Total Power Control Technology for Use with PID Temperature Controllers

Masato Tanaka
Technology Development Headquarters
Azbil Corporation

Toru Takagi
Advanced Automation Company
Azbil Corporation

Keywords
Temperature control, PID control, general-purpose controller, heating equipment, total power, electric heater

The heating equipment which are widely used in the industrial world consume a tremendous amount of power. For this reason a limit that is lower than the equipment's actual capacity is often set on power consumption in order to suit the company's power supply and equipment situation. This inevitably affects the equipment's heating performance. We have therefore developed a total power control technology which prevents the overall power consumption of a system of several PID temperature controllers from exceeding a preset limit, while at the same time maintaining a high level of tracking performance so that the temperature stays close to the set point.

1. Introduction

General-purpose controllers are widely used with heating equipment (e.g., for heat processing in semiconductor manufacturing, plastic molding, and food pasteurization and sterilization) as hardware specially designated for performing PID control to regulate the heating temperature. The power consumption of electric heaters regulated by these controllers varies significantly from very little to very large.

This paper presents a control technology[1] aimed at reducing the maximum power consumption (total power consumption) when general-purpose controllers are employed in a temperature control system that regulates more than one electric heater.

2. Issues related to heating equipment employing electric heaters

2.1 Constraints on general-purpose controllers

General-purpose controllers are mainly sold as B2B products by one industry to another. This control technology is rather ubiquitous in industrial fields because the products of manufacturers of general-purpose controllers are employed by the manufacturers of manufacturing systems, which are then distributed to end users. A solution for heating control, therefore, is provided while satisfying the constraint of making the control technology marketable to be distributed as mass-produced general-purpose products, although they are B2B2B products in the strict sense.[2]

As far as practical constraints are concerned, it is a prerequisite for mass-marketed control technologies in such general-purpose controllers to employ PID as a standard control method. Such controller products must be combined with thermocouples, resistance temperature detectors, and other common measurement instruments to form single-loop control systems. Moreover, any pursuit of more advanced PID-based functions must not significantly compromise this prerequisite. The total power control presented in this paper was developed in keeping with the prerequisite for marketability.[3]

2.2 Challenges of maximum power consumption limits

Ever since the nuclear accident triggered by the Great East Japan Earthquake, dealing with power crunches surfaced as a particularly urgent issue which compelled manufacturing plants and production lines to strictly manage power consumption. In manufacturing plants, heating equipment consumes a particularly large amount of power. Typically, their maximum power consumption is set to a lower level than their actual full capacity. For instance, demand management systems give instructions to all equipment to consume power within a certain limit.

To secure orders, manufacturers of heating equipment try to align the maximum power consumption of their equipment with these upper limits as required by heating equipment users. Figure 1 presents an example of eight plants that are planning to introduce heating equipment with almost the same performance and size.[1] Suppose that in this example, the acceptable maximum power consumption for each equipment is strictly set as presented in the figure, in view of the power management track record and other circumstances at each plant. Any manufacturer producing only a standard heating equipment with a maximum power consumption of 35 kW will lose orders for four out of the eight plants.

Let's say that heating equipment users (plants) were adopting 35 kW heating equipment without hesitation when the maximum allowable power consumption for their plants was 40 kW. However, problems arise when a 35 kW heating equipment has already been introduced and then the allowable maximum power consumption is changed to 32 kW for some reason, which could include anything from a change in the installation area to increased demand for power externally.

