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A Study on Applying Nonlinear Control to Gas Turbine Systems

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ABSTRACT

Gas turbines originally have nonlinear characteristics, but these characteristics do not vary largely in a range of normal operation. Therefore gas turbines are considered as almost linear systems, and linear control is sufficient to be applied. In gas turbines control, linear control has been core technology.

However, in recent years, gas turbines require finer control to achieve higher performance such as high efficiency, low emission and so on. In that case, it is necessary to consider nonlinear characteristics of gas turbines to cope with these requirements. So we consider that nonlinear control comes to more significant technology in gas turbine control.

For this reason, we are carrying out a study to apply nonlinear control to gas turbines. In this paper, we report two representative applications. The first one is the gas turbine starting control by the fuzzy control, and the other is the application of the optimizing method to VSV control.

NOMENCLATURE

A : VSV angle
C_p : Specific heat at constant pressure
G : Flow rate
H : Specific enthalpy
H_u : Lower calorific value
K_t : Turbine flow coefficient
M : Fuel flow rate
N : Number of revolution, Gas turbine speed
NOx : NOx concentration
P : Pressure
T : Temperature
W : Output power, Load Power
r : Number of fuzzy rule
u : Fitting grade to fuzzy rule
x : Control output
y : Output of fuzzy inference
η_a : Adiabatic efficiency
η_m : Mechanical efficiency
κ : Ratio of specific heat
π : Pressure ratio

Subscripts

1 : Compressor inlet
2 : Compressor outlet
3 : Turbine inlet
4 : Turbine outlet
T : Theoretical
a : Air
c : Compressor
dsn : Designed point
g : Combustion gas
l : Load
$\max$: Maximum
$\min$: Minimum
std : Standard Air
t : Turbine
* : Corrected Value

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INTRODUCTION

In many cases of designing control logics, we usually use models, which formulate characteristics of a controlled object. If the parameters which determine the response characteristics (sensitivities, response speeds) of a controlled object vary in the operating point, it is called a nonlinear system, and if they do not vary, it is called a linear system. When we consider a gas turbine as a controlled object, the gas turbine is the nonlinear system because its parameters vary as the operating point changes. However, the variation of these parameters is not so large in normal operations, except for the following cases: the starting process in which these parameters vary largely, and gas turbines for an airplane in which these parameters are influenced greatly by the ambient conditions. Therefore, in many cases, we deal with a gas turbine as a linear system approximately in normal operation. In addition to this, the formulation of models is simpler and designing control logic is easier.

The design method of control logics, which we apply to gas turbines in normal operation, usually bases on linear control for the reason mentioned above. The typical linear control is PID control, which feedbacks the state variable(s) (gas turbine speed and/or output power) and controls it(them) to the reference value(s) with PID controller(s). Most of the gas turbine systems control the fuel flow by this method. Controlling the fuel flow is the core part of gas turbine systems and they are designed basing on linear control in many cases. Thus, linear control is significant technology in designing gas turbine control systems.

On the other hand, some nonlinear controls have been applied to gas turbine systems. One of them is the scheduled control, which controls actuators with preset functions. It is applied to the fuel flow control in the starting process, the VSV (Variable Stator Vane) control and so on. Another one is the correcting control, which corrects the gas turbine characteristics affected by the ambient temperature and/or pressure by (a) correlation equation(s). They are examples of nonlinear control. These are simple cases in nonlinear control. Though there are some cases of nonlinear control applications such like this, more advanced nonlinear control is not applied enterprisingly.

However, when we consider the trend of gas turbine technologies in recent years, it is necessary that gas turbine systems should meet social requirements for high efficiency and low emission, which are increasing in the background of environmental problems, and should realize more advanced control technology ([3], Ryu, 2001). For these requirements, we considered application of nonlinear control, which can deal with nonlinear systems, is appropriate to gas turbines, because the characteristics of gas turbines are exactly nonlinear. Thus, we also consider that nonlinear control will come to be more significant in designing of gas turbine systems in the future.

For these reasons, we have studied application of nonlinear control to gas turbines. In this paper, we report two representative studies. One is the method to apply the fuzzy control to the starting process of gas turbines, which makes us control the fuel flow in the starting process against the large variation of gas turbine characteristics mentioned above. Also, we show the experimental result on the pilot plant about this control method. The other is the application of the nonlinear optimal method to the VSV control, which we have studied to meet the requirement of environmental problems. The characteristics of the thermal efficiency and the NOx concentration are nonlinear, and multiple demands for control must be met at the same time. Therefore, we considered that this method is effective for high efficiency and low NOx. In this paper, we also report our study about this method with the result of mathematical simulation.

THE GAS TURBINE STARTING CONTROL BY THE FUZZY CONTROL

Characteristics of Gas Turbines in the Starting Process

As the response characteristics (sensitivities, response speeds) of gas turbines are greatly affected by the air flow rate, which is the working substance of gas turbines, and they largely vary especially in the starting process because the air flow rate changes in a large scale as gas turbine speed increases. In addition, the combustion efficiency is complicatedly affected by the air/fuel ratio and the combustion temperature, and this factor also affects response characteristics of gas turbines. Therefore, gas turbines in the starting process show very complicated nonlinear characteristics, and it is difficult to control appropriately by using linear control. This is the reason that the scheduled control using a preset function is usually applied to the fuel flow control in the starting process.

In this process, there is also a serious problem if the EGT (Exhaust Gas Temperature) rises too high right after the fuel is ignited. The over rising of the EGT means that the combustion temperature is too high, and it causes damage on the hot section parts by burn out. Therefore, the EGT must be watched not to be too high in the starting process, and gas turbines are stopped in emergency if the EGT rises over the limit value.

