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GAS TURBINE CONTROL DEVICE AND GAS TURBINE CONTROL METHOD

Abstract

A gas turbine control device including a frequency analysis unit, a database, a combustion state prediction unit, and a correction amount calculation unit. The frequency analysis unit performs a frequency analysis of the vibration of a pressure or an acceleration inside a combustor, at an operation point specified by a process amount of the gas turbine, and outputs a frequency analysis result. The database stores the frequency analysis result and the process amount as analysis data for each operation point. The combustion state prediction unit predicts a combustion state using a prediction model constructed using analysis data. When a search start condition is met that defines the elapse of a wait time which is set based on past search records in an operation point region including an operation point, the correction amount calculation unit calculates a correction amount to be added to a control signal for the gas turbine.

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Background/Summary

TECHNICAL FIELD
[0001] The present disclosure relates to a gas turbine control device and a gas turbine control method.
[0002] The present application claims priority based on Japanese Patent Application No. 2022-096221 filed in Japan on Jun. 15, 2022, the contents of which are incorporated herein by reference.
BACKGROUND ART
[0003] In a gas turbine driven by using a combustion gas generated by a combustor, based on an output of a generator connected to the gas turbine, an ambient air temperature, or a humidity, a flow rate of a fuel or of air supplied to the combustor to generate the combustion gas is determined in advance. Values thereof are finely adjusted in a trial run, and are used for an operation. However, the trial run is actually performed in a limited period of time. Therefore, the value adjustment which takes all weather conditions into consideration cannot be achieved by the trial run. In addition, performance of a compressor for compressing the air supplied to the gas turbine may deteriorate, or a filter for removing foreign substances contained in the air may suffer aging defects including clogging. Therefore, there is a probability that an actual flow rate deviates from a planned flow rate or an adjusted flow rate in the trial run. In this case, there is a probability that combustion stability of the gas turbine is lowered, and that a combustion state of the gas turbine may deviate from a management range. There is a probability that this deviation of the combustion state from the management range leads to a malfunction such as a failure of the turbine, and the malfunction greatly hinders an operation of the gas turbine. Therefore, from the viewpoint of protecting the gas turbine and improving an operation rate, it is desirable to suppress and avoid the deviation of the combustion state from the management range as much as possible.
[0004] For example, PTL 1 discloses a technique for suppressing this deviation of the combustion state from the management range in the gas turbine. In PTL 1, based on a result obtained by performing frequency analysis on vibration of a pressure or of acceleration inside the combustor of the gas turbine, characteristics of combustion vibration are analyzed as the combustion state, and the flow rate of the fuel supplied to the combustor or the flow rate of the air is adjusted so that the combustion vibration is suppressed within the management range. Furthermore, adjusted process values are accumulated in a database, and subsequently, accumulated data in the database is used to improve reliability when the flow rate of the fuel or the flow rate of the air is adjusted to suppress the combustion vibration.
CITATION LIST
Patent Literature
[0005] [PTL 1] Japanese Unexamined Patent Application Publication No. 2005-155590
SUMMARY OF INVENTION
Technical Problem
[0006] In this type of gas turbine control device, when an operating point of the gas turbine is moved to suppress the combustion state within the management range as disclosed in PTL 1,

surrounding operating points are searched for by automatically increasing or decreasing a fuel flow rate so that the combustion state is stabilized within the management range, and characteristic data relating to the combustion state at the operating points is collected. In this manner, more information can be accumulated in the database to improve the reliability. From the viewpoint of ascertaining the characteristics of the combustion state with high reliability, based on the information accumulated in the database in this way, it is desirable that information acquired under various operating conditions is accumulated in the database.

[0007] However, as described above, data collected at the operating points searched for while the fuel flow rate is automatically increased or decreased within the management range of the combustion state is extremely similar. Even when the same search is performed many times, only the similar data is collected, and it is difficult to collect various data. In contrast, when the operating point is searched for to collect various data, the combustion state deviates from the management range, thereby causing an increased probabilityprobability of the combustion vibration.

[0008] At least one embodiment of the present disclosure is made in view of the above-described circumstances, and aims to provide a gas turbine control device and a gas turbine control method which can collect various characteristic data while maintaining a combustion state within a management range.

[0009] Solution to Problem

[0010] According to at least one embodiment of the present disclosure, in order to solve the above-described problems, there is provided a gas turbine control device including a frequency analysis unit for outputting a frequency analysis result by performing a frequency analysis on vibration of a pressure or of acceleration inside a combustor of a gas turbine at operating points specified by a process amount of the gas turbine, a database for storing the frequency analysis result and the process amount as analysis data for each of the operating points, a combustion state prediction unit for predicting a combustion state of the gas turbine by using a prediction model constructed by using the analysis data, and a correction amount calculation unit for calculating a correction amount to be added to a control signal of the gas turbine to operate the gas turbine at a search candidate point where the combustion state predicted by the state prediction unit falls within a management range, out of search candidate points in which the operating point is a start point, when a search start condition defining an elapse of a waiting time set based on a past search result in an operating point region including the operating point is satisfied.

[0011] According to at least one embodiment of the present disclosure, in order to solve the above-described problems, there is provided a gas turbine control method including a step of outputting a frequency analysis result by performing a frequency analysis on vibration of a pressure or of acceleration inside a combustor of a gas turbine at operating points specified by a process amount of the gas turbine, a step of storing the frequency analysis result and the process amount as analysis data for each of the operating points, a step of predicting a combustion state of the gas turbine by using a prediction model constructed by using the analysis data, and a step of calculating a correction amount to be added to a control signal of the gas turbine to operate the gas turbine at a search candidate point where the combustion state predicted by the state prediction unit falls within a management range, out of search candidate points in which the operating point is a start point, when a search start condition defining an elapse of a waiting time set based on a past search result in an operating point region including the operating point is satisfied.

Advantageous Effects of Invention

[0012] According to at least one embodiment of the present disclosure, it is possible to provide a gas turbine control device and a gas turbine control method which can efficiently collect analysis data used to construct a prediction model for predicting characteristics relating to combustion stability of a gas turbine while maintaining an operating state of the gas turbine within a management range.