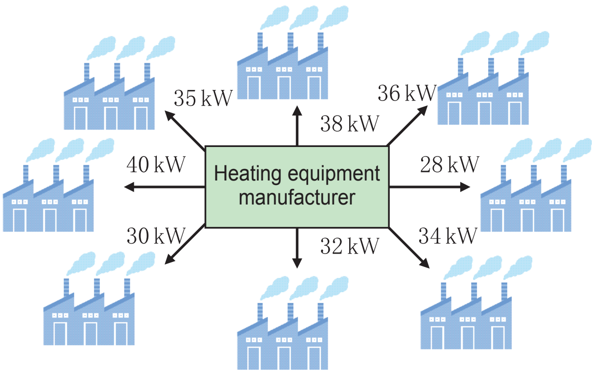

Figure 1. Different Requirements for Maximum Power Consumption by Users

2.3 Technical challenges to be addressed

One of the conventional methods of suppressing the total amount of electricity that is simultaneously supplied to heating equipment including multiple electric heaters (as in Figure 2), where multiple areas simultaneously heat up, is to start each heat treatment section sequentially following a prescribed sequence. However, launching such manufacturing systems with time lags inevitably involves variations in the time required for startup and in the power consumption. This results in the need for sufficiently large time lags in order to switch from one step of the launch process to another. Accordingly, a sequential startup of heating equipment having three control systems would take at least three times the time required for starting up one heating control system.[4]

Total power control as presented in this paper is achieved by performing step response control (changing the set point (SP) in steps and raising the temperature with tracking control to continue consuming a large amount of power) with more than one temperature control system while making sure that the total power consumption does not exceed a defined level (allotted total power (PW)) and trying to minimize impairment of the tracking performance with the SP. In order to provide a technology that can be marketed on a large scale from manufacturers of heating equipment to users around the world, operation has been simplified to setting an upper limit on the output. This leads to constant frequency response characteristics of the PID control loop and facilitates the use of such heating equipment.

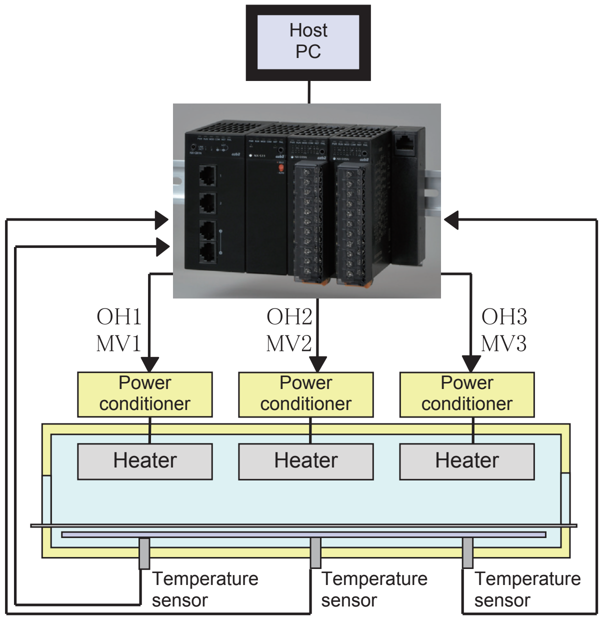

Figure 2. More Than One Heater in a Heating Equipment

3. Algorithm for total power control

3.1 Design guidelines

Startup of heating equipment in sequence with time lags inevitably requires a time margin to adjust for the power consumption. The resulting delay in launching the equipment translates into inefficiency. To put it more simply, step changes to the SP are basically repeated disruptions of SP tracking control.

Even more time for stabilizing power consumption is necessary for heating equipment where there is interference between loops, since the loops that were launched earlier experience disturbances associated with interference from the loops that are still heating up, making the process all the more inefficient. The most efficient way to start up heating equipment, therefore, is to simultaneously heat up the heaters while keeping the total power consumption within a defined range and synchronizing the heaters so that they finish heating up, ideally, at the same time. Hence, in the ideal situation, the equipment would use all of the allotted power while making sure that the total power consumption is kept under a defined level.[4]

3.2 Process flow

The process flow can be outlined as follows.[4]

(1) Enter the allotted total power (PW).

(2) Enter the actual reading of the total power consumption (PR) as measured in real time.

(3) Update the settings to compare the actual reading of the total power consumption (PR) and the allotted total power (PW) and, if PR is larger than PW, bring the correction factor (HS) below its current value.