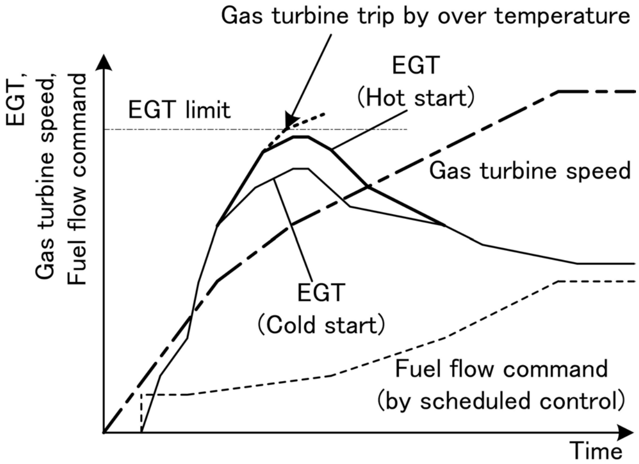


Fig. 1 Characteristics of Gas Turbines at the Starting Process

By the way, the variation of gas turbine characteristics in the starting process mentioned above appears strikingly in the EGT as shown in Fig. 1. It seems to be caused by the combustion efficiency, which affects the combustion temperature greatly, and the efficiency is affected by various factors as mentioned above. In particular, the combustion temperature greatly varies whether the interval time after the previous operation is sufficient or not. The starting process which has the sufficiently long interval time is called “cold start”, and if the interval time is not sufficiently long it is called “hot start”. In case of cold start, it can prevent rapid rising of the combustion temperature because the combustor is cooled sufficiently, and the heat which is generated by combustion is absorbed into the hot section parts around the combustor. On the other hand, in case of hot start, the combustion temperature tends to rise rapidly, and the EGT easily exceeds the limit value because the combustor has a large amount of the residual heat, and it makes the combustion temperature rises, so that there is a risk that the gas turbine may be into trip.

In addition, not only the difference between cold start and hot start but also the ambient temperature affects the variation of the EGT’s characteristics mentioned above. The ambient temperature has a large difference (about 30 (K) or more) between in summer and in winter at one place, although the grade of this difference depends on the environmental conditions. Also, the difference largely affects the combustion temperature because gas turbines operate with air as the working substance. It means that gas turbines tend to exceed the EGT’s limit value and have a higher risk of trip in summer than in winter.

The scheduled control, which is used for the fuel flow control in the starting process up to this time, cannot meet the variation of characteristics in the starting process because it usually controls the fuel flow rate only by a function, which presets the fuel flow command increasing as gas turbine speed increases. Therefore, the schedule is preset at a low level to prevent the EGT exceeds the limit value under the condition in which the EGT easily rises such as hot start. However, there is risk of un-fire and late start which occur due to the lack of the combustion energy under the condition of low temperature conditions such as in cold start. These also make the gas turbine trip.

These problems may make the reliability be lost in the starting process and interfere with operation of the gas turbine. To cope with these problems, some measures such as correcting the scheduled control according to the ambient temperature and adding logics to reduce the fuel flow command temporarily in case of the EGT rising higher have been taken. However, the variation of characteristics in the starting process is so large and complicated that it is difficult to adjust the control parameters perfectly in these methods. Therefore, a lot of process of trial and error on actual gas turbines is necessary, and it takes long time to search and get the most appropriate control parameters.

By the way, if a human being controls the fuel flow rate based on his senses, he or she may increase the fuel flow command when the EGT is low sufficiently, and decrease it when the EGT is high. In this case, he or she may control such as “increase a little” or “decrease a lot”. The fuzzy control can realize such sensuous operation automatically. Most of the nonlinear methods need models, which formulate characteristics of a controlled object, for designing and evaluating the control system, but the fuzzy control does not need them because it is the method that can formulate the control rules which is based on senses of a human being into an automatic control logic. From this reason, we considered that the fuzzy control is an appropriate method for the gas turbine starting control. In the following sections, we explain the application method of this and report the experimental result on the pilot plant with an actual gas turbine.

Application of the Fuzzy Control to the Gas Turbine Starting Control

The fuzzy Control is based on the fuzzy theory explicated in 1965 by Zadeh, who was a professor in the University of California. In the fuzzy theory, definition of things is expressed not with discrete boundary such as “0”, “1”, “2”, and the like, but with fuzzy expressions such as “a little ~”, “a lot ~”, and the like ([5], Zadeh, 1968). This theory has begun to be applied to control theory in the middle of 1970s, and some practical applications have appeared in 1980s. After that, as shown by Sugeno ([4], Sugeno, 1985), the fuzzy control has drawn the public attention at one time in Japan. Nowadays, although it is not noticed as once, it is mainly applied to control objects such as plants, which is difficult to formulate into models, combined with the Artificial Intelligence and so on.

In the fuzzy control, the behavior of controlled objects and environmental conditions are expressed by using fuzzy set(s), called membership function(s) as shown in Fig. 2, and it(they) judge(s) the state of a controlled object. This part is defined as the “IF part” (or “condition part”). On the other hand, it is determined how the controller should act under the result of this judgment based on rule(s). This(These) rule(s) is (are) organized based on the sense of a human being, and the control command(s) is(are) calculated with this(these) rule(s) which is(are) called the fuzzy rule(s). This part is defined as the “THEN part” (or “action part”). Fig. 3 shows the conceptual diagram of the fuzzy control logic. Here the IF part can consist of several conditions, and several outputs as the result from the THEN part can be obtained as well if the controlled object has several actuators. Therefore, the fuzzy control can be applied to multi inputs and multi outputs (MIMO) systems. Considering the starting process of gas turbines, there are some conditions for the IF part, but there is only a fuel control valve as a control actuator usually. This is an application to a multi inputs and single output (MISO) system.

