3091
11	75.0000	113.7909	175.0000	217.8048	149.2439	10.8396	0.0000	11.2091	0.0000	32.1952	28.5957
12	75.0000	118.6269	175.0000	227.1590	155.6973	11.4832	0.0000	6.3731	0.0000	22.8410	44.7859
13	75.0000	109.9195	175.0000	210.3211	144.0998	10.3404	0.0000	15.0805	0.0000	34.0098	21.3097
14	75.0000	106.5169	175.0000	203.7534	139.6446	9.9150	0.0000	16.5995	0.0000	32.2070	20.1935
15	75.0000	97.7591	175.0000	186.7942	128.3163	8.8696	0.0000	15.7052	0.0000	30.4383	19.2565

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* Corresponding author e-mail: ah_moukh81@yahoo.com

16	66.9267	86.0354	157.3384	163.8445	112.8058	6.9508	6.5034	9.2630	13.1040	17.9770	11.1526
17	64.3567	82.5845	152.1079	157.1279	108.2498	6.4267	6.2670	8.9007	12.6460	17.2415	10.7448
18	70.2283	90.4246	163.9694	172.4205	118.6056	7.6484	4.7717	10.8417	11.0306	21.0514	13.1045
19	75.0000	97.7587	175.0000	186.7942	128.3167	8.8696	0.0000	15.7058	0.0000	30.4385	19.2558
20	75.0000	109.9195	175.0000	210.3209	144.1000	10.3404	0.0000	15.0805	0.0000	34.0104	21.3092
21	75.0000	104.1014	175.0000	199.0675	136.4487	9.6177	0.0000	16.3587	0.0000	31.7072	19.9341
22	69.8758	89.9550	163.2556	171.5018	117.9838	7.5720	5.1242	10.5166	11.7444	20.4212	12.6936
23	60.7329	77.7306	144.7569	147.6549	101.8486	5.7239	5.9269	8.3869	11.9748	16.2445	10.1668
24	53.2615	67.7241	129.6225	128.1304	88.6662	4.4046	5.2222	7.3376	10.5812	14.1907	8.9684
Cost=42486 \$ Emission=18393 *lb* Loss=188.0734*M W*											

Table 8: Hourly power and spinning reserve schedule obtained from PDESRD.

T	P_1	P_2	P_3	P_4	P_5	Loss	S_1	S_2	S_3	S_4	S_5
1	54.6435	57.1700	119.8642	110.0669	71.7045	3.4491	5.3548	6.4940	9.1763	12.1029	7.8720
2	57.9625	61.1394	125.5631	117.5148	76.7065	3.8863	5.6792	6.8957	9.7245	12.8633	8.3373
3	63.2785	67.4963	134.7026	129.4411	84.7232	4.6417	6.2012	7.5468	10.5955	14.0764	9.0801
4	70.6055	76.2461	147.3041	145.8621	95.7752	5.7930	4.3945	8.9030	12.4328	16.6067	10.6631
5	74.3348	80.7086	153.7406	154.2273	101.4182	6.4295	0.6652	10.1014	14.0794	18.8569	12.0970
6	75.0000	89.7511	166.8002	171.2121	112.8887	7.6522	0.0000	12.9491	8.1998	24.1656	15.4856
7	75.0000	93.0520	171.5755	177.4096	117.0828	8.1199	0.0000	14.5615	3.4245	27.1808	17.4333
8	75.0000	99.1675	175.0000	188.8723	124.8425	8.8823	0.0000	16.0980	0.0000	30.0611	19.2409
9	75.0000	108.1170	175.0000	205.6167	136.1953	9.9290	0.0000	16.8830	0.0000	31.8653	20.2517
10	75.0000	111.5997	175.0000	212.1269	140.6284	10.3550	0.0000	13.4003	0.0000	34.8504	22.1493
11	75.0000	115.5769	175.0000	219.5520	145.7261	10.8550	0.0000	9.4231	0.0000	30.4480	32.1290
12	75.0000	120.5457	175.0000	228.8354	152.1186	11.4997	0.0000	4.4543	0.0000	21.1646	48.3811
13	75.0000	111.5995	175.0000	212.1271	140.6285	10.3550	0.0000	13.4005	0.0000	34.8504	22.1490
14	75.0000	108.1170	175.0000	205.6165	136.1954	9.9290	0.0000	16.8830	0.0000	31.8655	20.2515
15	75.0000	99.1671	175.0000	188.8723	124.8428	8.8823	0.0000	16.0983	0.0000	30.0610	19.2407
16	75.0000	84.6199	159.3891	161.5687	106.3759	6.9536	0.0000	10.6385	14.7931	19.8649	12.7035
17	74.3365	80.7081	153.7401	154.2269	101.4179	6.4295	0.6635	10.1017	14.0799	18.8572	12.0976
18	75.0000	89.7509	166.8007	171.2121	112.8884	7.6522	0.0000	12.9492	8.1993	24.1655	15.4860
19	75.0000	99.1675	175.0000	188.8722	124.8426	8.8823	0.0000	16.0978	0.0000	30.0614	19.2408
20	75.0000	111.5997	175.0000	212.1269	140.6284	10.3550	0.0000	13.4003	0.0000	34.8505	22.1493
21	75.0000	105.6266	175.0000	200.9648	133.0397	9.6311	0.0000	16.7529	0.0000	31.3102	19.9370
22	75.0000	89.2013	166.0051	170.1795	112.1898	7.5756	0.0000	12.6803	8.9949	23.6634	15.1614
23	70.2032	75.7693	146.6153	144.9666	95.1725	5.7269	4.7968	8.7732	12.2563	16.3656	10.5081
24	61.6828	65.5891	131.9581	125.8615	82.3163	4.4079	6.0446	7.3500	10.3354	13.7121	8.8580
Cost=42573 \$ Emission=18367 *lb* Loss=188.2731*M W*											