IF PR > PW THEN HS ← 0.99 HS

(4) Determine whether power consumption has reached the maximum level or not based on the manipulated variable corresponding to each control loop i (MV_i). Update the setting to compare actual reading of total power consumption (PR) and allotted total power (PW) and, if PR is smaller than PW, bring the correction factor (HS) above its current value.
IF $MV_i = OHx_i$ AND $PR < PW$
THEN $HS \leftarrow 1.001\ HS$

(5) Enter the power consumption of each control loop i (CTm_i) at maximum output. Remember that power consumption (CTm_i) at maximum output is a fixed value that is stored in advance.

(6) Calculate the power margin of each control loop i (CTr_i) according to the following equation.
$CTr_i = CTm_i\ (100.0 - MV_i) / 100.0$

(7) Calculate the maximum power consumption (BX) according to the following equation.
$BX = \Sigma CTm_i = CTm_1 + CTm_2 + \cdots + CTm_n$

(8) Calculate the total power margin (RW) according to the following equation.
$RW = \Sigma CTr_i = CTr_1 + CTr_2 + \cdots + CTr_n$

(9) Calculate the total reduction in power consumption (SW) according to the following equation.
$SW = BX - PW$

(10) Calculate the allotted amount of power consumption reduction of each control loop i (CTs_i) according to the following equation.
$CTs_i = SW\ (CTr_i / RW)$

(11) Calculate the upper limit of the output of each control loop i (OH_i) according to the following equation.
$OH_i = \{1.0 - (CTs_i / CTm_i)\}\ 100.0\ [\%]$

(12) Adjust the upper limit for output (OH_i) according to the following equation.
$OHx_i = OH_i\ HS$

(13) For each control loop i, enter the set point (SP_i) and the process value (PV_i) and calculate the manipulated variable (MV_i) by carrying out the following computation with PID control.
$MV_i = (100.0 / PB_i)$
$\{1 + (1 / TI_i\ s) + TD_i\ s\}\ (SP_i - PV_i)$
PB_i: proportional band
TI_i: integral time
TD_i: derivative time

(14) Process the manipulated variable (MV_i) based on the upper limit for the output.
IF $MV_i > OHx_i$ THEN $MV_i = OHx_i$

(15) Output the manipulated variable (MV_i).

3.3 Example of implementation in a controller

Figure 3 presents a sample implementation of the algorithm in general-purpose controllers. The controllers are Network Instrumentation Modules made by Azbil. The algorithm for total power control is implemented in the supervisor module and the PID control algorithm is included in the controller module as standard features. This technology, which allows the functions of a general-purpose controller to be expanded externally, was developed as a result of our pursuit of practicality.