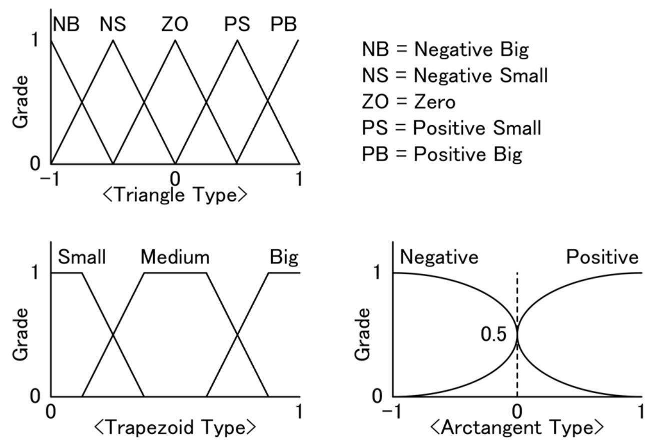


Fig. 2 Typical Samples of Membership Functions

Next, we explain the application of the fuzzy control to the starting control of gas turbines. Constructing rules in the starting process based on the senses of a human being, it is suitable that the control command to the fuel valve is output I order to the fuel flow rate is appropriately in the low range of the gas turbine speed, because it is important to keep the fuel flow rate sufficiently for igniting. This is the first rule. After the fuel is ignited and the combustion is stable, it is necessary that the gas turbine will increase its speed smoothly, so that it is suitable that the acceleration is controlled. This makes the gas turbine increase its speed without late start in case of low temperature conditions such as cold start. This is the second rule. In addition, the EGT must be controlled under its limit value when the EGT rises near the limit value to cope with over rising of the EGT in case of high temperature conditions such as hot start. This is the third rule. From these considerations, the three following basic rules are needed to construct the starting control of gas turbines.

Rule 1: If the gas turbine speed is in the low range, control the output fuel flow command appropriately for igniting.

Rule 2: If the gas turbine speed is in the high range, control the acceleration of the gas turbine.

Rule 3: If the EGT rises near its limit value, control the EGT under the limit value.

Also, IF part which is to judge these rules consists of the following three conditions; “the gas turbine speed is low”, “the gas turbine speed is high” and “the EGT raises near its limit value”, and the membership functions which express these conditions are put into two patterns as shown in Fig. 4.

In the action part, three control commands: the fuel flow command for igniting, the acceleration control command, and the EGT control command are needed to determine the control command. In the fuzzy control, the first step of the starting process until the fuel is ignited and combustion is stable is similar to the scheduled control, which is used up to this time. Therefore, the scheduled control using a preset function can be applied to the fuel flow command for igniting. Also, it is suitable that a feedback control such as PID control is used for the acceleration control and

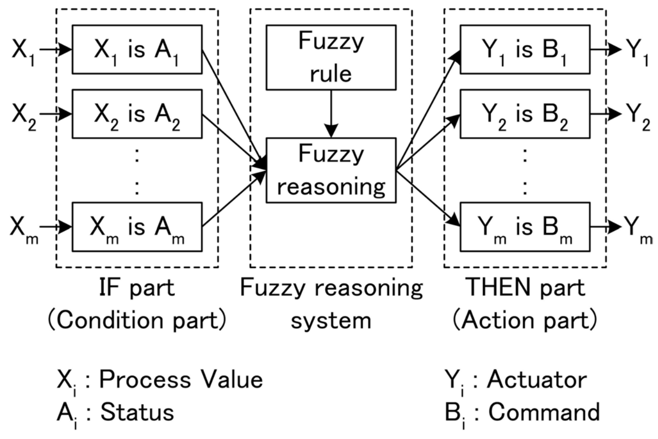


Fig. 3 The Conceptual Diagram of the Fuzzy Control Logic

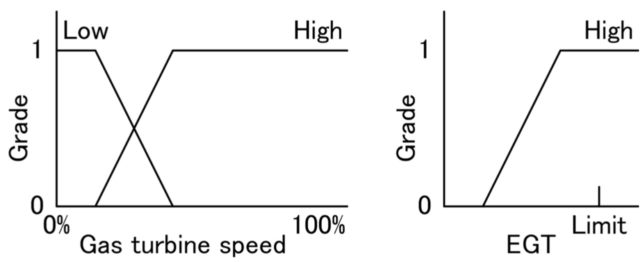


Fig. 4 Membership Functions for the Gas Turbine Starting Control

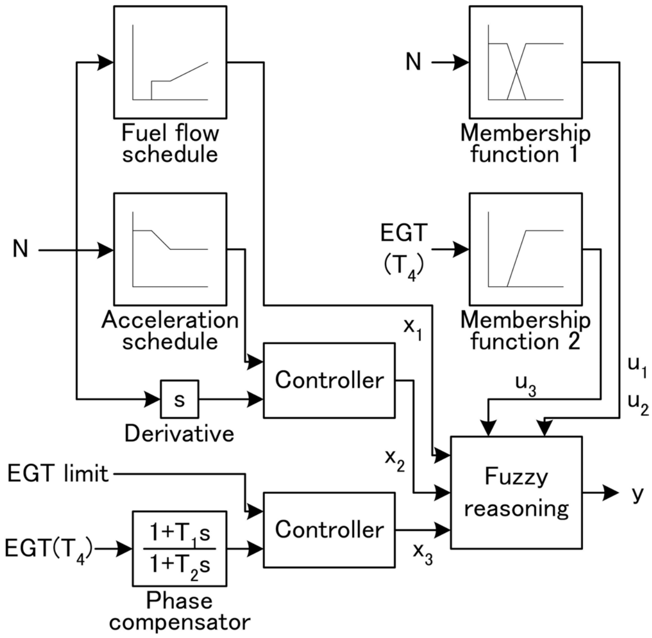


Fig. 5 The Block Diagram of the Gas Turbine Starting Control by the Fuzzy Control

