JFE TECHNICAL REPORT
No. 26 (Mar. 2021)

Guidance for Fuel and Power Management in Steel Works Through Model Predictive Control

OGASAHARA Tomoyoshi[*1] HAYASHI Koji[*2] YOSHIHARA Koji[*3]

Abstract:

In order to reduce energy loss in steel works, JFE Steel has developed a management guidance system which uses a model predictive control technology. The system predicts the fuel and power supply and demand accurately based on the production plan at each plant. Based on the predictions, the system calculates the operation condition at each process to achieve minimum energy loss through mathematical programming method. The guidance system has improved the operation.

1. Introduction

In a steel works, the byproduct gases generated by upstream processes, that is, blast furnaces, coke ovens and LD converters, and the electric power and steam obtained in their recovery processes, are utilized by various plants and power generating installation in the works, and supply shortages with respect to demand for fuels, steam and electric power in the works are covered by outside purchases.

In the management outlined above, it is necessary to determine the allocation of byproduct gases and steam to each process, the amounts of electric power and fuels (heavy oil, city gas) to be purchased, the amounts of byproduct gases to be stored, *etc*. so as to minimize energy loss based on the energy supply-and-demand condition, the operating condition of power generating installation, contractual information such as the unit purchase prices of fuels and electric power, *etc*. Because the detailed production plans of each plant and a huge volume of measured data are necessary to grasp the supply-and-demand condition several hours in the future, it is difficult for operators in charge of energy management to conduct the optimum management at all times while predicting supply-and-demand conditions without the support of a computer system.

To date, various optimum plant management methods have been proposed.

Fukuyama *et al.* [1)] proposed an optimum operation system comprising (a) load prediction function, (b) plant modeling function and (c) optimum operation function. This system quantifies the management problem as mixed integer nonlinear programming (programming in which the constraints and objective functions include nonlinear integer variables), and searches for the optimum operating conditions corresponding to the demand prediction values obtained by the particle swarmoptimization method. Although an optimization method based on this type of prediction is also effective for fuel, steam and power management of a steel works, this method is not suitable for application to guidance systems if the size of the problem becomes too large because it is difficult to obtain the optimum solution in a short time (e.g., about 5 minutes).

One proposed optimization system for the steel works utilizes a technique of reducing the management problem to a mixed integer linear programming problem (programming in which the constraints and objective functions include linear integer variables), and providing guidance to operators regarding the optimum fuel supply to the power generating installation by

† Originally published in *JFE GIHO* No. 45 (Feb. 2020), p. 26−31

*2 Manager,
Energy Technology Sec.,
Energy Dept.,
West Japan Works (Kurashiki),
(currently, Staff General Manager, Iron & Steelmaking Sec., Technical Solution Dept., Global Business Development Division)
JFE Steel

*1 Senior Researcher Deputy Manager,
Cyber-Physical System Research & Development Dept.,
(currently, Rolling & Processing Research Dept.)
Steel Res. Lab.,
JFE Steel

*3 Staff Manager,
(currently, Staff Deputy General Manager)
Business Process Innovation Team,
JFE Steel

solving that problem [2].

A formulation method which expands this technique [2] to an optimum allocation problem for fuels, steam and power in the steel works has also been proposed [3]. Because this technique [3] optimizes the management of fuel, steam and power, which have mutually-interactive effects, it is considered to be more effective for reducing energy loss than using the technique of optimizing [2] only the fuel supply.

Since the optimal computations are performed by inputting predicted supply-and-demand values in the above-mentioned existing techniques [2, 3], errors in supply-and-demand calculations influence the calculation results and cause deviation from the optimum management conditions. Therefore, it was difficult to operate close to the optimum managemental conditions due to the large error in supply-and-demand predictions under conditions where supply and demand fluctuates greatly.

To solve this problem, JFE Steel developed a highly accurate supply-and-demand prediction model using the production plans of all plants, and developed a fuel and power management guidance system which provides operators with guidance on the management conditions for minimizing energy loss based on supply-and-demand predictions calculated using this model. This system utilizes model predictive control technology [4] which obtains the optimum management conditions by mathematical programming based on supply-and-demand predictions.