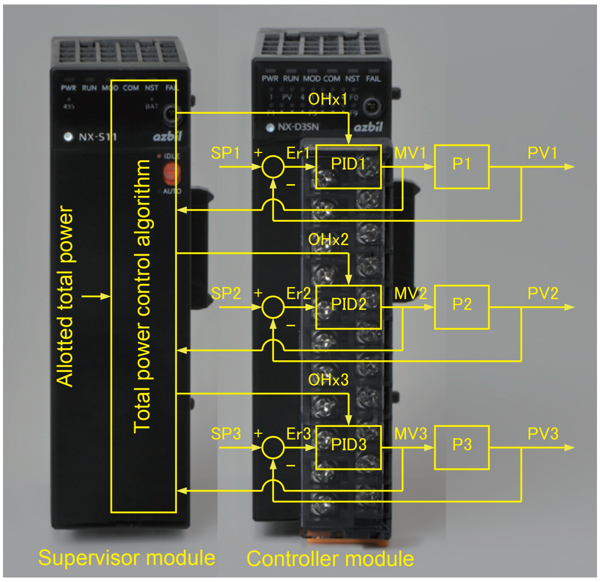

Figure 3. Example of Implementation with a General-Purpose Controller

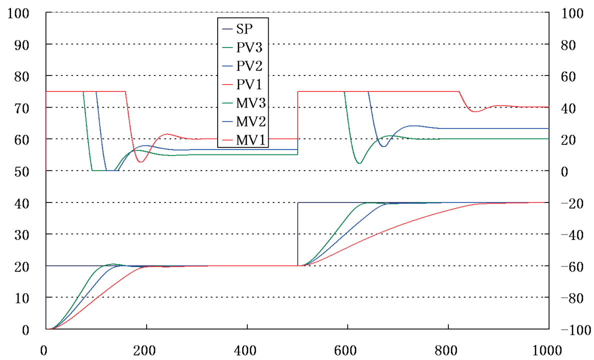

Figure 4. Rise in Temperature when the Upper Limit for the Output (OH) is Fixed

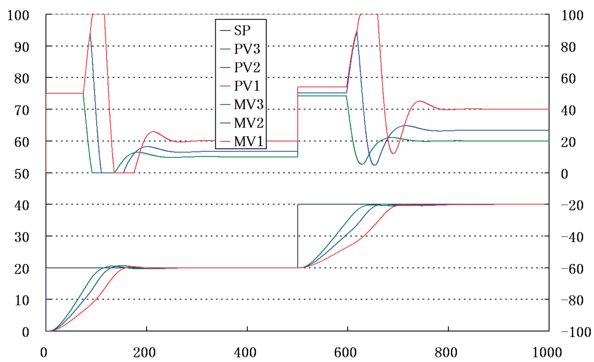

Figure 5. Rise in Temperature with Variable OH in a Total Power Control System

4. Example of total power control

4.1 Typical operation (step response)

Figures 4 and 5 present the results from step response simulation in a 3-loop control system when the allotted total power (PW) is kept constant.[1] The left axis represents temperatures SP, PV1, PV2, and PV3 (lower part of the figure) as percentage values whereas the right axis presents the manipulated variables MV1, MV2, and MV3 (upper part of the figure) as percentage values. The horizontal axis represents time in seconds.

Figure 4 shows the rise in temperature when the upper limit for the output (OH) is kept constantly at 50%. A slower rise in temperature PV1 is observed as a result of insufficient output especially in higher temperature ranges (right-hand part of the figure) when the manipulated variables MV1, MV2, and MV3 are large.

Figure 5 shows that the problem of the slower rise in temperature PV1 is resolved by heating with variable OH for performing total power control. The manipulated variable MV1 increases as MV2 and MV3 decrease once temperatures PV2 and PV3 have increased completely. In such simultaneous decreases and increases in the manipulated variable, the power allocation is regulated to maintain the allotted total power (PW).

4.2 Operation for comparison (ramp response)

Figures 6 and 7 present the results from ramp response simulations in order to describe the operation for total power control from another perspective. In this example, allotted total power (PW) is kept constant in a 3-loop control system.[1] In the top part of these figures, the left axis represents temperatures SP, PV1, PV2, and PV3 (ramp operation graph in the figure) as percentage values whereas the right axis presents power in watts (W). The horizontal axis represents time in seconds. In the lower part of these figures, the left axis represents manipulated variables MV1, MV2, and MV3 as percentage values whereas the horizontal axis represents time in seconds.

Figure 6 presents a profile of the rise in temperature when the upper limit for the output (OH) is fixed at 50%. In other words, the allotted total power is 300 W, or 50% of the total capacity of a 600-W heater. The manipulated variable gradually increases in keeping with the ramp operation until it reaches the upper limit (OH) for the output (50%). The MV does not increase any further and thus keeps the total power consumption from exceeding 300 W. In reality, however, the manipulated variable does not always reach the upper limit for the output (OH = 50%) and the total power reaches at most 250 W. That is, despite a sufficient margin with the allotted total power of 300 W, increase of the manipulated variable is limited. This phenomenon results in extreme slowdown of the rise in the temperature particularly with PV1 (time from 300–800 seconds) as shown in Figure 6.