the EGT control to control the target variables to the reference values surely. Although the gas turbine characteristics in the starting process vary greatly, the response speed of the acceleration does not vary so largely because it is mainly influenced by the inertia of the gas turbine, and this makes us use linear control for the acceleration control. Also, the EGT has a large variation of the characteristics, and the air flow rate largely changes in the starting process particularly. Consequently, this makes the coefficient of heat transfer and the response speed of the thermocouples vary greatly. However, as the response speed can be improved by using a phase compensator, this makes us apply linear control to the EGT control. Then, we constructed the control logic for the gas turbine starting control by using the fuzzy control, and the block diagram of it is shown in Fig. 5.

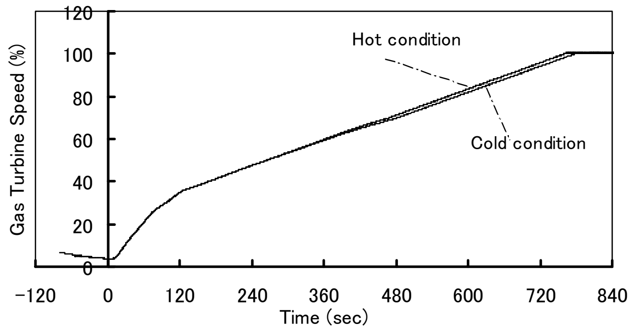
In addition, the part of the fuzzy reasoning, which determines the control command based on the fuzzy rules as shown in Fig. 5, is designed by one of the graphical methods called the center-of-gravity method in many cases of designing the fuzzy control. But the formulation of the center-of-gravity method is complicated and needs a large amount of calculations, so we considered this method is not suitable for installing to a computer, and we used the weighted averaging calculation such as the eq. (1).

$$y = \frac{\sum_{i=1}^{r} u_i x_i}{\sum_{i=1}^{r} u_i} \qquad (1)$$

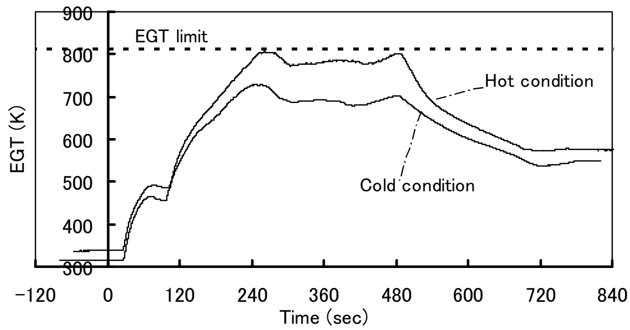
Also, the fuzzy control usually expresses control commands in the THEN part by the fuzzy set(s) such as the IF part, but this method requires not only a large amount of calculation but also too many parameters to be adjusted. Therefore, we do not use this method, and we use linear control to determine each control command in the THEN part.

Experimental Result of Application to an Actual Gas Turbine

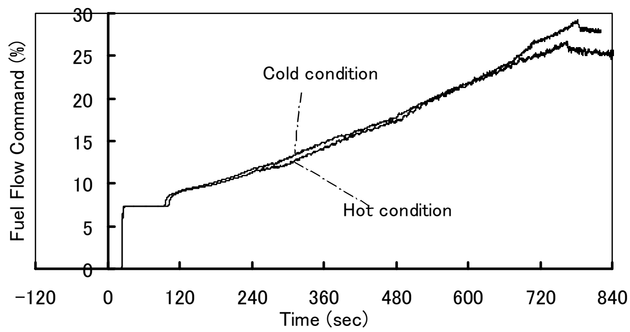
In this section, we show the experimental result and the



(a) Gas Turbine Speed



(b) EGT (Exhaust Gas Temperature)



(c) Fuel Flow Command

Fig. 6 The Experimental Result of Starting Control on an Actual Gas Turbine

evaluation of the effect of the fuzzy control to the starting control which are obtained through a test on an actual gas turbine. We applied the starting control mentioned above to a gas turbine developed by our company and carried out a test on a pilot plant for electricity generation. The most important point for evaluating the effect of this application is that the gas turbine can perform the starting process surely without late start in low temperature conditions such as cold start, and the EGT does not exceed its limit value in high temperature conditions such as hot start. We carried out the test both in winter and in summer to evaluate the effect of this application in these conditions. Here the test in winter means representative case in cold conditions, and the test in summer does it in hot conditions. We show the result of comparison between cold conditions and hot conditions in Fig. 6.

First of all, in case of the starting process in cold conditions, the gas turbine is accelerated smoothly by the fuel flow rate gradually increases after the fuel is ignited. As a result, we confirmed that the starting process works well as shown in Fig. 6. In these conditions, as the combustion temperature is not so high, the EGT does not rise near its limit value as shown Fig. 6-(b), so the rule for the EGT control is not activated.

Next, in case of the starting process in hot conditions, the EGT rises more than in case of cold conditions and nearly reaches its limit value when the fuel flow rate increases to accelerate the gas turbine after the fuel is ignited. At this point, the rule 3 which is defined as "If the EGT rises near its limit value, control the EGT under the limit value" is activated. Then, the fuel flow command is reduced to control the EGT under its limit value. Fig. 6-(b) and (c) show such actions of the control logic.