Description

BRIEF DESCRIPTION OF DRAWINGS

[0013] FIG. **1** is a view schematically illustrating a configuration of a gas turbine according to an embodiment.

[0014] FIG. **2** is a block diagram functionally illustrating a gas turbine control device according to the embodiment together with the gas turbine.

[0015] FIG. **3** is a block diagram illustrating a detailed functional configuration of the gas turbine control device in FIG. **2**.

[0016] FIG. **4** is a flowchart of a turbine control method executed by the gas turbine control device in FIG. **3**.

[0017] FIG. **5** is an example of a result obtained by performing a frequency analysis on a pressure fluctuation in Step S**101** in FIG. **4**.

[0018] FIG. **6** is a view schematically illustrating a first virtual space defined by a process amount of the gas turbine.

[0019] FIG. **7** is a view schematically illustrating a second virtual space defined by the process amount of the gas turbine.

[0020] FIG. **8** is a view schematically illustrating a third virtual space defined by the process amount of the gas turbine.

DESCRIPTION OF EMBODIMENTS

[0021] Hereinafter, some embodiments of the present invention will be described with reference to the accompanying drawings. Meanwhile, configurations described in the embodiments or illustrated in the drawings are not intended to limit the scope of the invention, and are merely examples for description.

[0022] First, a gas turbine **2** serving as a control target of a gas turbine control device according to at least one embodiment of the present disclosure will be described. FIG. **1** is a view schematically illustrating a configuration of the gas turbine **2** according to the embodiment. The gas turbine **2** includes a gas turbine body part **100** and a combustion unit **110**.

[0023] The gas turbine body part **100** includes a compressor **101** having an inlet guide vane **102**, a rotary shaft **103**, and a turbine **104**. The compressor **101** and the turbine **104** are connected by a rotary shaft **103**, and a generator **121** is connected to the turbine **104**.

[0024] A combustion gas introduction pipe **120** is connected to the turbine **104**. A combustion gas introduced from the combustion gas introduction pipe **120** drives the turbine **104**, and the combustion gas (exhaust gas) used for work is discharged to an outside. The turbine **104** is driven by the combustion gas to convert energy of the combustion gas into rotational energy. The rotational energy of the turbine **104** is used to drive the compressor **101** and the generator **121** which are connected to the turbine **104**.

[0025] The compressor **101** introduces air (intake) from the outside to generate compressed air, and feeds the generated compressed air to the combustor **111** via a compressed air introduction unit **112**. In addition, the compressor **101** is connected to the turbine **104** and the generator **121** via a rotary shaft **103**, and can be driven by the rotational energy of the turbine **104**. The generator **121** is driven in this way to convert the rotational energy into electrical energy.

[0026] The inlet guide vane **102** is a rotary vane on an air introduction side of the compressor **101**. The inlet guide vane **102** controls an angle of the rotary vane so that a flow rate of the air introduced into the compressor **101** can be adjusted even when a rotation speed is substantially constant.

[0027] The combustion unit **110** includes the compressed air introduction unit **112**, a bypass air introduction pipe **117**, a bypass valve **118**, a bypass air mixing pipe **119**, a combustion gas introduction pipe **120**, the combustor **111**, a main fuel flow control valve **113**, a pilot fuel flow

control valve **114**, a main fuel supply valve **115**, and a pilot fuel supply valve **116**.
[0028] The compressed air introduction unit **112** is connected to the compressor **101**, and is configured to guide the compressed air generated by the compressor to the combustor **111**. The bypass air introduction pipe **117** and the bypass air mixing pipe **119** are configured to mix the combustion gas generated in the combustor **111** in such a manner that a portion of the compressed air introduced by the compressed air introduction unit **112** is introduced into the combustion gas introduction pipe **120** by bypassing the combustor **111**. The bypass air introduction pipe **117** is connected to the compressed air introduction unit **112** on an upstream side of the combustor **111**, and the bypass air mixing pipe **119** is connected to the combustion gas introduction pipe **120** on a downstream side of the combustor **111**. In addition, a bypass valve **118** for adjusting a flow rate of the compressed air bypassing the combustor **111** is provided between the bypass air introduction pipe **117** and the bypass air mixing pipe **119**.
[0029] The main fuel flow control valve **113** is configured to control a flow rate of a main fuel supplied to a main burner (not illustrated) of the combustor **111**. The main fuel supply valve **115** is configured to control a supply state (on/off) of the main fuel to the main burner of the combustor **111**.
[0030] The pilot fuel flow control valve **114** is configured to control a flow rate of a pilot fuel supplied to a pilot burner (not illustrated) of the combustor **111**. The pilot fuel supply valve **116** is configured to control a supply state (on/off) of the pilot fuel to the pilot burner of the combustor **111**.
[0031] The combustor **111** is connected to the compressed air introduction unit **112** for supplying the compressed air, a pipe connected to the main fuel supply valve **115** for supplying the main fuel, a pipe connected to the pilot fuel supply valve **116** for supplying the pilot fuel, and the combustion gas introduction pipe **120** for feeding the combustion gas. In the combustor **111**, the compressed air introduced from the compressed air introduction unit **112**, and the main fuel and the pilot fuel are respectively supplied and combusted to generate a high-temperature and high-pressure combustion gas. The generated combustion gas is fed to the turbine **104** via the combustion gas introduction pipe **120**.
[0032] One end of the combustion gas introduction pipe **120** is connected to the combustor **111**, and the other end is connected to the turbine **104**. In addition, the bypass air mixing pipe **119** is connected to an intermediate portion of the combustion gas introduction pipe **120**.
[0033] Subsequently, a gas turbine control device **1** for controlling the gas turbine **2** having the above-described configuration will be described. For example, the gas turbine control device **1** is configured to include a central processing unit (CPU), a random-access memory (RAM), a read-only memory (ROM), and a computer-readable storage medium. As an example, a series of processes for realizing various functions are stored in the storage medium in a form of a program. The CPU reads the program in the RAM, and executes information processing and arithmetic processing. In this manner, various functions are realized. A form installed in advance in the ROM or other storage medium, a form provided in a state of being stored in a computer-readable storage medium, or a form of being delivered via wired or wireless communication means may be applied as the program. The computer-readable storage medium is a magnetic disc, a magneto-optical disc, a CD-ROM, a DVD-ROM, or a semiconductor memory.
[0034] FIG. **2** is a block diagram functionally illustrating the gas turbine control device **1** according to the embodiment together with the gas turbine **2**. The gas turbine **2** includes a process amount measurement unit **4**, a pressure fluctuation measurement unit **5**, an acceleration measurement unit **6**, and an operation mechanism **7**, as configurations relating to the control performed by the gas turbine control device **1**.
[0035] The process amount measurement unit **4** has a configuration for measuring a process amount indicating an operating condition or an operating state during an operation of the gas turbine **2**, and represents various measurement devices. The process amount measurement unit **4** is

