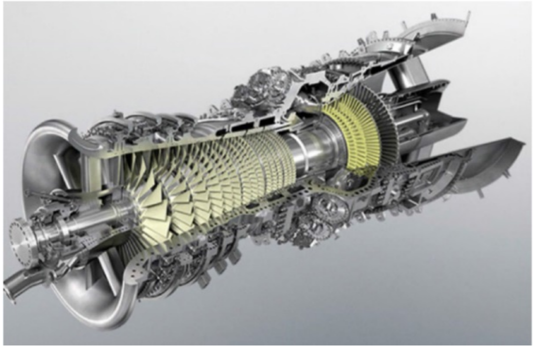
Next-Generation Gas Turbine Control for High Ramp Rate and Stable Combustion



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In order to deal with power output fluctuations caused by the increase in renewable energy, gas turbines for power generation are required to handle high ramp rates more than ever before. To enable high ramp rates, it is essential to achieve stable combustion under transient conditions and to improve controllability of the power output and turbine inlet temperature. In addition, keeping the turbine inlet temperature high even during transient conditions enables higher efficiency and lower CO_2 emissions. To realize these goals, Mitsubishi Heavy Industries, Ltd. (MHI) has developed a next-generation gas turbine control that combines a turbine inlet temperature estimation method based on a physical model and model predictive control that performs anticipatory control. This report outlines this technology and describes its verification status at our power plant validation facility.

1. Introduction

Beginning with the adoption of the Paris Agreement at the 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21) in 2015, the movement toward carbon neutrality has accelerated worldwide. The United States, the EU, and Japan have declared their goal of achieving carbon neutrality by 2050. In response to this trend, the share of natural energy, including renewable energy, in the total electricity generated in Japan exceeded 20% in 2021, which was a significant increase from 12% in 2014. The increased use of renewable energy contributes to CO_2 reduction. However, the amount of electricity generated using renewable energy depends on environmental conditions from time to time and is subject to large fluctuations, which is a disadvantage. In order to absorb these fluctuations in power generation, thermal power plants are required to operate flexibly such as high ramp rates, and the gas turbine combined cycle (GTCC), which emits the least amount of CO_2 among thermal power plants, is required to realize higher ramp rate operation than ever before.

On the other hand, stable operation of a gas turbine, one of the main components of a GTCC, requires precise control. If the fuel and air input balance is not appropriate, there is a risk of causing serious equipment damage due to combustion instability or temperature limit exceedance. When the ramp rate is increased, it becomes difficult to achieve stable operation with proper control of fuel and air. Therefore, we have developed a next-generation gas turbine control based on model predictive control.

The following chapter 2 provides an overview of the next-generation gas turbine control, chapter 3 describes the simulation and verification status at the power plant validation facility, and chapter 4 provides a summary.

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2. Next-generation gas turbine control

Figure 1 shows the configuration of our large stationary gas turbine. The gas turbine consists of the main components of a compressor, combustor, and turbine. Compressed air is combusted to generate over 1,600°C and over 2 MPaG, high-temperature and high-pressure combustion gas, which is then converted into power by the turbine.

The existing gas turbine control method and the next-generation gas turbine control method currently under development are overviewed below.