In addition, the fuel flow command is controlled to lower level through out the entire process in case of hot conditions than in case of cold conditions as shown in Fig. 6-(c). This means that the starting process in hot conditions needs less fuel than in cold conditions because the combustion temperature is easy to rise in hot conditions. For this result, we evaluated that this control method can adapt the difference of temperature conditions and control the fuel flow rate appropriately in any condition of temperature.

Lastly, we confirmed that this control method developed by us realizes high performance in the starting process, and it makes the gas turbine start surely and safely. Therefore, we consider that it is useful for practical applications, and it contributes to improvement of reliability in the gas turbine starting control. Although the fuzzy control needs complicated rules and fine adjustment of membership functions in the IF part and the THEN part to control a object finely in general, we designed this control method by minimum but necessary number of rules and combination with linear control considering characteristics of gas turbines in this case. And this makes us adjust control parameters more easily, so we consider that it is also a noticeable feature of this control method.

APPLICATION OF THE OPTIMIZATION METHOD TO THE VSV CONTROL

Necessity of the Optimization Method for the Gas Turbine Control

One of the significant themes in social concern about gas turbines is how to cope with environmental problems. Thus, the technologies which are for high efficiency to save energy and low NOx to reduce emission to environment is required. For this reason, various researches and developments for each element of gas turbines such as compressors, turbines and combustors have been carried out.

For example, there are some studies for compressors. The air flow rate and operating point of compressors can be changed by the VSV), and the air flow rate influences the thermal efficiency and the NOx concentration. This makes us realize high efficiency and low NOx by controlling the VSV appropriately. Therefore, control methods of the VSV have been researched. Originally, the VSV is installed to prevent rotating stall and to adjust the air flow rate appropriately as the gas turbine speed increases in the starting process. In addition to this, the VSV can change the operating point of a gas turbine in normal operation, and the thermal efficiency of a gas turbine varies according to this change. Therefore, it is possible to control the thermal efficiency of a gas turbine higher by operating the VSV appropriately. On the other hand, the characteristics of the NOx concentration is largely influenced by the air/fuel ratio, and it means the NOx concentration is influenced by the air flow rate. Therefore, the NOx concentration can also be controlled appropriately by the VSV to reduce the emission.

Another studies are for combustors. These are researches of the lean premixed combustion which makes the NOx concentration reduce by decreasing the combustion temperature to be low. However, in the lean premixed combustion, the fuel flow rate is so lean that burn off may easily occur in the operation with low range of load. Therefore, the multi-burner combustion system which consists of several burners; combination of premix burners and diffusion burners is developed, and an appropriate combination of these burners is selected according to the load range.

In these ways, gas turbines come to have several actuators and to use them more enterprisingly to cope with the requirement of high efficiency and low NOx in recent years. Consequently, it is necessary that the control logic acts more complicatedly and deals with nonlinear characteristics such as the thermal efficiency, the NOx concentration and so on. It is difficult to cope with nonlinear objects such as these by linear control, so that we are carrying out an application of nonlinear control to realize the high efficiency and low NOx.

There are several actuators which are available for high efficiency and low NOx mentioned above. In this study, we established the control method of the VSV as a first step, because it can change both the thermal efficiency and the NOx concentration. For the result of this study, we consider that the optimization method which is one of the nonlinear control methods is effective to apply the VSV control because not only characteristics of the thermal efficiency and the NOx concentration are nonlinear but also high efficiency and low NOx must be realized at the same time.

Originally, the optimization method as mentioned by Danzig ([1], Danzig, 1983) has been developed as a method of decision making in mathematical engineering also called optimization problem. In this method, the conditions to obtain optimal decisions (or solutions) are formulated by mathematical models, and the process to obtain optimal solutions is systemized. This theory about mathematical models is adaptable to control technology, and mathematical models in the optimization method correspond with models which formulate characteristics of controlled objects. Also, optimal solutions which are obtained by the optimization method correspond with control commands. For this reason, the optimization method can be adapted to control technology, and various studies of this application are carried out. In addition, mathematical models in the optimization method can include nonlinear formulations, and the process of this case is also systemized as nonlinear programming problem. Therefore, we can adapt the optimization method to controlled objects which have nonlinear characteristics.

We considered that it is necessary to confirm that this method can obtain the optimal solution for the VSV at first. Then, we carried out the evaluation by simulation. In the following section, we explain the modeling method which concretely expresses the problems of the VSV control (high efficiency and low NOx) by an optimization problem, and we report the simulation study using these models.

Nonlinear Modeling of Gas Turbine Characteristics

Main elements for modeling the characteristics of gas turbines are compressors, turbines and combustors. The characteristics of these elements can be formulated by physical models, and they come to mathematical models in an optimizing problem. The modeling method for each element is as follows.