Table 9: Comparison results for the dynamic dispatch problems with loss.

Problem	Cost	Emission	Loss
DED [66]	40121	20363	192.3639
DESRD	41875	22222	191.8299
DEESRD	42486	18393	188.0734
PDED [66]	40851	16546	188.299
PDESRD	42573	18367	188.2731

(i) Execution of the controller with disturbances. For this case we take

$$b^t_{p,i} = -\varepsilon_{p,i} + 2\varepsilon_{p,i} n(t), \quad b^t_{s,i} = -\varepsilon_{s,i} + 2\varepsilon_{s,i} n(t),$$

$$b^t_{u,j} = -\varepsilon_{u,j} + 2\varepsilon_{u,j} n(t), \quad b^t_{v,j} = -\varepsilon_{v,j} + 2\varepsilon_{v,j} n(t),$$

$$i = 1,\dots,5, \; j = 1,\dots,5, \; t = 2,3,\dots,$$

where $n(t)\in[0,1]$ is random variable taken from normal distribution. Let us choose two sets of bounds:

IRP-MPC-(I):

$$\varepsilon_{p,1}=3,\ \varepsilon_{p,2}=4,\ \varepsilon_{p,3}=2,\ \varepsilon_{p,4}=6,\ \varepsilon_{p,5}=3,$$
$$\varepsilon_{s,1}=2,\ \varepsilon_{s,2}=1,\ \varepsilon_{s,3}=2,\ \varepsilon_{s,4}=1,\ \varepsilon_{s,5}=2.$$

IRP-MPC-(II):

$$\varepsilon_{p,1}=9,\ \varepsilon_{p,2}=12,\ \varepsilon_{p,3}=6,\ \varepsilon_{p,4}=18,\ \varepsilon_{p,5}=9,$$
$$\varepsilon_{s,1}=6,\ \varepsilon_{s,2}=3,\ \varepsilon_{s,3}=6,\ \varepsilon_{s,4}=3,\ \varepsilon_{s,5}=6.$$

(ii) Demand with disturbances. Let us define the actual demand $\tilde{D}^t$ as:

$$\tilde{D}^t=\begin{cases}D^t & if \quad t=1\\ D^t+\varepsilon_D(1-2n(t))D^t & if \quad t=2,3,\dots,24\end{cases}$$

where $\varepsilon_D(1-2n(t))D^t$ is the relative change between the actual demand $\tilde{D}^t$ and the forecasted demand D^t. Since the forecasted spinning reserve load depend on the power demand, therefore, the actual spinning reserve equal to $0.1\tilde{D}^t$

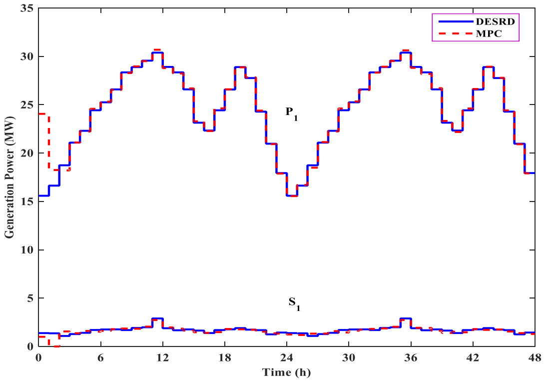

Fig. 1: Convergence of the MPC solutions to those of DESRD problem for the power and spinning reserve of unit 1.