In contrast, as Figure 7 demonstrates, the increase in temperature with variable OH in a total power control system avoids unnecessary restriction of the manipulated variable because the upper limit for output (OH) is constantly adjusted during the ramp response. All of the MV values reach the upper limit for output (OH) in around 500 seconds when the actual total power consumption reaches the allotted total power of 300 W. That is, an increase in the manipulated variable (MV) is not restrained as long as there is surplus power and the total power consumption does not exceed the allotted total power of 300 W.

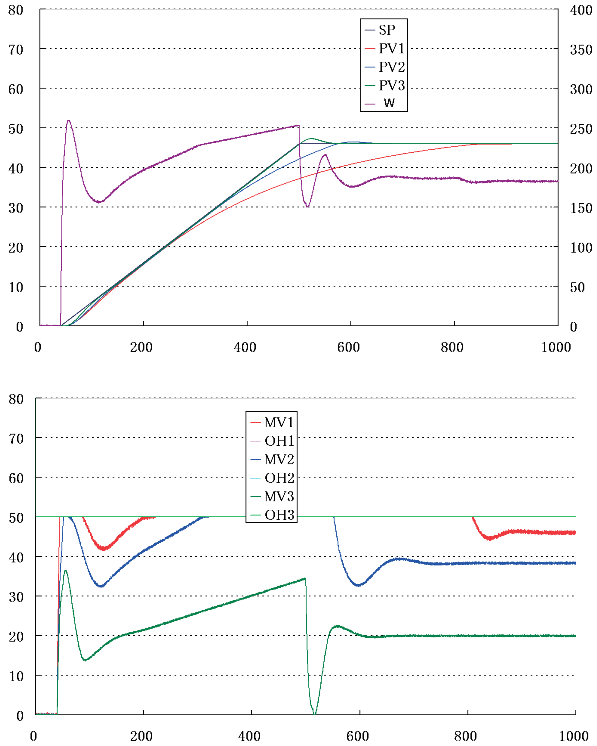

Figure 6. Rise in Temperature when the Upper Limit for the Output (OH) is Fixed
Top: Temperature (PV) and Power (W)
Bottom: Manipulated Variable (MV), (OH)

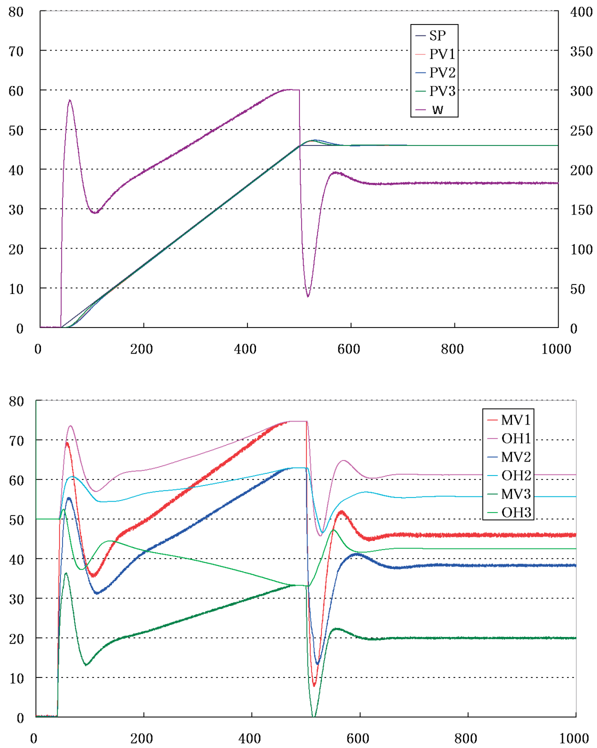

Figure 7. Rise in Temperature with Variable OH in a Total Power Control System
Top: Temperature (PV) and Power (W)
Bottom: Manipulated Variable (MV), (OH)

4.3 Validation with an actual heating equipment

This section presents the results from the experimental application of the presented technology to a heating equipment actually being used. Figures 8 and 9 show the results of the step response when the allotted total power (PW) is kept constant (850 W = approx. 70%) in a 3-loop control system (400 W × 3 = 1,200 W).[1] The left axis represents temperatures SP, PV1, PV2, and PV3 (upper part of the figures) in °C and the manipulated variables MV1, MV2, and MV3 (lower part of the figures) as percentage values. The right axis represents the actual measurement of power consumption (W) in watts. The horizontal axis represents time in seconds.