First of all, the models of a compressor consist of eq. (2): the equation of the air flow rate characteristic, eq. (3) and (4): the equation of the adiabatic compression, and eq. (5): the equation of the compressor power.

$$G_c^* = f_{cmpG}(\pi_c, N_c^*, A) \tag{2}$$

$$\frac{T_{2T}}{T_1} = \pi_c^{\frac{\kappa_a - 1}{\kappa_a}} \tag{3}$$

$$H_2 - H_1 = \frac{H_{2T} - H_1}{f_{cmp\eta}(\pi_c, N_c^*, A)} \tag{4}$$

$$W_c = \frac{1}{\eta_{mc}} \cdot G_c \cdot (H_2 - H_1) \tag{5}$$

In these equations, $f_{cmpG}()$ is the function of the air flow rate characteristic, and $f_{cmp\eta}(\,)$ is the function of the adiabatic efficiency characteristic: these functions are called compressor map. Also, $N_c^{\,*}$ is the corrected speed of a compressor, $G_c^{\,*}$ is the corrected air flow rate of a compressor, and they are expressed by eq. (6) and (7).

$$N_c^{\,*} = \frac{1}{\sqrt{T_1/T_{std}}} \cdot N \tag{6}$$

$$G_c^{\,*} = \frac{\sqrt{T_1/T_{std}}}{P_1/P_{std}} \cdot G_c \tag{7}$$

Furthermore, the gas turbine speed (N) is constant at the frequency of electricity generation when we regard a gas turbine for electricity generation as the target. Also, as the change of T_1 is usually small sufficient against T_{std}, we can regard T_1/T_{std} as a constant. Therefore, we can assume $N_c^{\,*}$ to be almost constant. For these reasons, eq. (2) can be transformed into eq. (8).

$$G_c = \frac{P_1}{P_{std}} \cdot \sqrt{\frac{T_{std}}{T_1}} \cdot f_{cmpG}(\pi_c, A) \tag{8}$$

On the other hand, the relation such as eq. (9) is formed when we assume that the working substance (air) is ideal gas.

$$H = C_{pa} \cdot T \tag{9}$$

Here we adopt eq. (9) to eq. (4), and substitute the obtained equation and eq. (3) for eq. (5), for the result we obtain eq. (10).

$$W_c = \frac{G_c \cdot C_{pa} \cdot T_1 \cdot (\pi_c^{\frac{\kappa_a - 1}{\kappa_a}} - 1)}{\eta_{mc} \cdot f_{cmp\eta}(\pi_c, A)} \tag{10}$$

As mentioned above, we obtain eq. (8) and (10) as physical models which express the characteristics of a compressor.

Next, the model of a turbine consists of eq. (11): the equation of the gas flow rate characteristic, eq. (12) and (13): the equation of the adiabatic expansion, and eq. (14): the equation of the turbine power, similar to the compressor models.

$$G_t^{\,*} = f_{tbnG}(\pi_t, N_t^{\,*}) \tag{11}$$

$$\frac{T_{4T}}{T_3} = \left(\frac{1}{\pi_t}\right)^{\frac{\kappa_g - 1}{\kappa_g}} \tag{12}$$

$$H_3 - H_4 = f_{tbn\eta}(\pi_t, N_t^{\,*}) \cdot (H_3 - H_{4T}) \tag{13}$$

$$W_t = \eta_{mt} \cdot G_t \cdot (H_3 - H_4) \tag{14}$$

In these equations, $f_{tbnG}(\,)$ is the function of the gas flow rate, and $f_{tbn\eta}(\,)$ is the function of the adiabatic efficiency: these functions are called turbine map. Also, in case of a turbine, it is possible to use eq. (15) which is called the ellipse low of turbines in spite of eq. (11).

$$G_t^{\,*} = K_t \cdot \sqrt{1 - \left(\frac{P_4}{P_3}\right)^2} \tag{15}$$

Furthermore, the adiabatic efficiency of a turbine does not vary so largely when a gas turbine is operated at constant speed such as electricity generation, so we can assume that $f_{tbn\eta}(\,)$ is almost constant. Also, the corrected gas flow rate $G_t^{\,*}$ is expressed by eq. (16), similar to the compressor models.

$$G_t^{\,*} = \frac{\sqrt{T_3/T_{dsn}}}{P_3/P_{dsn}} \cdot G_t \tag{16}$$

For these things, we can transform eq. (11) and (13) into eq. (17) and (18) respectively.

$$G_t = \frac{P_4}{P_{dsn}} \cdot \sqrt{\frac{T_{dsn}}{T_3}} \cdot K_t \cdot \sqrt{\pi_t^{\,2} - 1} \tag{17}$$

$$H_3 - H_4 = \eta_{at} \cdot (H_3 - H_{4T}) \tag{18}$$

On the other hand, the relation such as eq. (19) is formed when we assume that the working substance (combustion gas) is ideal gas, as it is similar to the compressor models.

$$H = C_{pg} \cdot T \tag{19}$$

Here we adopt eq. (19) to eq. (18), and substitute the obtained equation and eq. (12) for eq. (14), for the result we obtain eq. (20).

$$W_t = G_t \cdot \eta_{mt} \cdot \eta_{at} \cdot C_{pg} \cdot T_3 \cdot (1 - \pi_t^{\frac{\kappa_g - 1}{\kappa_g}}) \tag{20}$$

As mentioned above, we obtain eq. (17) and (20) as physical models which express the characteristics of a turbine.

In addition, it is formed that $\pi_c \cong \pi_t = \pi$ when we assume that the pressure loss of a combustor can be ignored and the ambient pressure is constant such that $P_1 \cong P_4 \cong P_{std} = const$. Also, the relations among eq. (8), (10), (17) and (20) are formed into eq. (21) and (22) because a compressor and a turbine operate under the balance of the flow rate of working substance and the power of each element.

$$G_c + M = G_t \tag{21}$$

$$W_c + W_l = W_t \tag{22}$$

Another, the model of a combustor is formulated by the balance of the income and the outgo of heat at the combustor. This is expressed as eq. (23).

$$G_t \cdot H_3 = G_c \cdot H_2 + H_u \cdot M \tag{23}$$

Here we can transform eq. (23) into eq. (24) when we use assumptions such as eq. (9) and (19).

$$T_3 = \frac{G_c \cdot C_{pa} \cdot T_2 + H_u \cdot M}{G_t \cdot C_{pg}} \tag{24}$$