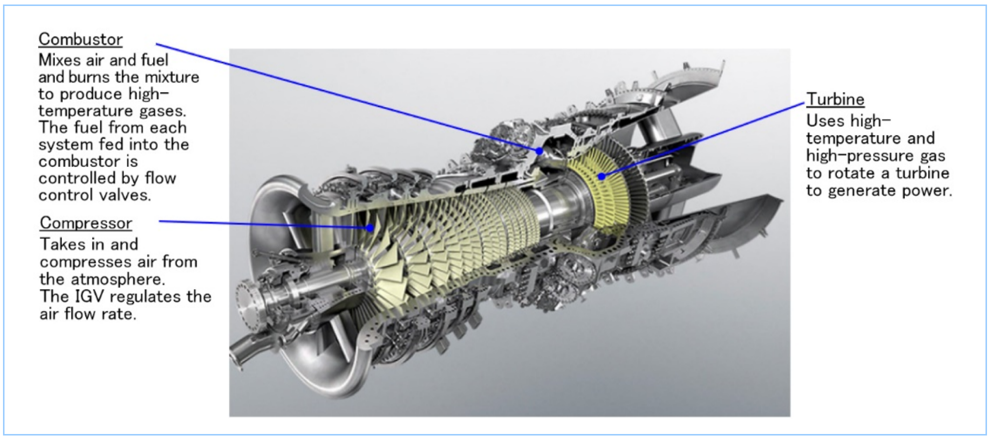

Figure 1 Configuration of stationary gas turbine

2.1 Overview and issues of existing gas turbine control method

(1) Existing gas turbine control method

During normal operation, gas turbines for power generation are operated at a constant speed to keep the power output following the demand. The power output is increased by increasing the fuel flow rate with the fuel flow control valve and the intake air flow rate with the inlet guide vane (IGV) at the compressor inlet, thereby increasing the working combustion gas flow rate and the combustion temperature of the gas turbine.

Figure 2 shows a conceptual diagram of the existing gas turbine control. The fuel flow rate is controlled by feedback control so that the power output follows the target value, and the fuel flow rate command is determined. The air flow rate is controlled by determining the opening of the IGV according to the preset table setting with respect to the power output.

The fuel distribution control of the combustor nozzle distributes the total fuel flow determined by the upper control to the multiple fuel systems. Fuel commands to each system are calculated by multiplying the total fuel flow rate command by the distribution ratio setting, which is calculated according to the table setting based on the turbine inlet temperature. However, since the turbine inlet temperature is very high and cannot be measured, a simple estimate calculated from the performance map using key state quantities such as power output and IGV opening is used.

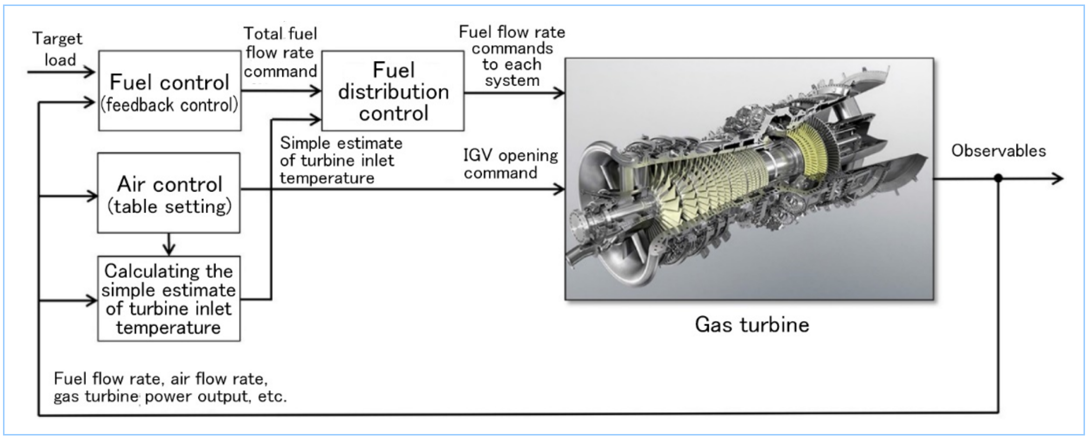

Figure 2 Conceptual diagram of existing gas turbine control

(2) Issues with existing gas turbine control

Issues with the existing gas turbine controls are listed below.

(i) Simultaneous attainment of stable combustion control and high ramp rate

The combustor of a gas turbine can achieve stable combustion when the fuel distribution is set appropriately according to the operating conditions. If the fuel distribution is not appropriate, there is a risk of combustion instability. As shown in (1), the fuel distribution is calculated using simple estimates based on the key state quantities and performance map. However, in the case of high-ramp rate operation, the accuracy of turbine inlet temperature estimation deteriorates, resulting in deviations from the appropriate fuel distribution according to the turbine inlet temperature.