Figure 8 shows a profile of the rise in temperature when the upper limit for output (OH) is fixed at 70%. The manipulated variable is kept from rising above the upper limit for the output (OH = 70%), which results in the least satisfactory situation wherein the corresponding temperature never reaches the set point.

Figure 9 shows a profile of the rise in temperature with variable OH in a total power control system. The amount of operation is set to above 80% or below 50% when heating begins depending on the difference in the upper limit for output as automatically determined based on the difference in the manipulated variable before heating starts. The timing of the progress in temperature rise is also adjusted. Power allocation is adjusted when the manipulated variable decreases with a control loop that completes heating more quickly to increase the manipulated variable of other control loops that are yet to complete heating while still not exceeding the total power consumption of 850 W. In this manner, all the temperatures reach the SP.

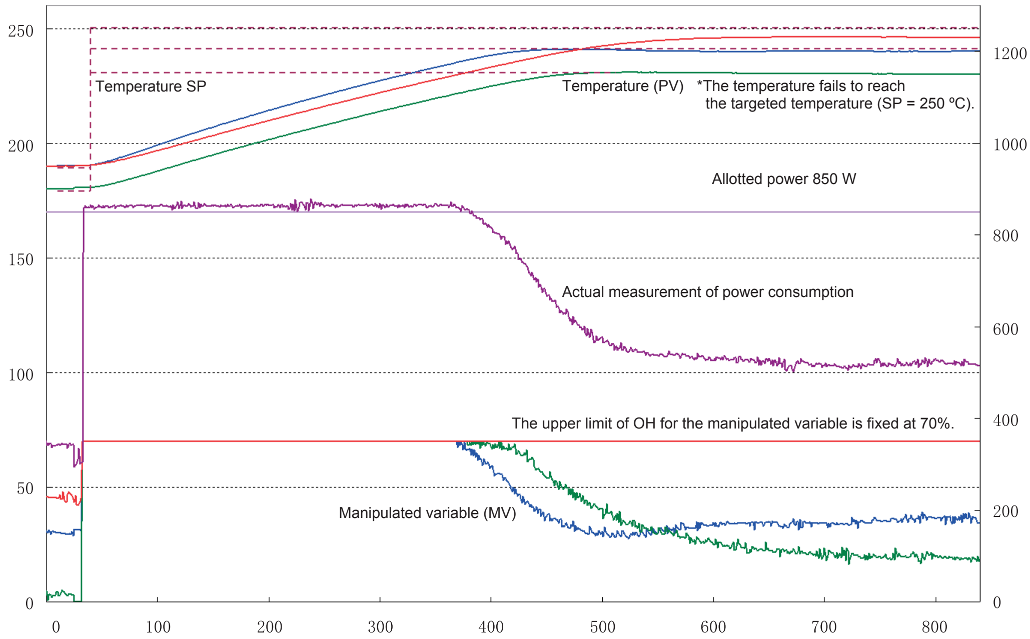

Figure 8. Rise in Temperature when the Upper Limit for the Output (OH) is Fixed

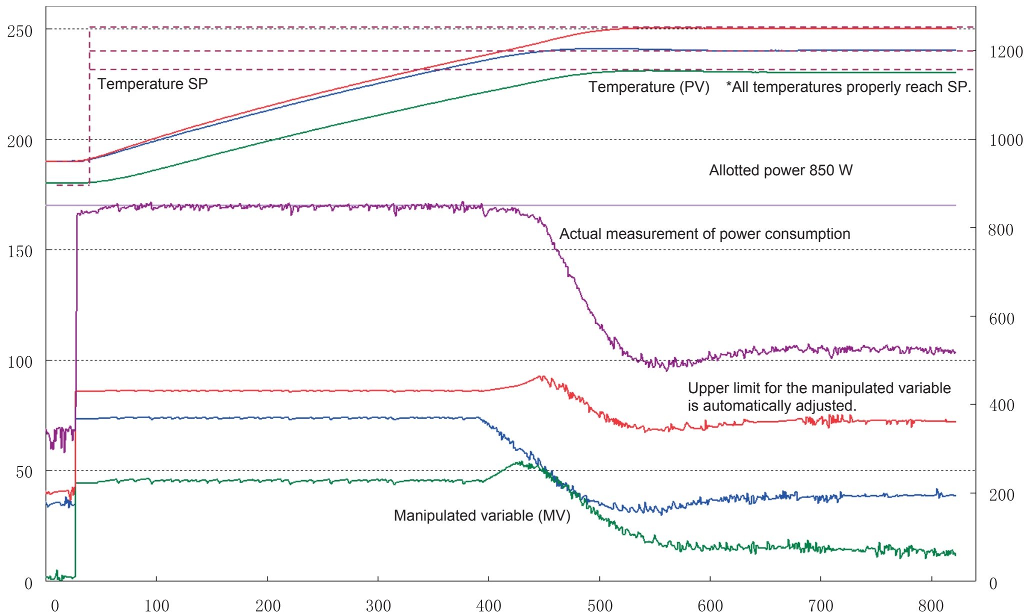

Figure 9. Rise in Temperature with Variable OH in a Total Power Control System

4.4 Energy-saving effect

The total power control system optimizes the total power consumption within a system. Nevertheless, it would be misleading to state that this control saves power. The system is designed to minimize detrimental effects experienced in loop-level control by smoothing the power consumption and thereby facilitating demand-response control at a higher level (i.e., optimization between different systems).

In this regard, it is crucial to interlink with the total energy management systems in production lines. Particular attention needs to be paid to avoid extremely low amounts of allotted total power. Total power control is intended to minimize inefficiency in power consumption control even when the allotted total power is reduced. But the technology still results in prolonged heating times. The longer the heating time, the longer the time the system releases heat until it starts running, which is disadvantageous in terms of energy conservation.