Also, T_2 in the eq. (24) is formulated such as eq. (25) by using eq. (3) and (4), which express the characteristics of a compressor, and assumption of eq. (9).

$$T_2 = T_1 \cdot \{ \frac{\pi_c^{\frac{\kappa_a - 1}{\kappa_a}} - 1}{f_{cmp\eta}(\pi_c, A)} + 1 \} \tag{25}$$

Lastly, the model of the NOx characteristic is necessary to evaluate the NOx concentration. However, it is difficult to formulate the NOx characteristic into physical model because the NOx characteristic is influenced by various factors complicatedly. Therefore, in this study we applied an experimental equation as the characteristic model such as eq. (26) which is obtained from experimental data.

$$NOx = f_{NOx}(\,) \tag{26}$$

As mentioned above, the nonlinear models for the optimization problem are formulated by eq. (8), (10), (17), (20), (21), (22), (24), (25) and (26). In these equations, we regard physical constants and parameters which are given as ambient conditions as constants. Also, we regard variables which are almost constant as constants. Then, this problem comes to solve the simultaneous equations with unknown variables A, M, T_3, π and NOx.

Simulation Result of Application of the Optimization Method to the VSV Control

In the optimization problem, it is necessary that the condition which must be optimize is given. This condition is given as a performance index, and it is defined that the condition will be maximum or minimum when it is optimized. In this study, we defined the performance index such as eq. (27) to realize high efficiency which is one of the most important requirements. Here eq. (27) means that the optimal solution is obtained when the fuel flow rate will be minimized at any load

$$C = \frac{M}{W_l} \tag{27}$$

Also, the nonlinear models of a gas turbine mentioned above are called equality constraints in the optimization method. In addition to them, some variables have the ranges in which the variables can exist, and we can give the ranges for each variable by some inequalities. These inequalities are called inequality constraints. In the gas turbine control, the ranges in which actuators can move and the allowable limits for the combustion temperature and so on are given as the inequality constraints. Also, we can give a condition for the allowable NOx concentration as an inequality constraint when we want to solve the optimization problem under the allowable NOx concentration. In this study, we gave the inequality constraints such as eq. (28), (29), (30) and (31) considering these things mentioned above.

$$M_{\min} \le M \le M_{\max} \tag{28}$$

$$A_{\min} \le A \le A_{\max} \tag{29}$$

$$T_3 \le T_{3\max} \tag{30}$$

$$NOx \le NOx_{\max} \tag{31}$$

Then, we evaluated whether we can obtain the optimal solution of the VSV command which makes the efficiency be maximum under the allowable NOx concentration by mathematical simulation. In this simulation study, we adopted the SQP (Sequential Quadratic Programming Method) which is generally used for nonlinear optimization problems to solve them. The detail algorithm of the SQP has been shown by Powell ([2], Powell, 1978).

Fig. 7 shows simulation result mentioned above, and this result shows the optimal solution for the VSV command in the entire range from no load to full load (Fig. 7-(a)). Here the characteristics of the thermal efficiency and the NOx concentration are influenced by the ambient temperature, so we carried out some cases for several conditions of the ambient temperature: T_1 = 263, 273, 288, 303 and 313 (K) (T_1 = -10, 0, 15, 30, 40 (deg C)). For this result, we confirm that we can obtain the optimal solution for the VSV command by this application in the entire range of the gas turbine operation in any condition of the ambient temperature. By the way, the VSV command is fixed to about 0.5(-) in the low range and the middle range of the gas turbine load as shown in Fig. 7-(a) because the VSV command is limited on the low side such as eq. (29): we set the limit value of the VSV command to 0.5(-) on the low side in this simulation. Also, Fig. 7-(c) shows the NOx concentration in this simulation. For this result, the optimal solution for the VSV command satisfies the allowable NOx concentration: we set the allowable NOx concentration to 1.0(-) in eq. (31). However, we used an experimental equation (not physical equation) as the model of the NOx concentration mentioned above. Although we may obtain different result if this model is given by other formulation, the optimization method enables us to obtain the optimal solution in any case.

Also, Fig. 8 shows the effect of improvement using the optimization method which is obtained by simulation study. This