When the load on the gas turbine changes, the injection of fuel and air is determined so as to achieve the preset operating line (power output and turbine inlet temperature settings), but as the ramp rate increases, the actual operating line deviates from the target line, increasing the risk that stable operation cannot be achieved (**Figure 3**).

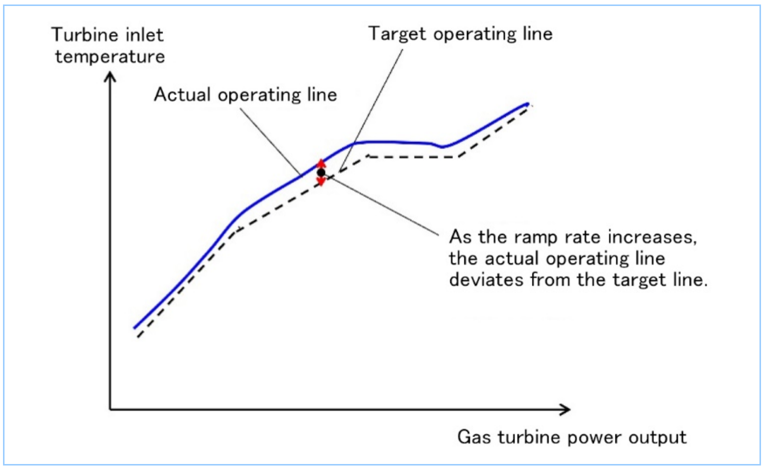

Figure 3 Deviation from target turbine inlet temperature operating line

(ii) Improvement of power output following performance near the rated output

When the power output rises near the rated load, the power output following performance deteriorates because the power output rise rate is suppressed so that the turbine inlet temperature does not exceed the upper limit from the standpoint of equipment protection (**Figure 4**).

(iii) Realization of high-efficiency operation under partial load conditions and reduction of CO_2 emissions

One method for achieving high-efficiency operation and reducing CO_2 emissions is to keep the turbine inlet temperature high even under partial load conditions. With the conventional control method, it is necessary to conduct partial load operation with a margin with respect to the upper temperature limit due to concerns about excessive turbine inlet temperature rise (**Figure 5**).