installed in an appropriate portion on the gas turbine **2**, and a measurement result thereof is output to a controller **10** of the gas turbine control device **1** at each predetermined time interval. Here, for example, the process amount is generated power (generated current and generated voltage) of the generator **121**, an air temperature and humidity around the gas turbine **2**, a fuel flow rate and pressure in each part of the gas turbine **2**, an air flow rate and pressure, a combustion gas temperature in the combustor **111**, a combustion gas flow rate, a combustion gas pressure, a rotation speed of the compressor **101** or the turbine **104**, and concentration of emission including nitrogen oxide (NOx) contained in an exhaust gas of the turbine **104** and carbon monoxide (CO).

[0036] Here, in addition to an operable “operation amount” such as the amount of the fuel or the air supplied to the gas turbine **2**, the process amount measurement unit **4** may measure “the amount in an inoperable state”, for example, such as meteorological data including an air temperature and a magnitude (MW) of a load of the generator determined at a request (in this case, the “process amount” includes “an operation amount (plant data)” and “the amount in an inoperable state”).

[0037] The pressure fluctuation measurement unit **5** is a pressure measurement device attached to the combustor **111**. The pressure fluctuation measurement unit **5** outputs a pressure fluctuation measurement value inside the combustor **111** which is generated by combustion at each predetermined time interval, to the gas turbine control device **1** in accordance with a command from the controller **10**.

[0038] The acceleration measurement unit **6** is an acceleration measurement device attached to the combustor **111**. The acceleration measurement unit **6** measures acceleration of the combustor **111** which is generated by combustion at each predetermined time interval, in accordance with a command from the controller **10**, and outputs a measurement value thereof to the gas turbine control device **1**.

[0039] The operation mechanism **7** is a mechanism that operates opening degrees of the main fuel flow control valve **113**, the main fuel supply valve **115**, the pilot fuel flow control valve **114**, and the pilot fuel supply valve **116** in accordance with a command from the controller **10**. In this manner, the operation mechanism **7** controls the flow rates of the main fuel and the pilot fuel. In addition, the operation mechanism **7** operates an opening degree of the bypass valve **118** in accordance with a command from the controller **10**, and controls the flow rate of the air supplied to the combustor **111**. Specifically, in the combustor **111**, the flow rate of the air supplied to the combustor **111** is controlled by increasing (or decreasing) the opening degree of the bypass valve **118** and by increasing (or decreasing) the air flow rate flowing to the bypass side. In addition, the operation mechanism **7** operates an angle of the rotary vane of the inlet guide vane **102** in accordance with a command from the controller **10**, and controls the flow rate of the air introduced into the compressor **101**.

[0040] The gas turbine control device **1** includes the controller **10** and an automatic adjustment unit **20**. The controller **10** receives measurement values output from the process amount measurement unit **4**, the pressure fluctuation measurement unit **5**, and the acceleration measurement unit **6**, and transfers the measurement values to the automatic adjustment unit **20**. In addition, based on a command from the automatic adjustment unit **20**, the controller **10** outputs signals for operating the main fuel flow control valve **113**, the main fuel supply valve **115**, the pilot fuel flow control valve **114**, the pilot fuel supply valve **116**, the bypass valve **118**, and the inlet guide vane **102**, which are operation targets, to the operation mechanism **7**.

[0041] FIG. **3** is a block diagram illustrating a detailed functional configuration of the gas turbine control device **1** in FIG. **2**, and FIG. **4** is a flowchart of a turbine control method executed by the gas turbine control device **1** in FIG. **3**.

[0042] In the gas turbine control devices **1**, the automatic adjustment unit **20** includes an input unit **21**, a state ascertaining unit **22**, a frequency analysis unit **23**, a correction amount calculation unit **24**, a combustion state prediction unit **25**, a database **26**, and an output unit **28**. These configurations function as follows when the gas turbine control method illustrated in FIG. **4** is executed.

[0043] First, various data transferred from the controller **10** (process amount, pressure, and acceleration which are output from the process amount measurement unit **4**, the pressure fluctuation measurement unit **5**, and the acceleration measurement unit **6** which are illustrated in FIG. **2**) are input to the input unit **21** (Step S**100**). Various data input to the input unit **21** are delivered to the state ascertaining unit **22** and the frequency analysis unit **23** when necessary, and are used for various processes described later.

[0044] Subsequently, the frequency analysis unit **23** performs a frequency analysis on pressure fluctuations (measurement result of the pressure fluctuation measurement unit **5**) or acceleration (measurement result of the acceleration measurement unit **6**) in the various data acquired in Step S**100** (Step S**101**). The frequency analysis in Step S**101** is performed by applying Fast Fourier Transformation (FFT) to fluctuations in the pressure or the acceleration. A frequency analysis result obtained by the frequency analysis unit **23** is output to the state ascertaining unit **22** and the combustion characteristic ascertaining unit **25**.

[0045] Here, FIG. **5** is an example of a result obtained by performing a frequency analysis on a pressure fluctuation in Step S**101** in FIG. **4**. In FIG. **5**, a horizontal axis represents a frequency, and a vertical axis represents vibration intensity (level). As illustrated in FIG. **5**, combustion vibration (pressure vibration or acceleration vibration) generated in the combustor **111** has a plurality of vibration frequencies. The frequency analysis may be performed by dividing the frequency into a plurality of frequency bands. Here, the frequency band is a frequency region which is a minimum unit for correspondence, based on a result obtained by the frequency analysis unit **23** performing the frequency analysis.