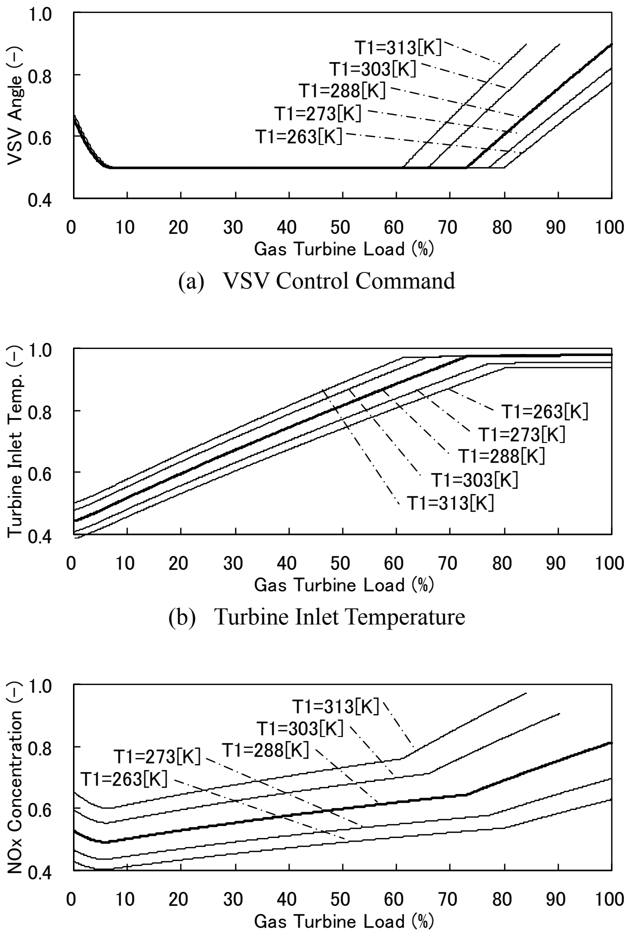
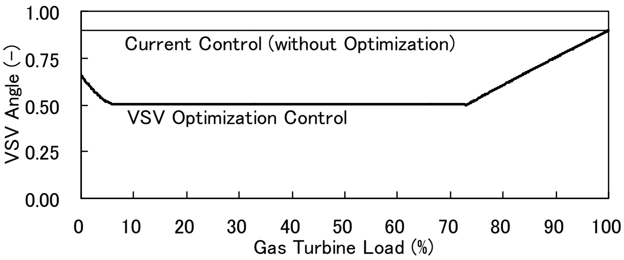
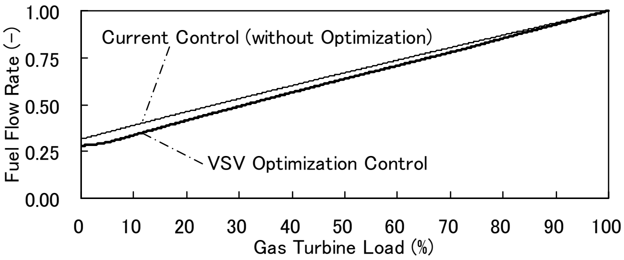


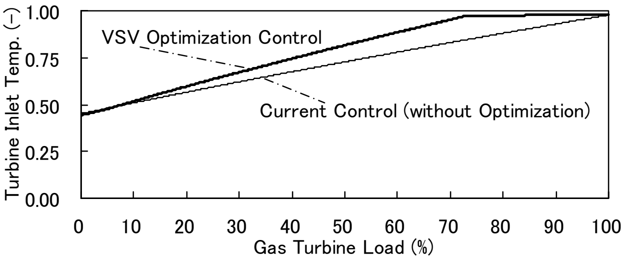
Fig. 7 The Simulation Result of Optimizing Calculation



(a) VSV Control Command



(b) Fuel Flow Rate



(c) Turbine Inlet Temperature

Fig. 8 Comparison of the Current Control and the VSV Optimization Control

result shows comparison between the VSV control with the optimization method and current control method used up to this time (the ambient temperature is 273 (K) in both cases). We evaluated that the fuel flow rate in case of using the optimization method is less than in case of the current control method, and this effect is large in the low range of the load as shown in Fig. 8-(b). Fig. 9 shows the ratio of fuel flow rate in case of the optimization method against the current control method which is defined as the "Fuel Expenses Ratio" to show the effect of improvement for the thermal efficiency clearly.

In addition, the TIT (Turbine Inlet Temperature) is higher, and the thermal efficiency is increased more. This means that to close the VSV and to reduce the air flow rate are better for high efficiency, and Fig. 7-(a) and (b) show this characteristic. Therefore, it is a better way that the VSV is closed to the minimum angle in the low and the middle range of the load to increase the TIT. Also, it is suitable that the VSV is operated to control the TIT to near the allowable maximum value given as eq. (30) in the high range of the load.

CONCLUSION

In recent years, social requirements for gas turbines such as high efficiency and low NOx are increasing in background of the environmental problems, and control systems of gas turbines should realize more advanced performance to meet these requirements. Also, it is necessary that these control systems can deal with nonlinear objects, which have large variation of the characteristics. Therefore, we considered that application of

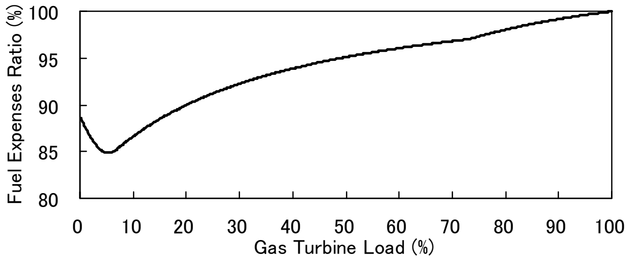


Fig. 9 Improvement of the Fuel Expenses by the VSV Optimization Control

nonlinear control to gas turbines is suitable to cope with nonlinear objects, and we are carrying out a study of applications of nonlinear control. In this paper, we reported two representatives of our study: one is the gas turbine starting control by the fuzzy control and the other is the application of the optimization method to the VSV control.

In the former, we reported the gas turbine starting control by the fuzzy control, and we explained characteristics of gas turbines in the starting process, the formulation of the fuzzy rules, and the construction of the control logic. Also, we reported the experimental result on an actual gas turbine and the evaluation of the effect of this control method which can perform the starting process surely without late start and over rising of the EGT in any condition of temperature.

In the latter, we reported the application of the optimization method to the VSV control, and we explained the formulation of the nonlinear models of gas turbines and the application of the optimization problem to the VSV control. Also, we confirmed that we can obtain the optimal solution for the VSV command to realize high efficiency and low NOx, and the thermal efficiency is improved by this control method.

However, the algorithms to solve the optimization problems are so large and complicated that it is difficult to install them in computers. Also, these algorithms take much time because they need a lot of iterations of calculation, so it is difficult to execute them on-line. Recently, some studies of these algorithms have been carried out, and some advanced algorithms have been developed. Therefore, we will carry out a study to apply these algorithms and develop applications to actual machines from now on.

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