This paper presents an outline of the fuel, steam and power flow in a steel works, and then introduces the functions and applications of this guidance system.

2. Fuel, Steam and Power Flow in Steel Works

Figure 1 shows the fuel, steam and power flow in a steel works. In a steel works, byproduct gases, namely, blast furnace gas (B gas), coke oven gas (C gas) and LD converter gas (LD gas) generated by the blast furnaces, coke ovens and LD converters, respectively, and mixed gas (M gas), in which the heating value is adjusted by mixing those gases, are used by various manufacturing plants and power plants located in the steel works. In cases where the gas supply is insufficient for demand by plants in the works, that demand is satisfied by supplementary purchases of city gas, and when the gas supply for power plants falls short of the specified amount, this shortfall is covered with supplementary purchases of heavy oil. Because these supplementary fuels must be purchased from external sources, costs and energy loss are incurred, corresponding to the consumption of the fuels. Conversely, when the gas supply exceeds demand in the works, the gases are detoxified by combustion and then released into the

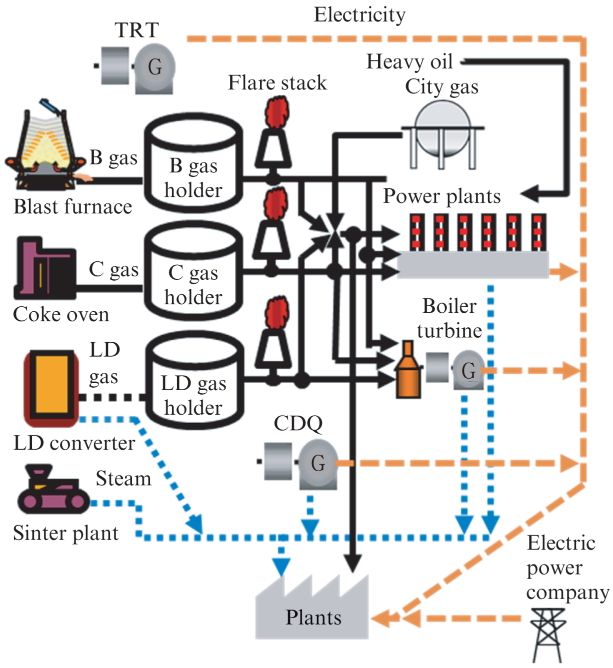

Fig. 1　Fuel, steam, and power flow in steel works

atmosphere, but this practice should be held to the minimum because it results in energy loss. To avoid these problems, it is necessary to adjust the use of gas holders (storage facilities for byproduct gases) and the amounts of gases allocated to plants. Steam for use in the works is supplied by converter gas, boilers for recovery of waste heat from sintering furnaces, the boilers of the coke dry quenching (CDQ) equipment and extraction of steam from the intermediate stage of turbines at power plants. When the supply of steam is inadequate for demand, steam is purchased from an external source. The electric power demand of production plants in the steel works is met by power generation by the CDQ, blast furnace top-pressure recovery turbine (TRT) and on-site power plants, together with purchases of power from electric power utilities when necessary. Power purchases must be managed so as not to exceed the contractual amount (purchase limit). It is also necessary change electric power management depending on the time period and supply-and-demand condition, the unit cost of electric power differs depending on the time period. For example, if there is a margin in the byproduct gas supply during a time period when the cost of electricity is high, the amount of purchased power is reducing by setting the output of the on-site power plants to a high level.

3. Guidance System

This chapter presents an overview of the developed guidance system and its functions.