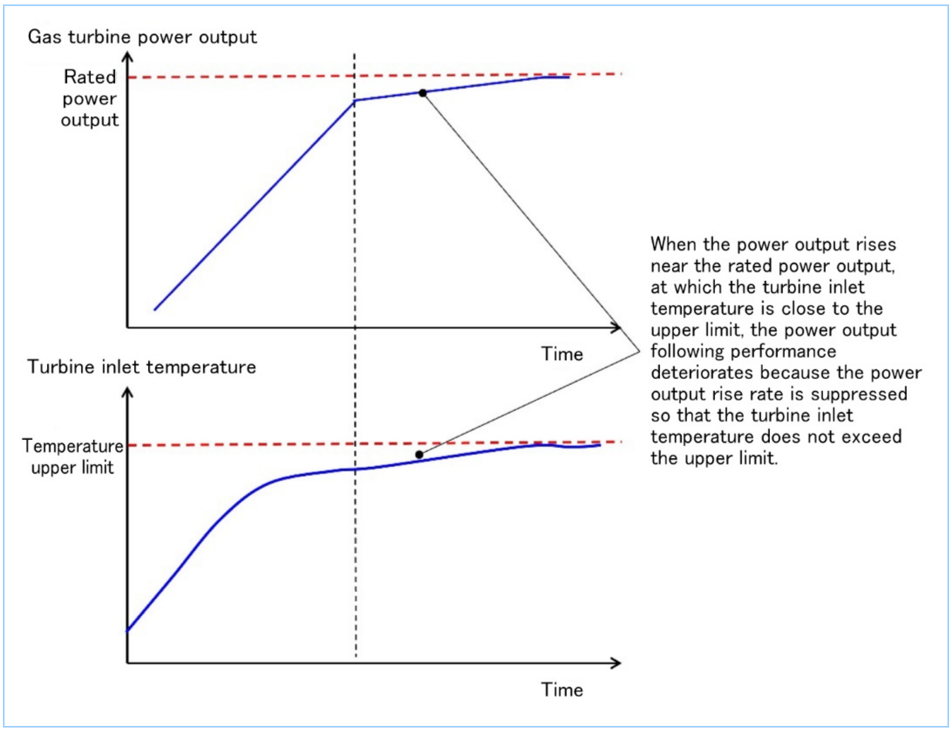

Figure 4 Deterioration of power output following performance near the rated power output

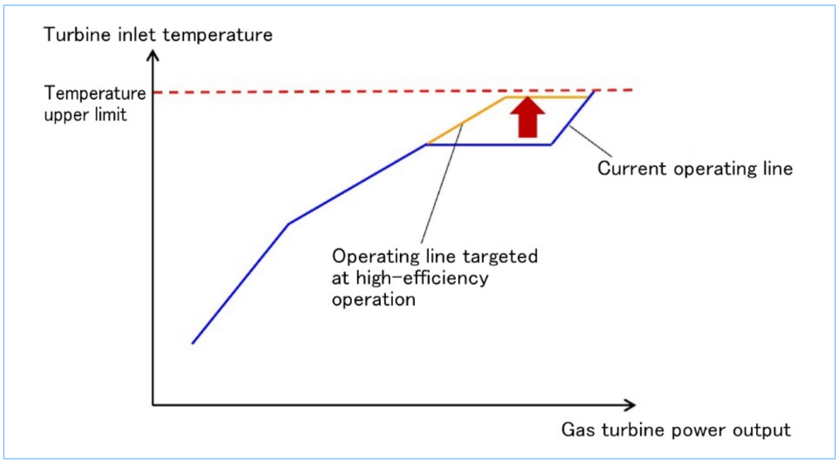

Figure 5 High efficiency operating line of current operating line of turbine inlet temperature operation

2.2 Next-generation gas turbine control

In order to solve the issues described in section 2.1, we are developing a next-generation gas turbine control to achieve high following performance and stable operation even at high ramp rates. **Figure 6** shows a conceptual diagram of the next-generation gas turbine control. While the conventional control (described in section 2.1) does not control the turbine inlet temperature directly because it was difficult to evaluate accurately in real time, the feedback control is simultaneously used to improve the control accuracy of the turbine inlet temperature, in addition to the power output, for the next-generation gas turbine control. The technological features of this method are (1) accurate turbine inlet temperature calculation using turbine inlet temperature estimation based on a physical model, and (2) improved following performance using model predictive control, which predicts future behavior. The details are explained below.