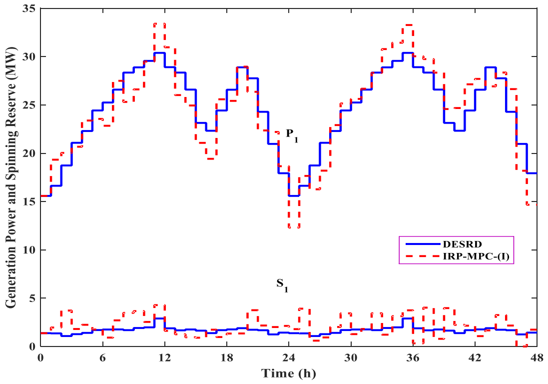

Fig. 2: The power and reserve of unit 1 under DESRD problem and IRP-MPC-(I).

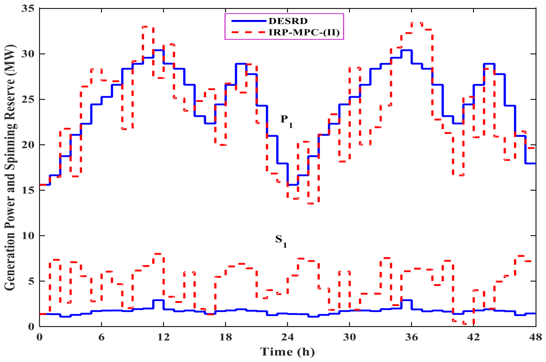

Fig. 3: The power and reserve of unit 1 under DESRD problem and IRP-MPC-(II).

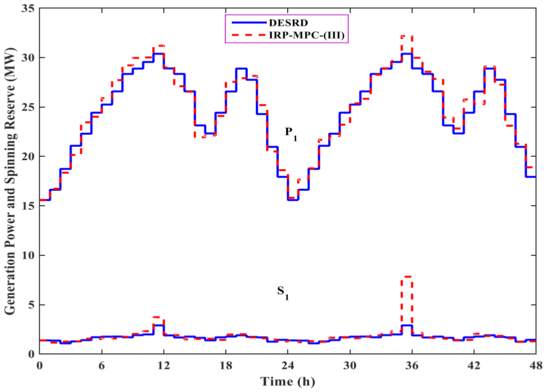

Fig.4: The power and reserve of unit 1 under DESRD problem and IRP-MPC-(III).

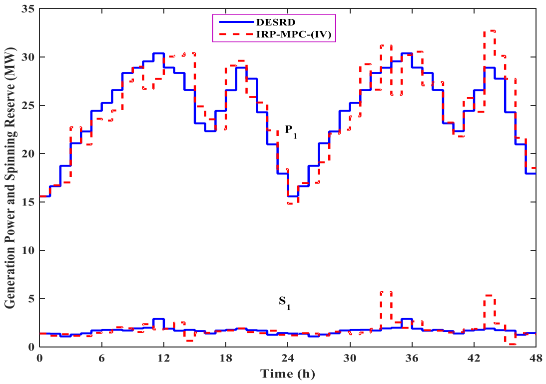

Fig. 5: The power and reserve of unit 1 under DESRD problem and IRP-MPC-(IV).

Now let us consider two values of ε_D:

IRP-MPC-(III): $\varepsilon_D={}^{5}\!/_{100}$,

IRP-MPC-(IV): $\varepsilon_D={}^{10}\!/_{100}$.

This means that the power demand is perturbed with 5% and 10% of the nominal one.

We have tested the MPC strategy against IRP-MPC-(I) , IRP-MPC-(II), IRP-MPC-(III) and IRP-MPC-(IV). In these cases the initial P^1 and S^1 for the MPC are chosen as the optimal solution of the DESRD, DEESRD and PDESRD problems. It has been shown in Figures 2, 3, 7, 8, 12 and 13 that the MPC can keep the solution near to the optimal solution of the DESRD, DEESRD and PDESRD problems.

From Figures 4, 5, 9, 10, 14 and 15, we can see that, in spite of increasing the disturbance, the MPC still has the robustness when applying to DESRD, DEESRD and PDESRD problems.