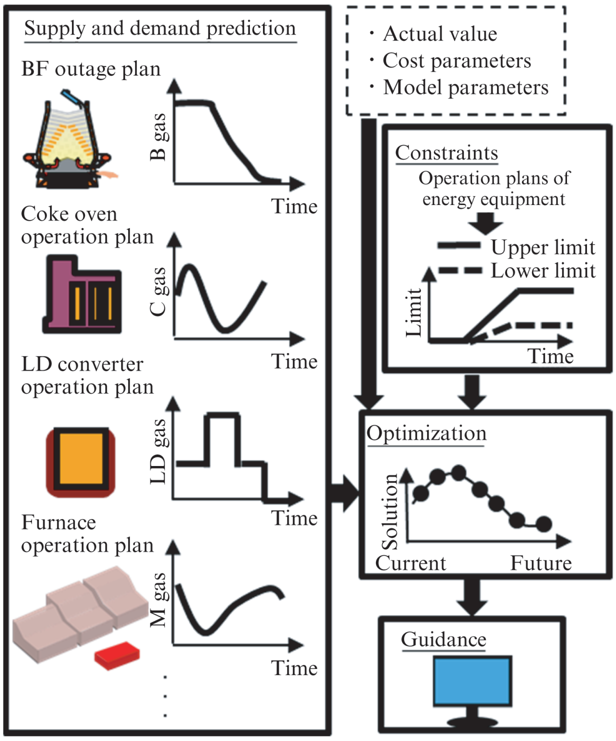

Fig. 2　Guidance system for fuel and power management

Table 1　Output and required inputs of each prediction model

Number of model	Output	Input
#1	B gas supply	・Blast furnace outage plan
#2	B gas demand	・Blast furnace outage plan ・Amount of throughput in coke oven
#3	C gas supply	・Amount of throughput in coke oven
#4	C gas demand	・Blast furnace outage plan ・Amount of throughput in coke oven
#5	LD gas supply	・Start/Finish time of blowing of O2 at LD converter ・Molten steel weight
#6	M gas demand	<Hot strip mill, Plate mill> ・Furnace: Insert and extraction time of each slab ・Dimensions and weight of each slab
#7	Electricity demand	<Hot strip mill, Plate mill> ・Furnace: Extraction time of each slab ・Dimensions and weight of each slab ・Rolling conditions of each slab
#8	Steam supply	・Start/Finish time of blowing of O2 at LD converter ・Operation plan of Sinter plant ・Operation plan of CDQ boiler
#9	Steam demand	<RH> ・Start/Finish time of RH processing ・Molten steel weight

3.1 Overview of Guidance System

The concepts of the Cyber-Physical System [5] and Society 5.0 [6] have been proposed in recent years. The aim of these concepts is to create value by concentrating the huge amount of data in physical space (big data) in cyberspace, analyze these data by various techniques and feed the results back to physical space. JFE Steel is also creating and improving its data infrastructure to promote development based on these concepts, and now has the capability to collect various types of measured data as well as the production plans of all plants. The company has also created an environment that enables comparatively fast solutions of mixed integer linear programming problems by enhancing the performance of the related solvers [7].

In order to achieve high accuracy in supply-and-demand predictions that cannot be solved with existing techniques, JFE Steel developed highly accurate supply-and-demand prediction models using the production plans of each plant, and developed a guidance system for fuel and power management which provides the optimum allocations of fuel and power in real time based on predictions calculated using the prediction models.

Figure 2 shows an overview of the guidance system. The system comprises a supply-and-demand prediction function, a constraint value generation system, optimum management simulation and a guidance function.

The supply-and-demand prediction function predicts supply and demand for fuels and electric power up to several hours in advance using a set calculation cycle. **Table 1** shows the outputs and required inputs for each prediction model. Here, the objects of predictions of #6 M gas demand and #7 electric power demand are limited to the hot strip mill and plate mill, which consume large amounts of M gas and power, and the object of #9 steam demand is the RH (secondary refining equipment). For other plants which consume comparatively small amounts, it is assumed that demand at the present point in time will continue in the future. The supply-and-demand prediction function is discussed in detail in section 3.3.

The constraint value generation function generates constraint values such as the lower limit for management of energy equipment (gas holders and power generating installation), which are necessary in the optimum management simulation based on the operation/stop plans of each facility.

Optimum management simulation obtains the management conditions for minimizing energy loss by solving a mixed integer linear programming problem expressing the management problem based on the supply-and-demand prediction values, constraint values, measured values, cost parameters such as the unit cost of electric power, which are necessary for calculating energy loss, and equipment model parameter data. For this problem, the management conditions from the present time to several hours in the future are calculated on the same calculation cycle as supply-and-demand predictions, and the optimum management conditions are obtained in time series. Details of the optimum management simulation are presented in the following section 3.2.