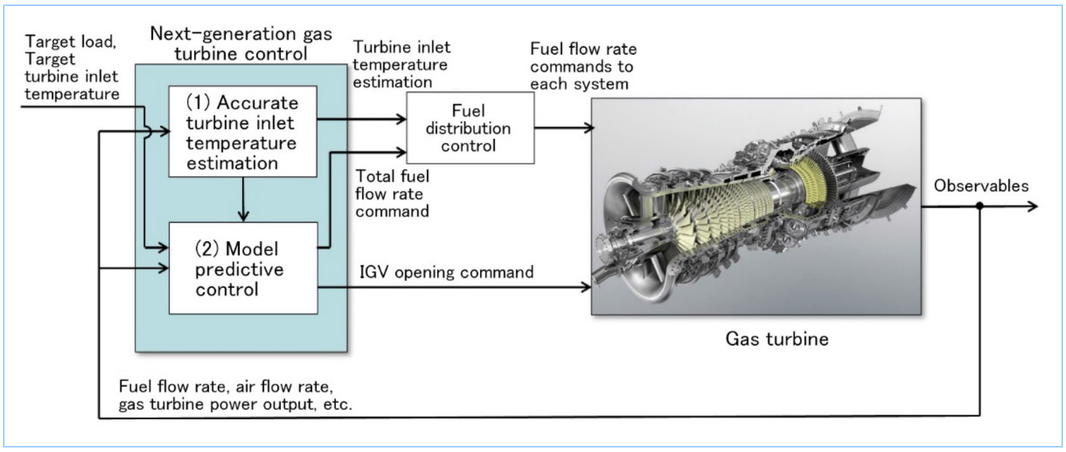

Figure 6 Conceptual diagram of next-generation gas turbine control

(1) Turbine inlet temperature estimation based on physical model

We developed a method to accurately calculate the turbine inlet temperature, which is an important state quantity as an indicator of combustion control. The unique feature of this method is that it combines two physical models to achieve both static accuracy and transient behavior accuracy. **Figure 7** shows an overview of this method.

The first physical model calculates an accurate turbine inlet temperature by calculating the heat balance using sensor values for the entire gas turbine, such as exhaust gas temperature and gas turbine power output. However, this physical model has the disadvantage that its accuracy can only be guaranteed in a stabilized state due to the large delay in sensor measurement. The second physical model calculates the turbine inlet temperature without delay by calculating the heat balance around the combustor. However, this physical model has errors in the model equation for fuel flow rate calculation, so that the accuracy of the absolute value is insufficient. By correcting the error in the calculated fuel flow rate in the second physical model with the true value of the fuel flow rate calculated from the stable state data in the first physical model, it becomes possible to determine the turbine inlet temperature with high accuracy in both stable and transient operations.

By using the turbine inlet temperature estimates calculated with this method, which are highly accurate and free from transient deviations, as input values for fuel distribution control and model predictive control as described in (2) below, stable combustion and high-ramp rate operation can be achieved.

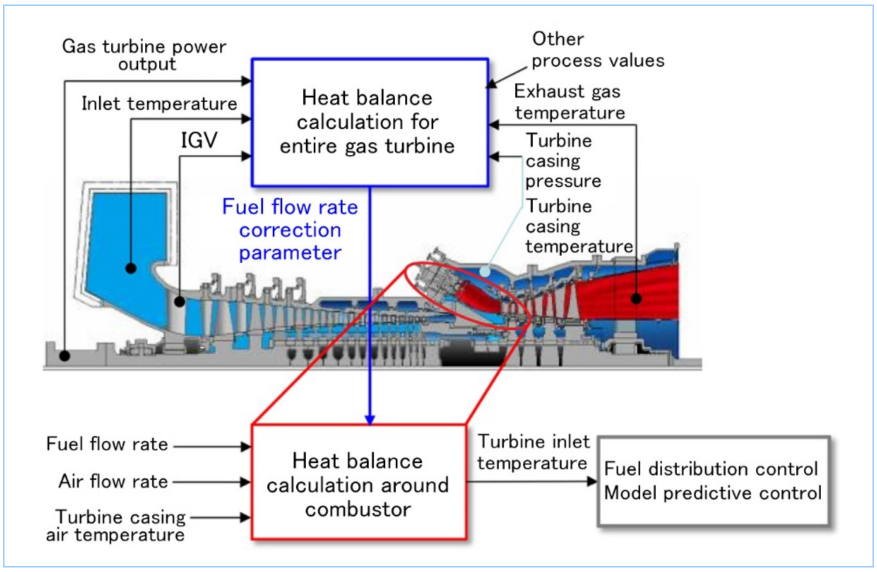

Figure 7 Turbine inlet temperature estimation based on physical model

(2) Anticipatory control of gas turbine power output and turbine inlet temperature based on model predictive control

Model predictive control is a method of calculating control inputs by repeating optimization calculations at each step, taking into account constraint conditions while predicting future behavior based on a "prediction model" that represents the behavior of the target. Using an analogy of driving a car, it is easy to understand the process by imagining a series of actions of predicting future behavior based on the shape of the curve in front of you and the driving status of the car in front of you, tracing the center of the lane, and operating the accelerator pedal and steering wheel early to avoid colliding with the guardrails or cars in front (**Figure 8**).