The widespread application of this technology in industries crucially depends on whether manufacturers and users can share the same way of thinking and play their respective roles at different levels of total power control across sectors.

5. Conclusion

This paper has presented total power control as a technology conducive to controlling power consumption in heating equipment by employing general-purpose controllers for performing control at the loop level.

Total power control is intended to harmonize the operation of loops by adjusting the upper limit of the output and is designed to keep the closed loop characteristics (frequency characteristics) constant provided that the characteristics of the target system do not change.

The main role of such systems is to perform temperature control and the priority task for general-purpose controllers at the loop level is to ensure stable operation of temperature control and to enable anyone at worksites to safely use the systems. The authors hope that this paper has helped its readers to understand the idea behind the design of total power control technology.

References

[1] Masato TANAKA: "Total Power Control Technology Applied in PID Temperature Control," *Industrial Heating*, Japan Industrial Furnace Manufacturers Association, Vol. 50, No. 6, 2013, pp. 13–18.

[2] Hiroto HAMANE, Nobutomo MATSUNAGA, Masato TANAKA, Ikuo NANNO, and Kazuyoshi MIYAZAKI: "Industrial Trends in General-purpose Controllers and New Technologies," *Technical Report*, Institute of Electrical Engineers of Japan, No. 1180, 2010.

[3] Masato TANAKA: "Discussion of Control Technologies in Terms of Business," *Instrumentation and Control*, The Society of Instrument and Control Engineers, Vol. 52, No. 5, 2013, pp. 413–418.

[4] Masato TANAKA and Mayumi MIURA: "Total Energy Limiting and Controlling Device, and Total Electric Power Limiting and Controlling Device and Method," JP-A-2012-048370.

Affiliation of Authors

Masato Tanaka	Product Development Department Technology Development Headquarters
Toru Takagi	Sales Department 4 Advanced Automation Company