The guidance function provides guidance to operators by displaying the solutions obtained by the optimum management simulation, together with the current measured data.

3.2 Optimum Management Simulation

This section explains optimum management simulation, which obtains the optimum management conditions.

3.2.1 Formulation of optimization problem

The problem solved by this function is the problem of minimizing the evaluation function f under constraint conditions comprising linear inequality and linear equality constraints. The evaluation function and constraint conditions are expressed by Eq. (1) to Eq. (4).

• Evaluation function

$$f = c^T x \quad \text{(1)}$$

• Constraint conditions

$$Ax \le b \quad \text{(2)}$$
$$A_{eq} x \le b_{eq} \quad \text{(3)}$$
$$l_b \le x \le u_b \quad \text{(4)}$$

where, c, b, b_{eq}, l_b, and u_b are real number vectors, and A and A_{eq} are real number matrices. x is a decision variable vector (element: continuous variable or integer variable).

In this system, the sum of energy loss ($f_{loss}(k)$) and a penalty for evaluation of stability of management ($f_{penalty}(k)$) is set in the evaluation function f (Eq. 5). Here, the subscript k (=1, 2,..., N) indicates a time in the future. If the calculation cycle of the prediction value is T (min), this corresponds to a future time Tk (min) from the present. $f_{loss}(k)$ is the sum of the energy losses by consumption of fuels (heavy oil, city gas, steam), purchased power and generated electric power, and $f_{penalty}(k)$ is the sum of the value obtained by multiplying the temporal change in the decision variable and the amount of relaxation of the constraint conditions. Including $f_{penalty}(k)$ in the evaluation function suppresses temporal changes in the decision variables, and relaxation of the constraints makes it easier to obtain solutions. The evaluation function which is finally set is the total value until the final time N.

$$f = \sum_{k=1}^{N} \left(f_{loss}(k) + f_{penalty}(k) \right). \quad \text{(5)}$$

Next, the constraint conditions set in this paper will be presented.

3.2.2 Gas and steam balance constraints

These are equality constraints which require that the supply and demand (consumption) of the various gases (B gas, C gas, LD gas, M gas) and steam must be equal at all times. As an example, Eq. 6 shows the equality equation of the balance constraint of B gas.

$$\sum_{i=1}^{n_{Bs}} S_{Bi}(k) = \sum_{j=1}^{n_{Bd}} D_{Bj}(k), \quad k = 1, 2, \cdots, N. \quad \text{(6)}$$

where, n_{Bs}: number of supply facilities (i.e., blast furnaces), n_{Bd}: number of demand facilities, $S_{Bi}(k)$: amount of B gas supply from the i-th blast furnace (GJ/h) and $D_{Bj}(k)$: amount of consumption of B gas by facility j (GJ/h) (includes gas intake/payout of gas holders). $S_{Bi}(k)$ is a prediction value, and $D_{Bj}(k)$ is the prediction value of the decision variable.

3.2.3 Gas holder model

In a steel works, gas holders are installed for each type of gas and have the role of eliminating supply-and-demand imbalances by adjustment of the amount of gas intake/payout by the holder.

The constraint equations for the gas holder level are shown in Eq. 7 and Eq. 8.

$$H_L(1) = H_{LMea} + H_G(1)T/60, \quad \text{(7)}$$
$$H_L(k) = H_L(k-1) + H_G(k)T/60, (k = 2, \cdots, N). \quad \text{(8)}$$

where, $H_L(k)$: gas holder level (GJ), $H_G(k)$; amount of gas holder intake/payout (GJ/h), H_{LMea}: measured value of gas holder level (GJ) and T: cycle (min). Here, $H_L(k)$ and $H_G(k)$ are the decision variables.