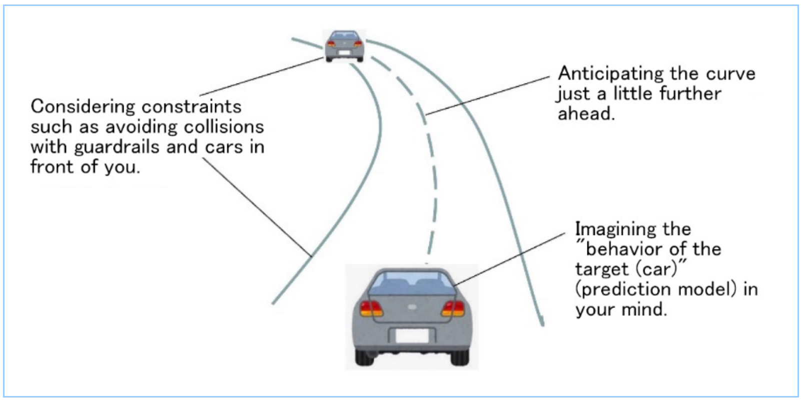

Figure 8 Analogy between driving a car and model predictive control

Details of applying model predictive control to a gas turbine are described below. A target trajectory is set for the gas turbine power output and turbine inlet temperature up to a few seconds into the future. The future behavior of the gas turbine is predicted using a "prediction model" that represents the behavior of the gas turbine to follow this target trajectory, and the fuel flow rate command and IGV opening command are calculated at each step by optimizing an evaluation function that considers the trade-off between the target trajectory following performance and the stability (**Figure 9**). This method enables the gas turbine power output and turbine inlet temperature to follow the target values with high accuracy.