[0046] Subsequently, various data input in Step S**100** and a frequency analysis result obtained in Step S**101** are stored (added or updated) in the database **26** as analysis data (Step S**102**). The analysis data is stored to include the frequency analysis result at an operating point specified by the process amount included in the various data input in Step S**100**. As will be described later, a series of steps illustrated in FIG. **4** is repeatedly performed while the operating points are searched for, and the analysis data is sequentially stored in the database **26** for each operating point.

[0047] The analysis data accumulated in the database **26** in this way is used to construct a prediction model for predicting a combustion state of the gas turbine in the combustion state prediction unit **25**. A method for constructing the prediction model is not limited, and a regression analysis or machine learning using the analysis data can be used.

[0048] Subsequently, it is determined whether or not a state of the gas turbine ascertained by the state ascertaining unit **22** deviates from a management range (Step S**103**). In the determination in Step S**103**, the state ascertaining unit **22** ascertains the state of the gas turbine, based on process values included in various data input in Step S**100** and the frequency analysis result obtained in Step S**101**. The state is compared with a preset management range to determine whether or not the state deviates from the management range.

[0049] The state of the gas turbine ascertained by the state ascertaining unit **22** includes the presence or absence of the combustion vibration generated in the gas turbine, NOx or CO concentration contained in the exhaust gas from the gas turbine, or the combustion state of an accidental fire. In addition, the management range as a determination reference in Step S**103** is defined by reference values (for example, an upper limit reference value and a lower limit reference value) corresponding to respective parameters indicating the states of the gas turbines. In an example in FIG. **5**, the vibration intensity of the gas turbine is illustrated as an example of the state of the gas turbine. When the vibration intensity deviating from a management value (threshold value) which is the management range defined for the vibration intensity is detected, it can be determined that the combustion vibration is generated in the gas turbine. This management value may be set for each frequency band.

[0050] As a result, when it is determined that the state of the gas turbine deviates from the management range (Step S**103**: YES), the gas turbine control device **1** takes countermeasures so that the state of the gas turbine does not deviate from the management range (Step S**104**). For example, when the combustion vibration is generated due to a factor where the state of the gas turbine deviates from the management range, the countermeasure taken in Step S**104** may be countermeasures for suppressing the combustion vibration such as adjustment of the flow rate of the fuel or the air (adjustment of an air-fuel ratio), or may be stopping the operation of the gas turbine **2**.

[0051] On the other hand, when it is determined that the state of the gas turbine does not deviate from the management range (Step S**103**: NO), the gas turbine control device **1** determines whether or not the operating point is being searched for by the automatic adjustment unit **20** (Step S**105**). When the operating point is not being searched for (Step S**105**: NO), that is, when searching for the operating point starts from now, a past search result in an operating point region including a current operating point is checked (Step S**106**). In Step S**106**, for example, the analysis data stored in the database **26** is searched for. In this manner, the past search result is checked by searching past analysis data in the operating point region including the current operating point. More specifically, the past search result is checked, based on whether or not the analysis data stored in the database **26** has data included in the operating point region including a checking target operating point. More preferably, the past search result is checked, based on whether or not the analysis data stored in the database **26** has sufficient data for constructing a reliable prediction model in the operating point region.

[0052] In the present embodiment, the analysis data stored in the database **26** also serves as data for constructing the prediction model and reference data for checking the presence or absence of the past search result in the operating point region. However, the analysis data for constructing the prediction model and the reference data for checking the presence or absence of the past search result in the operating point region may be respectively stored in separate databases. That is, the database **26** may include a database for storing the analysis data for constructing the prediction model and a database for storing the reference data for checking the presence or absence of the past search result in the operating point region.

[0053] The operating point region handled in Step S**106** is a range having a predetermined spread including a certain operating point. For example, when used as the analysis data used for constructing the prediction model, the operating point region is defined to include a range in which contributions to the operating point and the prediction model can be regarded as substantially equal, that is, a range which can be regarded as similar to a certain operating point.

[0054] Subsequently, the automatic adjustment unit **20** sets a waiting time included in a search start condition, based on the past search result checked in Step S**106** (Step S**107**). The search start condition is a condition for starting the search for a search candidate point that is a subsequent movement destination candidate of the operating point in Step S**109** (to be described later), and is defined under a condition that the waiting time set in Step S**107** elapses.

[0055] The waiting time is set in Step S**107** to become shorter as the number of data included in the operating point region including the operating point in the analysis data stored in the database **26** decreases. In this manner, collecting the analysis data in the operating point region having the small number of data is promoted. Accordingly, reliability of the prediction model constructed by using the analysis data can be effectively improved.

[0056] Subsequently, the automatic adjustment unit **20** determines whether or not the search start condition is satisfied as the waiting time set in Step S**107** elapses (Step S**108**). When the search start condition is satisfied (Step S**108**: YES), a search candidate point is selected (Step S**109**). The search candidate point is selected as a movement destination candidate of the operating point, based on a predetermined search algorithm.

[0057] Subsequently, the combustion state prediction unit **25** predicts a combustion state for the search candidate point selected in Step S**109** (Step S**110**). In Step S**110**, the combustion state when the operating point of the gas turbine shifts to the search candidate point is predicted by using the prediction model constructed by using the analysis data stored in the database **26**. For example, the combustion state of the gas turbine which is predicted in Step S**110** includes the presence or absence of the combustion vibration generated in the gas turbine, NOx or CO concentration contained in the exhaust gas from the gas turbine, and the presence or absence of an accidental fire.

[0058] Subsequently, the automatic adjustment unit **20** determines whether or not the combustion state predicted in Step S**110** deviates from the management range (Step S**111**). The management range serving as a determination reference in Step S**111** is defined by reference values (for example, an upper limit reference value and a lower limit reference value) corresponding to respective parameters indicating the combustion states of the gas turbines. That is, in Step S**111**, the combustion state predicted by the combustion state prediction unit **25** is determined to be substantially similar to Step S**103** described above. In this manner, it is determined whether or not the combustion state at the search candidate point deviates from the management range.

[0059] As a result, when it is determined that the combustion state of the gas turbine at the search candidate point does not deviate from the management range (Step S**111**: YES), the automatic adjustment unit **20** commands the correction amount calculation unit **24** to output a correction value for shifting to the search candidate point searched for in Step S**109** (Step S**112**). As a result, the operating point of the gas turbine shifts to the search candidate point searched for in Step S**109**, and the process returns to Step S**100**.