The upper and lower limits for management are set in $H_L(k)$ and $H_G(k)$, and the constraints shown in Eq. 9 and Eq. 10 are imposed to respond to those limits.

$$L_{H_L} \le H_L(k) \le U_{H_L}, \quad \text{(9)}$$
$$L_{H_G} \le H_G(k) \le U_{H_G}. \quad \text{(10)}$$

The upper and lower limit constraints shown in Eq. 11 and Eq. 12 are imposed for temporal changes in $H_G(k)$.

$$\Delta L_{H_G} \le \left(H_G(1) - H_{GMea} \right) / (T/60) \le \Delta U_{H_G}. \quad \text{(11)}$$
$$\Delta L_{H_G} \le \left(H_G(k) - H_G(k-1) \right) / (T/60) \le \Delta U_{H_G}, \quad (k = 2, 3, \cdots, N). \quad \text{(12)}$$

3.2.4 Power balance model

This is an equality constraint which requires that the total of the power generated in the works (TRT, CDQ, power generating installation) and the power purchased from external power suppliers must equal the amount of demand (consumption) of plants in the steel works.

3.2.5 Power generating installation model

As an example, the following explains the power plant model of a thermal power generating installation which generates power using the various byproduct gases (B gas, C gas, M gas) and heavy oil as fuels, as shown in **Fig. 3**. This plant converts high pressure steam, which is generated corresponding to the total heating value of the byproduct gases and heavy oil, to the rotational energy of the turbine that drives the generator. This can be regarded as a system in which the total heating value of the byproduct gases and heavy oil is the input, and the generated electric power is the output. The input-output characteristics of this system are nonlinear. As shown in **Fig. 4**, these input-output characteristics are expressed by a piecewise linear function comprising M inflection points, which is expressed as follows:

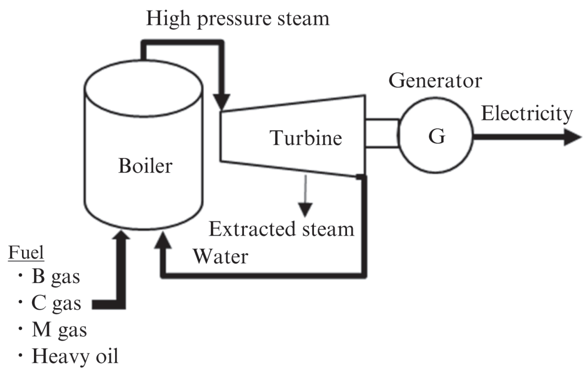

Fig. 3 Thermal power plant

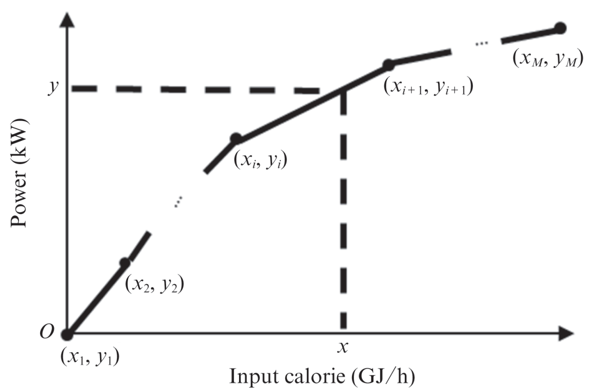

Fig. 4 Curve approximation through piecewise linear function

$(x_1, y_1), (x_2, y_2)\ldots(x_M, y_M)$
where, $x_1 < x_2 < \ldots x_M$

This function can be described by the total input calorie x (k) (GJ/h) at each time k, and the equality constraint and inequality constraint [8] expressing the relationship with the amount of generated power y (k) (kW) corresponding to the input calorie values.

In addition, power generation decreases when steam is extracted from the turbine intermediate stage to satisfy steam demand. In order to consider the condition, if the volume of steam extraction is V_{Es} (k) (ton/h) and the constant showing the resulting decrease in power generation is $\alpha_{ES} < 0$ (kW/(ton/h)), the power generation considering steam extraction y' (k) (kW) can be described by the equality constraint shown in Eq. 13.