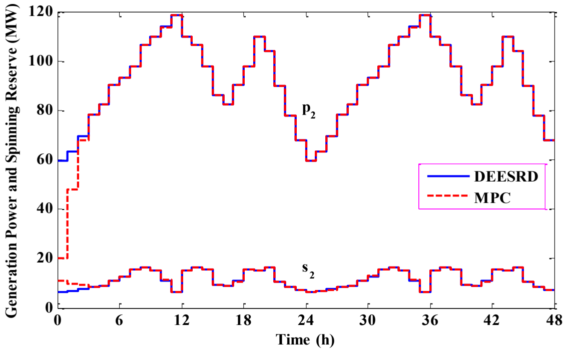

Fig. 6: Convergence of the MPC solutions to those of DEESRD problem for the power and spinning reserve of unit2.

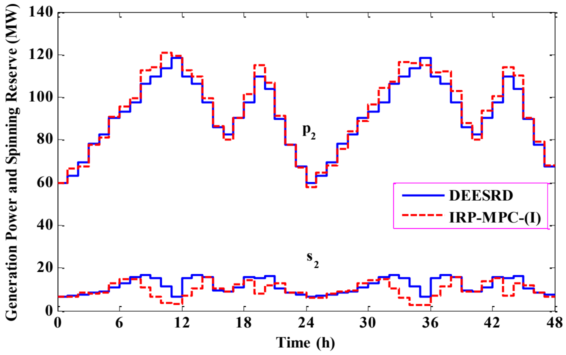

Fig.7: The power and reserve of unit 2 under DEESRD problem and IRP-MPC-(I).

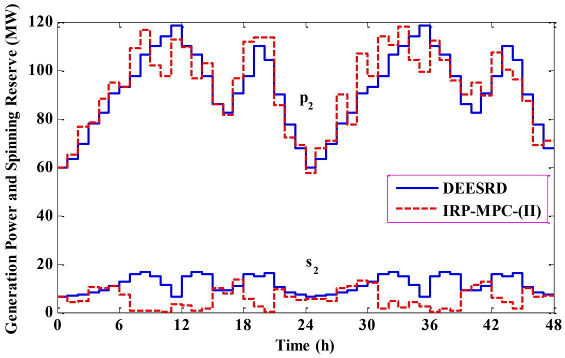

Fig. 8: The power and reserve of unit 2 under DEESRD problem and IRP-MPC-(II).

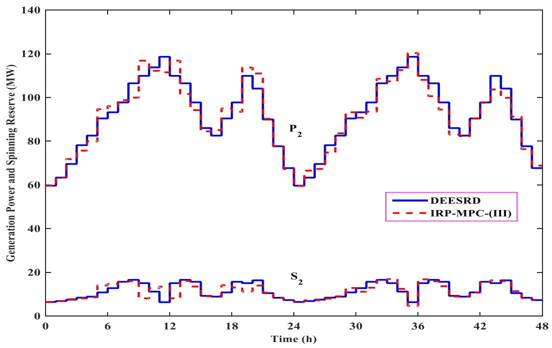

Fig. 9: The power and reserve of unit 2 under DEESRD problem and IRP-MPC-(III).

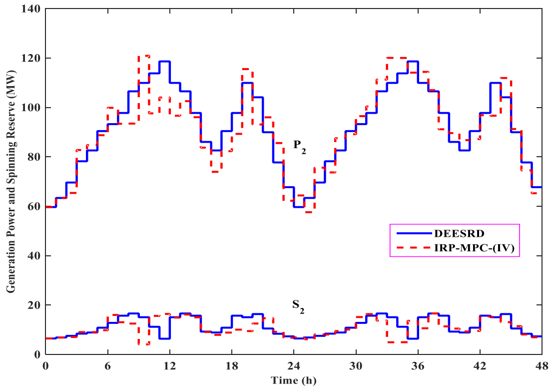

Fig. 10: The power and reserve of unit 2 under DEESRD problem and IRP-MPC-(IV).

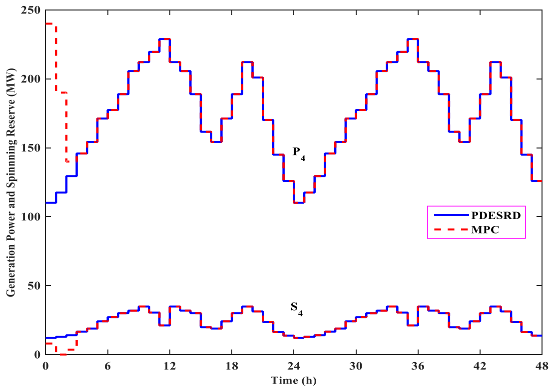

Fig.11: Convergence of the MPC solutions to those of PDESRD problem for the power and spinning reserve of unit 4.