[0060] On the other hand, when it is determined that the combustion state of the gas turbine at the search candidate point deviates from the management range (Step S**111**: NO), the process returns to Step S**113**. In Step S**113**, it is determined whether or not a search end condition is satisfied. When the search end condition is not satisfied (Step S**113**: NO), the process proceeds to Step S**109** to select the subsequent search candidate point. In this case, for the subsequent search candidate point as well, the analysis data used for constructing the prediction model is collected by moving the operating point within a range in which the combustion state of the gas turbine which is predicted by the combustion state prediction unit **25** does not deviate from the management range.

[0061] When the search end condition is satisfied (Step S**113**: YES), the operating point of the gas turbine returns to the point before the search (Step S**114**).

[0062] As described above, in this gas turbine control method, the above-described process is repeatedly performed. In this manner, while the operating point of the gas turbine moves to the search candidate point in which the combustion state does not deviate from the management range, the analysis data used for constructing the prediction model can be collected.

[0063] Here, in Step S**107**, the waiting time is set to be variable, based on the past search result in the operating point region including the operating point of the gas turbine. For example, when there is no past search result in the operating point region, a first waiting time is set as the waiting time. On the other hand, when there is the past search result in the operating point region, a second waiting time longer than the first waiting time is set as the waiting time. That is, when there is the past search result in the operating point region, the waiting time is set to be longer, compared to when there is no past search result.

[0064] When there is no past search result in the operating point region, the analysis data collected in the past for the operating point region is not stored in the database **26**. Therefore, when the operating point of the gas turbine shifts to the search candidate point included in the operating point region, the analysis data is not stored in the database **26**, and there is a high probability of obtaining data which greatly contributes to prediction accuracy when the prediction model is constructed. Therefore, in this case, the relatively short first waiting time is set as the waiting time. In this manner, it is possible to promote data collection in the operating point region where there is no past search result.

[0065] On the other hand, when there is the past search result in the operating point region, the analysis data collected in the past for the operating point region is stored in the database **26**.

Therefore, even when the operating point of the gas turbine shifts to the search candidate point included in the operating point region, the operating point is similar to the analysis data previously stored in the database **26**, and there is a high probability of obtaining data which contributes less to prediction accuracy when the prediction model is constructed. Therefore, in this case, the relatively long second waiting time is set as the waiting time. In this manner, it is possible to suppress the collection of similar data in the operating point region where there is the past search result.

[0066] In addition, the operating point region which is a target for determining the presence or absence of the past search result for setting the waiting time in Step S**107** may be defined in such a manner that a first virtual space V**1** defined by the process amount of the gas turbine **2** is divided. Here, FIG. **6** is a view schematically illustrating the first virtual space V**1** defined by the process amount of the gas turbine **2**. In FIG. **6**, the first virtual space V**1** is defined as a two-dimensional space by two types of process amounts A and B, and is divided into a plurality of areas to correspond to a numerical range of the respective process amounts A and B. In this case, in Step S**107**, it is determined which area of the first virtual space V**1** the operating point of the gas turbine belongs to, and the area to which the operating point belongs is specified as the operating point region (in FIG. **6**, the area corresponding to the operating point region to which the operating point belongs is illustrated by dark hatching).

[0067] In FIG. **6**, a two-dimensional space defined by two types of the process amounts A and B is illustrated as an example of the first virtual space V**1**. However, the first virtual space V**1** may be a multi-dimensional space defined by more types of the process amounts.

[0068] In an example illustrated in FIG. **6**, a case where the presence or absence of the past search result is determined in units of the area divided by the first virtual space V**1** in Step S**107** is illustrated as an example. However, the presence or absence of the past search result may be determined, based on a Euclidean distance to a value obtained by normalizing the operating state.

[0069] In addition, the waiting time may be set in Step S**107**, based on the number of data included in the past search result in the operating point region. In this case, when there is the past search result in the operating point region, the number of the analysis data stored in the database **26** is specified as the past search result. For example, the waiting time is set to be shortened as the number of the data decreases. The analysis data in the operating point region having a small number of the past search results greatly contributes to reliability improvement of the prediction model. Therefore, the short waiting time for the operating point having the small number of the data included in the past search result is set. In this manner, it is possible to promote collection of the analysis data in the operating point region.

[0070] In addition, in selecting the search candidate point in Step S**109**, uncertainty o of the prediction model is evaluated for each search route settable in a second virtual space V**2** defined by the process amount, and the search candidate point may be selected from the search route having a high uncertainty σ. In this case, each of the search routes settable in the second virtual space V**2** may be defined as a route including the operating points in which the process amounts are different at a predetermined interval (for example, at an equal interval). Here, FIG. **7** is a view schematically illustrating the second virtual space V**2** defined by the process amounts A and B of the gas turbine **2**. In an example in FIG. **7**, in the second virtual space V**2**, a first search route R**1** (process amount B is fixed to zero) in which only the process amount A is changed at a regular interval, and a second search route R**2** (process amount A is fixed to zero) in which only the process amount B is changed at a regular interval are illustrated.

[0071] The automatic adjustment unit **20** calculates the uncertainty σ for each operating point in the first search route R**1** and the second search route R**2**. Specifically, operating points a**1**, a**2**, a**3**, a**4**, . . . and so on belong to the first search route R**1**. The operating point al has an average value p1=0.3 and a standard deviation σ1=0.1 for a process value A. The operating point a**2** has an average value p2=0.5 and a standard deviation σ2=0.2 for the process value A. The operating point a**3** has an average value p3=0.7 and a standard deviation σ3=0.3 for the process value A. The operating point a**4** has an average value p4=1.1 and a standard deviation σ4=0.2 for the process value A. Here, when a preset allowable range (p<1.0) is defined for the process value A, uncertainty σA relating to the first search route R**1** is obtained through the following equation by using the standard deviation of the operating points included in the allowable range.