$$y'(k) = y(k) + \alpha_{Es} V_{Es}(k) \quad \text{(13)}$$

When the C gas calorie V_C (k) allocated to a certain power plant is equal to or lower than a regulated amount V_{th}, it is necessary to use heavy oil at a regulated amount of L_{HO} or more. This type of IF-THEN rule in mixed integer programming can also be described as an inequality constraint. If a binary variable (decision variable δ_C (k)) is introduced, in which the case where the C gas calorie V_C (k) is equal to or smaller than a regulated value V_{th} is 1, and the case where V_C (k) is larger than V_{th} is 0, the above-mentioned rule can be expressed by the inequality equation shown in Eq. 14.

$$-M\delta_C(k) + \epsilon \le V_C(k) - V_{th} \le M\left(1 - \delta_C(k)\right) \quad \text{(14)}$$

where, M is an extremely large constant, and ε is a small constant. The lower limit constraint of the heavy oil calorie V_H (k) can be described by the inequality in Eq. 15 by using δ_C (k).

$$V_H(k) \ge \delta_C L_{HO} \quad \text{(15)}$$

In this connection, in the optimum management simulation, allocation calculations are performed by the branch and bound method [9] so as to minimize heavy oil consumption from the viewpoint of energy loss. The branch and bound method is a technique for efficiently searching solutions to optimization problems that include discrete variables. Among the feasible solutions (solutions that satisfy all constraints, not limited to the optimum solution), this technique searches only candidate solutions with a possibility of improving the evaluation function, and does not search solutions with no prospect of improvement, by solving problems in which some discrete variables are relaxed to continuous variables, and comparing the values of those evaluation functions and the evaluation functions of feasible solutions. This avoids listing all combinations of the values of discrete variables.

3.2.6 Constraints for minimizing temporal change in decision variables

Excessive temporal change in the decision variables for fuel allocation, *etc*. are minimized by including those changes in the penalty ($f_{penalty}(k)$) of the evaluation function. The following presents the constraint equation for calculating the absolute value of temporal changes.

Assuming a certain fuel allocation decision variable is $V_x(k)$, the decision variable expressing the maximum value of the magnitude of its temporal changes is $\Delta V_x(k) \geq 0$ and the measured value at the present time is I_x, the inequality constraints shown by Eq. 16 and Eq. 17 are imposed.

$$-\Delta V_x(1) \leq \left(V_x(1) - I_x\right)/(T/60) \leq \Delta V_x(1), \quad \cdots \quad (16)$$

$$-\Delta V_x(k) \leq \left(V_x(k) - V_x(k-1)\right)/(T/60) \leq \Delta V_x(k), \quad (k = 2, 3, \cdots, N). \quad \cdots \quad (17)$$

Further, assuming the weighting constant $\alpha_x \geq 0$, the penalty term of evaluation function is set as shown in Eq. 18.

$$f_{penalty}(k) = \alpha_x \Delta V_x(k) \quad \cdots \quad (18)$$

3.2.7 Other constraints

Although the details of other constraints will be omitted here, for example, constraints are also applied to the following:

- Purchased power constraint
- Equipment management modes and management rules
- Constraints for considering operational risks such as fuel/steam shortages, *etc*.
- Upper/lower limits and speed of changes in fuel and steam allocation amounts

3.3 Supply-and-Demand Prediction Function

This is a function for predicting the supply and demand of fuels and electric power. In this section, prediction of LD gas generation will be explained as one example.

LD gas is generated by the decarburization reaction that occurs during refining in the LD converter. The volume of LD gas generated depends on the hot metal treatment amount, the converter blowing pattern and other factors. In this system, the operational information which is necessary for predictions is collected from the process computer used in converter operation in real time at a certain cycle, and the amount of LD gas generation is calculated by a multiple regression model using that information as the explanatory variable.