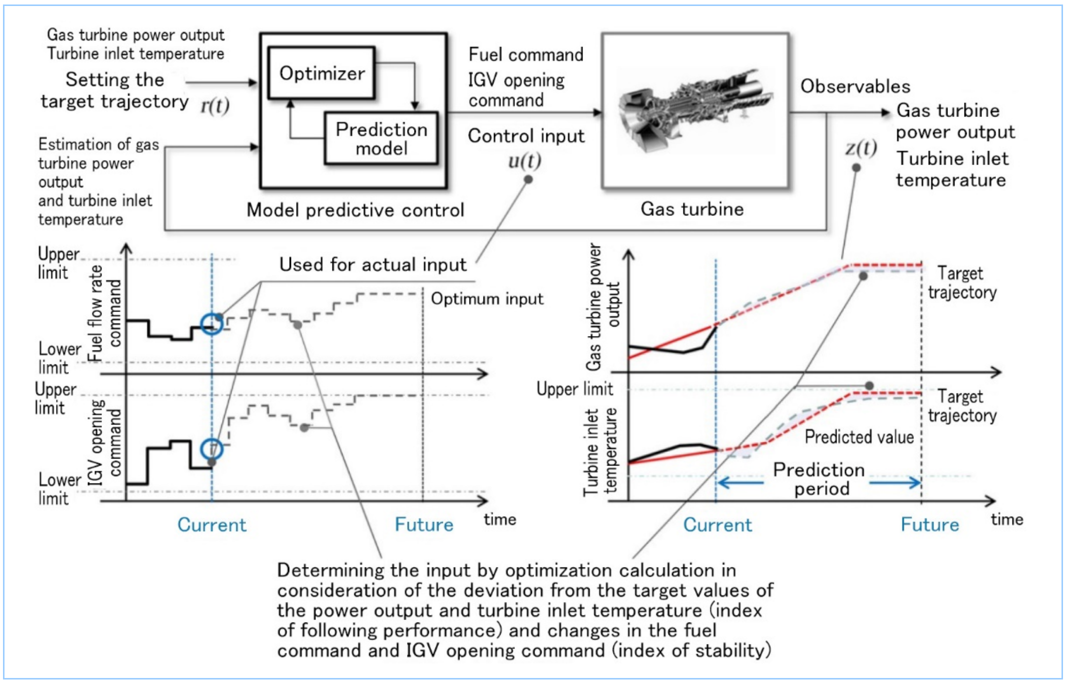

Figure 9 Model predictive control for gas turbine

3. Verification using simulation and verification at power plant validation facility

To verify the operation of the next-generation gas turbine control system developed in chapter 2, we conducted simulation verification using dynamic response analysis and verification of the actual system at our power plant validation facility in Takasago Machinery Works.

3.1 Verification using simulation

We have dynamic analysis technology to calculate the behavior of plant pressure, temperature, flow rate, etc., in a time series. Using a general-purpose analysis tool (MATLAB/Simulink), we constructed dynamic analysis models of the gas turbine, conventional gas turbine control, and next-generation gas turbine control, and simulated various operations, including load changes, to verify the operation and control performance (**Figure 10**).

In addition to the above desktop analysis, HILS (Hardware in the Loop Simulation) verification was conducted as the next-step verification. This is a real-time simulation using a controller for the actual equipment, and it was verified that the control algorithm could be implemented on the actual controller as specified and that the intended operation could be realized.

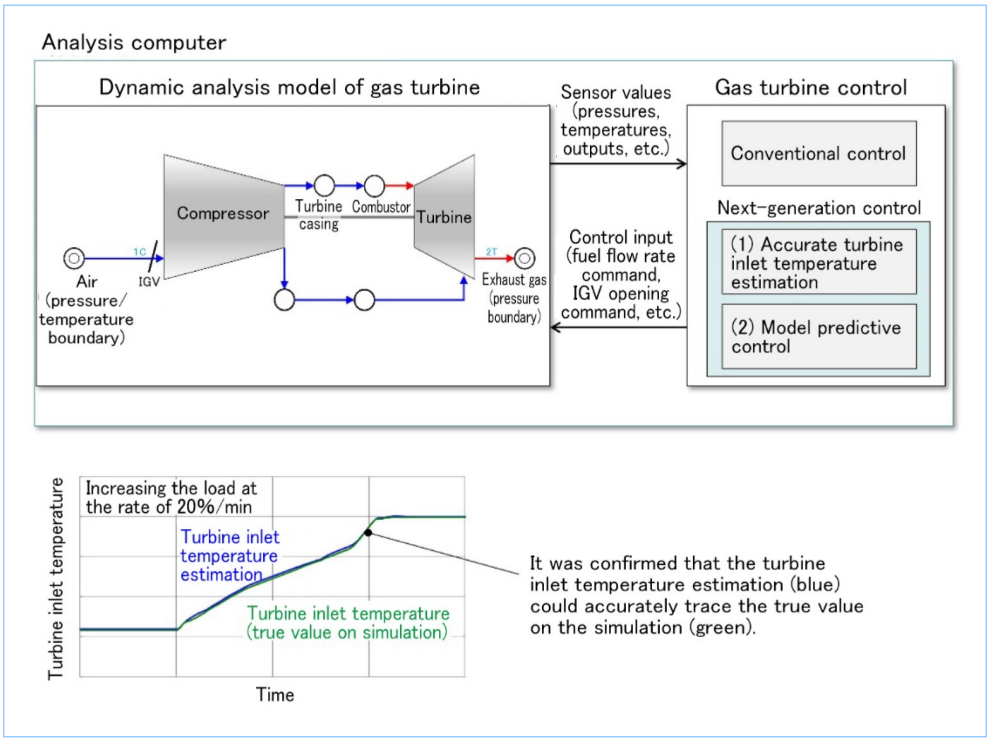

Figure 10 Simulation analysis (accuracy verification of turbine inlet temperature estimation)

3.2 Verification using actual equipment

Following the simulation using verification, we conducted an actual equipment demonstration test of the next-generation gas turbine control using our power plant validation facility in Takasago Machinery Works.