[00001] $A = (\sigma 1 + \sigma 2 + \sigma 3) / 3 = (0.1 + 0.2 + 0.3) / 3 = 0.2$

[0072] Similarly, operating points b**1**, b**2**, b**3**, . . . , and so on belong to the second search route R**2**. The operating point b**1** has an average value p1=0.5 and a standard deviation σ1=0.2 for a process value B. The operating point b**2** has an average value p2=0.3 and a standard deviation σ2=0.6 for the process value B. Here, when the operating points b**1** and b**2** are included in a range of upper and lower limiters for the process value B, uncertainty σB for the second search route R**2** is obtained through the following equation by using the standard deviation of the respective operating points.

[00002] $B = (\sigma 1 + \sigma 2) / 2 = (0.2 + 0.6) / 2 = 0.4$

[0073] The automatic adjustment unit **20** compares the uncertainties σA and σB obtained for the first search route R**1** and the second search route R**2** in this way. In this manner, the automatic adjustment unit **20** preferentially selects the search candidate point from the search route having the high uncertainty. In this example, the uncertainty σB corresponding to the second search route R**2** is higher than the uncertainty σA corresponding to the first search route R**1**. Therefore, the search candidate point is selected from the second search route R**2** earlier than the first search route R**1**. In this way, the search candidate point is preferentially selected from the search route having the high uncertainty in the second virtual space V**2**. In this manner, it is possible to suitably collect the analysis data which greatly contributes to the improvement of the reliability of the prediction model.

[0074] In the present embodiment, a case where both the uncertainties σA and σB when the first search route R**1** and the second search route R**2** are compared are calculated as an average value of the standard deviations of the respective operating points belonging to the respective search routes has been described as an example. However, other references such as a maximum value or a minimum value may be compared for the standard deviation of the respective operating points belonging to the respective search routes.

[0075] In addition, in Step S**112**, when the correction value is output so that the operating point of the gas turbine **2** shifts to the search candidate point selected in Step S**109**, a change speed of a control signal with respect to the gas turbine **2** in accordance with the correction value may be changed to be variable. In this case, the change speed of the control signal may be set, based on at least one of behavior stability of the gas turbine from the current operating point to the search candidate point selected in Step S**109**, or the number of data included in the past search result in the operating point region including the current operating point.

[0076] FIG. **8** is a view schematically illustrating a third virtual space V**3** defined by the process amount of the gas turbine **2**. In the third virtual space V**3**, a region C where the behavior stability of the gas turbine **2** is expected to be relatively high, based on a prediction result of the combustion state prediction unit **25**, and a region D where the behavior stability of the gas turbine **2** is expected to be relatively low, based on the prediction result of the combustion state prediction unit **25** are illustrated as an example.

[0077] For example, in the region C, the behavior stability of the gas turbine **2** is high. Therefore, the correction amount per unit time is increased. In this manner, it is possible to increase the change speed of the control signal when the correction amount for shifting to the search candidate point selected in Step S**109** is added. In this manner, in the region C where the behavior of the gas turbine **2** is expected to be stable, the change speed of the control signal is increased. In this manner, the operating point can quickly shift to the search candidate point serving as a shifting destination.

[0078] In addition, in the region D, the behavior stability of the gas turbine **2** is low. Therefore, the

correction amount per unit time is decreased. In this manner, the change speed of the control signal can be decreased when the correction amount for shifting to the search candidate point searched for in Step S**109** is added. In this manner, in the region D where the behavior stability is low, the change speed of the control signal is suppressed. In this manner, it is possible to reduce a probability that the behavior of the gas turbine **2** becomes unstable while the operating point shifts.
[0079] In addition, the change speed of the control signal when the operating point shifts over the regions C and D may further depend on the number of data included in the past search result in the operating point region including the operating point. For example, when the number of data included in the past search result in the operating point region is small, the change speed is increased. In this manner, it is possible to promote data collection in the operating point region having the small number of data. On the other hand, when the number of data included in the past search result in the operating point region is large, the change speed is decreased. In this manner, it is possible to achieve a cautious change which can further reduce the probability that the behavior of the gas turbine becomes unstable while the operating point shifts.
[0080] In addition, the change speed of the control signal with respect to the gas turbine **2** in accordance with the correction value may be set, based on the uncertainty of the prediction model at the search candidate point selected in Step S**109**. When the uncertainty of the prediction model at the search candidate point is equal to or greater than a reference value, the change speed of the control signal is increased. In this manner, the operating point can quickly shift to the search candidate point having the high uncertainty of the prediction model. Accordingly, the collection of the data which greatly contributes to the construction of the prediction model can be promoted. On the other hand, when the uncertainty of the prediction model at the search candidate point is smaller than the reference value, the change speed of the control signal is decreased. In this manner, a shifting speed of the operating point to the search candidate point having the low uncertainty is suppressed. Accordingly, it is possible to further reduce the probability that the behavior of the gas turbine becomes unstable while the operating point shifts.
[0081] As described above, according to each of the above-described embodiments, it is possible to provide the gas turbine control device and the gas turbine control method which can efficiently collect the analysis data used for constructing the prediction model for predicting the characteristics relating to the combustion stability of the gas turbine, while stably maintaining the operating state of the gas turbine.
[0082] In addition, it is possible to appropriately replace the components in the embodiment described above with well-known components within the scope which does not depart from the concept of the present disclosure, and the embodiments described above may be appropriately combined with each other.
[0083] For example, contents described in each of the above-described embodiments are understood as follows.
[0084] (1) The gas turbine control device according to an aspect includes the frequency analysis unit (**23**) for outputting the frequency analysis result by performing the frequency analysis on the vibration of the pressure or of the acceleration inside the combustor (**111**) of the gas turbine (**2**) at the operating points specified by the process amount of the gas turbine, the database (**26**) for storing the frequency analysis result and the process amount as the analysis data for each of the operating points, the combustion state prediction unit (**25**) for predicting the combustion state of the gas turbine using the prediction model constructed by using the analysis data, and the correction amount calculation unit (**24**) for calculating the correction amount to be added to the control signal of the gas turbine to operate the gas turbine at the search candidate point where the combustion state predicted by the state prediction unit falls within the management range, out of the search candidate points in which the operating point is the start point, when the search start condition that defines the lapse of the waiting time set based on the past search result in the operating point region including the operating point is satisfied.