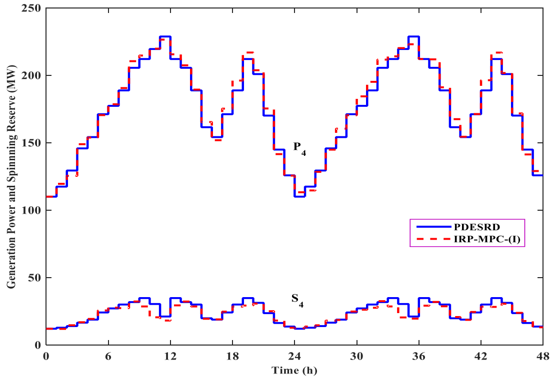

Fig. 12: The power and reserve of unit 4 under PDESRD problem and IRP-MPC-(I).

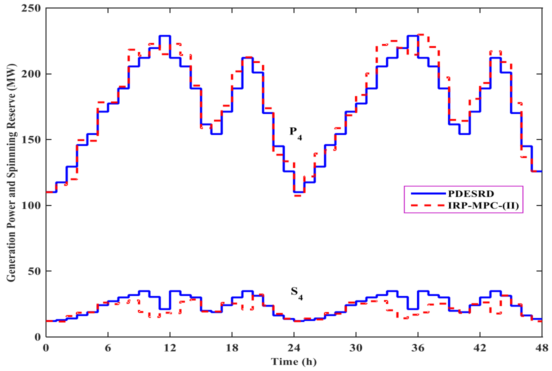

Fig. 13: The power and reserve of unit 4 under PDESRD problem and IRP-MPC-(II).

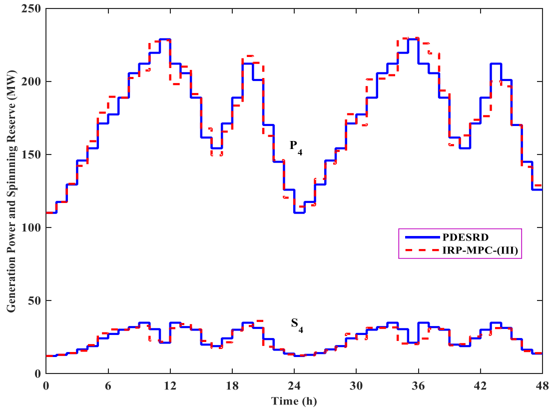

Fig. 14: The power and reserve of unit 4 under PDESRD problem and IRP-MPC-(III).

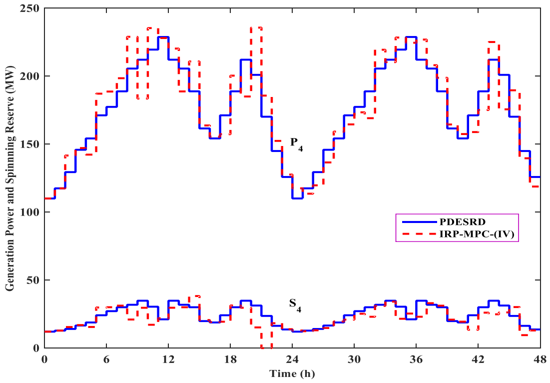

Fig. 15: The power and reserve of unit 4 under PDESRD problem and IRP-MPC-(IV).

5 Conclusions

Spinning reserve plays a more important role in maintaining the power system reliability and security against sudden load changes and generation outages. In this paper, we have formulated dynamic economic emission and spinning reserve dispatch (DEESRD) problem which integrates the spinning reserve into the DEED problem. DEESRD determines the optimal power and spinning reserve allocation by simultaneously minimizing the power and spinning reserve costs, and the amount of emission under dynamic constraints and other constraints. This problem helps GENCOs to participate in the market by submitting bids for both energy and reserve. Since the optimal solutions of the DEESRD problem are open-loop, we have introduced a suitable version of MPC approach to construct closed-loop solutions. The performance of the MPC has been investigated by applying the MPC strategy to the DEESRD problems with test system consisting of five generating units.

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Ahmed M. Shehata has received the Ph.D. degree from Al-Azhar University, Assiut, Egypt, in 2013. He is an assistance professor at Bisha University. His research interests include model predictive control, optimization, energy efficiency and power systems