As a result, we verified that the deviation of the turbine inlet temperature estimation from the target value was significantly reduced in load change operation at a higher ramp rate (20%/min) compared to conventional operation (5-10%/min) and the upper temperature limit was quickly reached without transiently exceeding it when reaching the rated temperature, and that the gas turbine power output quickly increased to the limit output constrained by the upper turbine inlet temperature limit and the desired operation (**Figure 11**).

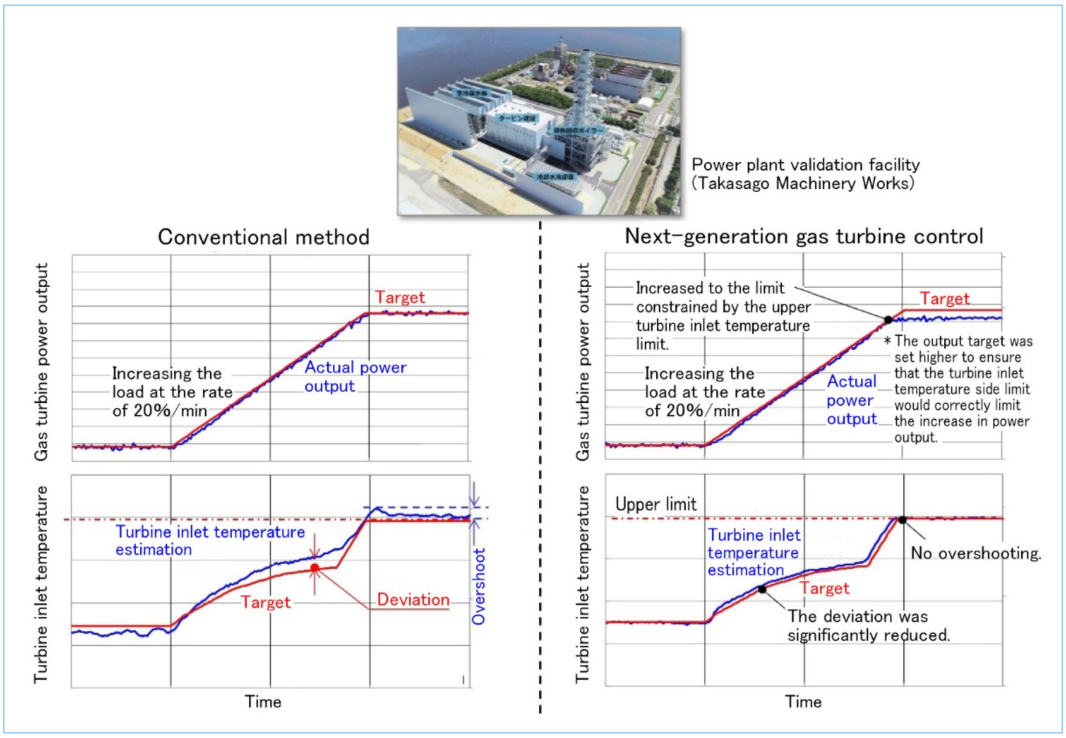

Figure 11　Test result at power plant validation facility

4. Conclusion

This report introduced the next-generation gas turbine control, our approach for high-ramp rate operation of gas turbines for power generation, for which demand is expected to increase in the future.

The next-generation gas turbine control system combines a turbine inlet temperature estimation method based on a physical model and model predictive control that anticipates the future to achieve both stable combustion control and high ramp rates. We have verified this method using our power plant verification facility in Takasago Machinery Works and reported the results in this report.

Moving forward, we will increase the functionality of this control by expanding the operational conditions under which it can be used, and will conduct long-term verification through electric supply operation using the power plant verification facility to promote efforts toward its commercialization.

References

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(2) Kazuki Morimoto et al., Validation Results of 1650°C Class JAC Gas Turbine at T-point 2 Demonstration Plant, Mitsubishi Heavy Industries Technical Review, Vol.58 No.1 (2021)