[0085] According to the aspect (1) above, the result obtained by performing the frequency analysis on the vibration of the pressure or of the acceleration inside the combustor of the gas turbine is accumulated in the database as the analysis data for each of the operating points. The analysis data accumulated in the database is used for constructing the prediction model, and the prediction model is used for predicting the combustion state by the state prediction unit. The correction amount calculation unit determines that the search start condition is satisfied when the waiting time set based on the past search result at the operating point of the gas turbine elapses. When the search start condition is satisfied, the correction amount to be added to the control signal is calculated to operate the gas turbine at the search candidate point where the combustion state predicted by the combustion state prediction unit falls within the management range, out of the search candidate points in which the operating point is the start point. In this manner, the operating point of the gas turbine shifts to the search candidate point within a range in which the combustion state falls within the management range. Accordingly, new analysis data can be collected at the search candidate point.

[0086] (2) According to another aspect, in the aspect (1) above, when there is the past search result in the operating point region, the correction amount calculation unit is configured to set a second waiting time which is longer than a first waiting time corresponding to when there is no past search result in the operating point, as the waiting time.

[0087] According to the aspect (2) above, when the operating point region including the operating point has the past search result, the waiting time is set to be longer, compared to when there is no past search result. In this manner, the analysis data collected at the search candidate points in which the operating point belonging to the operating point region having the past search result is the start point relatively contributes less to the accuracy of the prediction model. Therefore, repeated collection of similar analysis data can be suppressed by setting the waiting time to be longer. On the other hand, the analysis data collected at the search candidate points in which the operating point belonging to the operating point region having no past search result is the start point greatly contributes to the accuracy of the prediction model. Therefore, collection can be promoted by setting the waiting time to be shorter.

[0088] (3) According to another aspect, in the aspect (1) or (2) above, the operating point region is specified as a region to which the operating point belongs out of a plurality of areas where a first virtual space defined by the process amount is divided.

[0089] According to the aspect (3) above, the operating point region in which the presence or absence of the past search result is determined is specified in units of the area where the first virtual space defined by the process value is divided. In this manner, the operating point region having a predetermined spread with respect to the operating point can be regarded as a similar range, and the waiting time can be set, based on the past search result in the operating point region.

[0090] (4) According to another aspect, in any one of the aspects (1) to (3) above, the waiting time is set to become shorter as the number of data included in the operating point region including the operating point out of the analysis data stored in the database decreases.

[0091] According to the aspect (4) above, the short waiting time is set for the operating point having the small number of data included in the operating point region including the operating point, out of the analysis data stored in the database. In this manner, the collection of the analysis data in the operating point region can be promoted. In this manner, the collection of the analysis data in the operating point region having the small number of data is promoted. Accordingly, the reliability of the prediction model constructed by using the analysis data can be effectively improved.

[0092] (5) According to another aspect, in any one of the aspects (1) to (4) above, the correction amount calculation unit is configured to evaluate uncertainty of the prediction model for each search route settable in a second virtual space defined by the process amount, and to preferentially select the search candidate point from the search route having the high uncertainty.

[0093] According to the aspect (5) above, the uncertainty of the prediction model is evaluated for each of the search routes settable in the second virtual space, and the search candidate point is preferentially selected from the search route having the high uncertainty. In this manner, the search candidate point is preferentially selected from the search route having the high uncertainty of the prediction model. Accordingly, the analysis data which greatly contributes to the improvement of the reliability of the prediction model can be efficiently collected.
[0094] (6) According to another aspect, in the aspect (5) above, the search route is defined as a route including the operating points where the process amounts are different at a predetermined interval in the second virtual space, and the correction amount calculation unit calculates the uncertainty of the search route, based on the uncertainty of the prediction model at each of the operating points included in the search route.
[0095] According to the aspect (6) above, the uncertainty of each search route is calculated, based on the uncertainty of each operating point included in each search route. In this manner, the uncertainty of each search route can be properly evaluated, based on the limited number of data.
[0096] (7) According to another aspect, in any one of the aspects (1) to (6) above, the correction amount calculation unit is configured so that a change speed of the control signal becomes variable by adding the correction amount, based on at least one of the number of data included in the past search result or stability of the combustion state predicted by the combustion state prediction unit at the search candidate point.
[0097] According to the aspect (7) above, when the correction amount is added to the control signal to operate the gas turbine at the search candidate point, the change amount of the control signal becomes variable, based on at least one of the number of data collected in the past in the operating point region or the stability of the combustion state at the search candidate point. In this manner, while the data is quickly collected, based on the contribution to the improvement of the reliability of the prediction model of the collected data and the stability of the combustion state when the operating point shifts to the search candidate point, a probability that the combustion state becomes unstable can be effectively reduced.
[0098] (8) According to another aspect, any one of the aspects (1) to (7) above further includes a state ascertaining unit (**22**) for ascertaining a state of the gas turbine at the operating point, based on the process amount.
[0099] The correction amount calculation unit stops calculating the correction amount, when the state ascertained by the state ascertaining unit deviates from the management range.
[0100] According to the aspect (8) above, when the state of the gas turbine which is ascertained by the state ascertaining unit deviates from the management range, searching for the operating point is stopped by adding the correction amount to the control signal. In this manner, it is possible to properly take countermeasures for restoring the state of the gas turbine to the management range.
[0101] (9) The gas turbine control method according to an aspect includes a step of outputting a frequency analysis result by performing a frequency analysis on vibration of a pressure or of acceleration inside a combustor of a gas turbine at operating points specified by a process amount of the gas turbine, a step of storing the frequency analysis result and the process amount in a database as analysis data for each of the operating points, a step of predicting a combustion state of the gas turbine by using a prediction model constructed by using the analysis data, and a step of calculating a correction amount to be added to a control signal of the gas turbine to operate the gas turbine at a search candidate point where the combustion state predicted by the state prediction unit falls within a management range, out of search candidate points in which the operating point is a start point, when a search start condition defining an elapse of a waiting time set based on a past search result in an operating point region including the operating point is satisfied.
[0102] According to the aspect (9) above, the result obtained by performing the frequency analysis on the vibration of the pressure or of the acceleration inside the combustor of the gas turbine is accumulated in the database as the analysis data for each of the operating points. The analysis data

accumulated in the database is used for constructing the prediction model, and the prediction model is used for predicting the combustion state by the state prediction unit. The correction amount calculation unit determines that the search start condition is satisfied when the waiting time set based on the past search result at the operating point of the gas turbine elapses. When the search start condition is satisfied, the correction amount to be added to the control signal is calculated to operate the gas turbine at the search candidate point where the combustion state predicted by the combustion state prediction unit falls within the management range, out of the search candidate points in which the operating point is the start point. In this manner, the operating point of the gas turbine shifts to the search candidate point within a range in which the combustion state falls within the management range. Accordingly, new analysis data can be collected at the search candidate point.