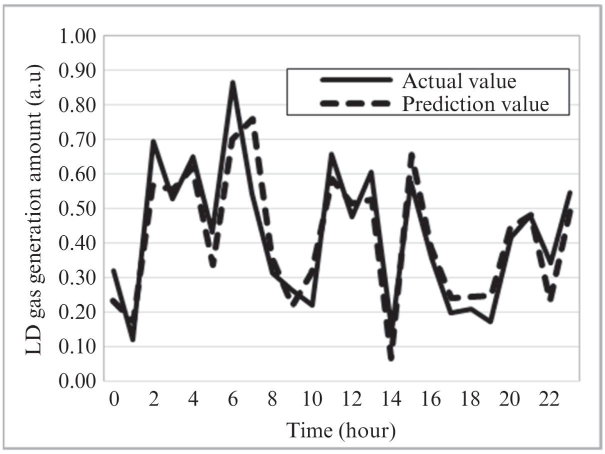

Fig. 5 Comparison between prediction and measurements of LD gas generation

Figure 5 shows a time-series comparison of the measured values and predicted values. Highly accurate prediction is possible, corresponding to increases and decreases in the amount of LD gas generation (measured values) depending on convert operation.

4. Calculation Example and Results of Actual Management

This chapter presents an example of a calculation, and then describes the energy loss reduction effect achieved by actual management of the guidance system.

Figure 6 shows an example of a power generating installation output calculation. In order to minimize the amount of power purchased during daytime, which has a large effect on energy loss, a large amount of gas is allocated to the plant and output is set at a high level during this time period.

Next, the effects of actual management will be

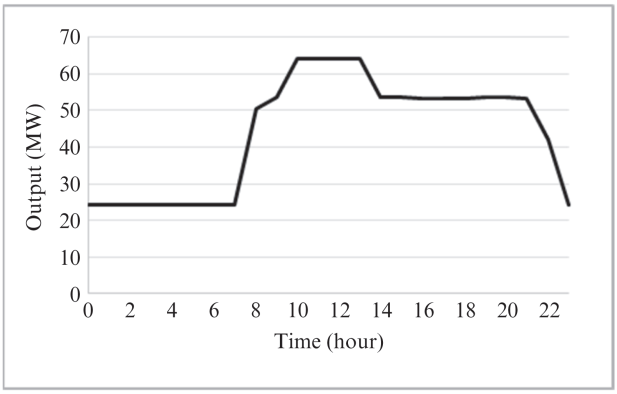

Fig. 6 Calculation result: output of power plant

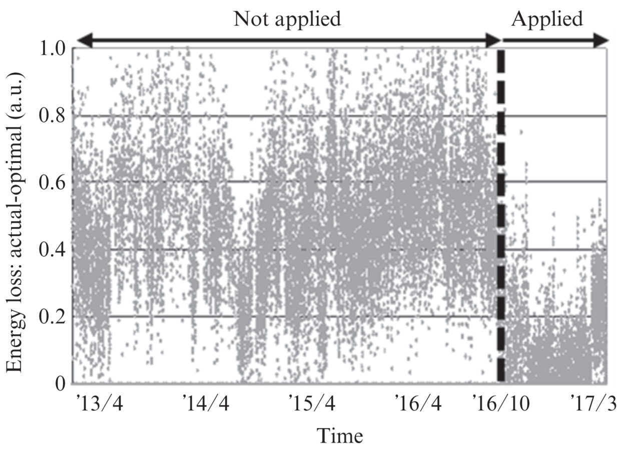

Fig. 7 Trend of difference between actual energy loss and optimal energy loss

explained. Conducting energy management in accordance with the guidance system reduces the difference between the actual energy loss and the optimal energy loss, and the energy loss reduction effect is expressed by that reduction. **Figure 7** shows a time-series chart of the difference between the actual value and the optimal value (=actual value — optimal value). As the value of energy loss on the ordinate approaches 0, the actual management approaches the optimal management condition. Because the difference between the actual energy loss and optimal energy loss decreased after this system was applied in October 2016, it can be understood that the system is contributing to reduction of energy loss.

5. Conclusion

- JFE Steel developed a fuel and power management guidance system for the purpose of minimizing energy loss.
- This system consists of a supply-and-demand prediction function that predicts the supply-and-demand condition of fuels and electric power with high accuracy based on the production plans of each plant, a constraint generation function that generates the constraint values necessary in optimum management simulations based on the operating condition of the equipment, the optimum management simulation function utilizing model predictive control technology, which obtains the management conditions for minimizing energy loss by mathematical programming, and the guidance function.
- Fuel and power management was improved by application of this system.

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