REFERENCE SIGNS LIST

[0103] **1**: Gas turbine control device [0104] **2**: Gas turbine [0105] **4**: Process amount measurement unit [0106] **5**: Pressure fluctuation measurement unit [0107] **6**: Acceleration measurement unit [0108] **7**: Operation mechanism [0109] **10**: Controller [0110] **20**: Automatic adjustment unit [0111] **21**: Input unit [0112] **22**: State ascertaining unit [0113] **23**: Frequency analysis unit [0114] **24**: Correction amount calculation unit [0115] **25**: Combustion state prediction unit [0116] **26**: Database [0117] **28**: Output unit [0118] **100**: Gas turbine body part [0119] **101**: Compressor [0120] **102**: Inlet guide vane [0121] **103**: Rotary shaft [0122] **104**: Turbine [0123] **110**: Combustion unit [0124] **111**: Combustor [0125] **112**: Compressed air introduction unit [0126] **113**: Main fuel flow control valve [0127] **114**: Pilot fuel flow control valve [0128] **115**: Main fuel supply valve [0129] **116**: Pilot fuel supply valve [0130] **117**: Bypass air introduction pipe [0131] **118**: Bypass valve [0132] **119**: Bypass air mixing pipe [0133] **120**: Combustion gas introduction pipe [0134] **121**: Generator [0135] V**1**: First virtual space [0136] V**2**: Second virtual space [0137] V**3**: Third virtual space

Claims

1-9. (canceled)

10. A gas turbine control device comprising: a frequency analysis unit for outputting a frequency analysis result by performing a frequency analysis on vibration of a pressure or of acceleration inside a combustor of a gas turbine at operating points specified by a process amount of the gas turbine; a database for storing the frequency analysis result and the process amount as analysis data for each of the operating points; a combustion state prediction unit for predicting a combustion state of the gas turbine by using a prediction model constructed by using the analysis data; and a correction amount calculation unit for calculating a correction amount to be added to a control signal of the gas turbine to operate the gas turbine at a search candidate point where the combustion state predicted by the state prediction unit falls within a management range, out of search candidate points in which the operating point is a start point, when a search start condition defining an elapse of a waiting time set based on a past search result in an operating point region including the operating point is satisfied.

11. The gas turbine control device according to claim 10, wherein when there is the past search result in the operating point region, the correction amount calculation unit is configured to set a second waiting time which is longer than a first waiting time corresponding to when there is no past search result in the operating point, as the waiting time.

12. The gas turbine control device according to claim 10, wherein the operating point region is specified as a region to which the operating point belongs out of a plurality of areas where a first virtual space defined by the process amount is divided.

13. The gas turbine control device according to claim 10, wherein the waiting time is set to become shorter as the number of data included in the operating point region in the analysis data stored in the database decreases.

14. The gas turbine control device according to claim 10, wherein the correction amount calculation unit is configured to evaluate uncertainty of the prediction model for each search route settable in a second virtual space defined by the process amount, and to preferentially select the search candidate point from the search route having the high uncertainty.

15. The gas turbine control device according to claim 14, wherein the search route is defined as a route including the operating points where the process amounts are different at a predetermined interval in the second virtual space, and the correction amount calculation unit calculates the uncertainty of the search route, based on the uncertainty of the prediction model at each of the operating points included in the search route.

16. The gas turbine control device according to claim 10, wherein the correction amount calculation unit is configured so that a change speed of the control signal becomes variable by adding the correction amount, based on at least one of the number of data included in the past search result or stability of the combustion state predicted by the combustion state prediction unit at the search candidate point.

17. The gas turbine control device according to claim 10, further comprising: a state ascertaining unit for ascertaining a state of the gas turbine at the operating point, based on the process amount, wherein the correction amount calculation unit stops calculating the correction amount, when the state ascertained by the state ascertaining unit deviates from the management range.

18. A gas turbine control method comprising: a step of outputting a frequency analysis result by performing a frequency analysis on vibration of a pressure or of acceleration inside a combustor of a gas turbine at operating points specified by a process amount of the gas turbine; a step of storing the frequency analysis result and the process amount as analysis data for each of the operating points; a step of predicting a combustion state of the gas turbine by using a prediction model constructed by using the analysis data; and a step of calculating a correction amount to be added to a control signal of the gas turbine to operate the gas turbine at a search candidate point where the combustion state predicted by the state prediction unit falls within a management range, out of search candidate points in which the operating point is a start point, when a search start condition defining an elapse of a waiting time set based on a past search result in an operating point region including the operating point is satisfied.

19. The gas turbine control device according to claim 11, wherein the operating point region is specified as a region to which the operating point belongs out of a plurality of areas where a first virtual space defined by the process amount is divided.

20. The gas turbine control device according to claim 11, wherein the waiting time is set to become shorter as the number of data included in the operating point region in the analysis data stored in the database decreases.

21. The gas turbine control device according to claim 11, wherein the correction amount calculation unit is configured to evaluate uncertainty of the prediction model for each search route settable in a second virtual space defined by the process amount, and to preferentially select the search candidate point from the search route having the high uncertainty.

22. The gas turbine control device according to claim 11, wherein the correction amount calculation unit is configured so that a change speed of the control signal becomes variable by adding the correction amount, based on at least one of the number of data included in the past search result or stability of the combustion state predicted by the combustion state prediction unit at the search candidate point.

23. The gas turbine control device according to claim 11, further comprising: a state ascertaining unit for ascertaining a state of the gas turbine at the operating point, based on the process amount, wherein the correction amount calculation unit stops calculating the correction amount, when the state ascertained by the state ascertaining unit deviates from the management range.