

DESCRIPTION

TITLE OF INVENTION:

Grid System and Control Device of Grid System

TECHNICAL FIELD

[0001] The present disclosure relates to a grid system and a control device of a grid system.

BACKGROUND ART

[0002] A grid system for stably controlling variations in grid frequency and variations in grid voltage caused by power variations in a power grid is described in Japanese Patent No. 6510741 (PTL 1).

[0003] PTL 1 describes stabilization of a grid system by inputting or outputting an active power and a reactive power from a power converter to a distribution grid. Specifically, control of an active power for change in grid frequency (hereinafter also referred to as "f-P control") and control of a reactive power for change in grid voltage (hereinafter also referred to as "V-Q control") are performed.

[0004] According to PTL 1, in these f-P control and V-Q control, a power command value is corrected in accordance with proportional (P) control that multiplies a frequency change amount and a voltage change amount by a proportional gain, thereby imparting a drooping characteristic. Further, a dead band in which the power command value is not corrected is provided for a small change of grid frequency and grid voltage.

CITATION LIST

PATENT LITERATURE

[0005] PTL 1: Japanese Patent No. 6510741

SUMMARY OF INVENTION

TECHNICAL PROBLEM

[0006] However, in PTL 1, since the f-P control and the V-Q control are performed by proportional control using a single gain, the proportional control gain is defined by the slope of the drooping characteristic. As a result, control stability may be deteriorated in some cases due to influences of a time lag element and the like.

[0007] The present disclosure is made to solve such a problem and an object of the present disclosure is to provide control for a grid system capable of grid stabilizing control having a predetermined drooping characteristic, without deteriorating control stability.

SOLUTION TO PROBLEM

[0008] According to an aspect of the present disclosure, a grid system includes a distribution

grid to which a voltage source device is connected, a detector to detect a state quantity of the distribution grid, a power conversion device, and a grid control unit. The power conversion device inputs or outputs a power for changing the state quantity to the distribution grid. The grid control unit calculates a power command value for the power conversion device from a deviation between the state quantity obtained from an output of the detector and a control target of the state quantity such that a drooping characteristic for compensating for the deviation is provided. The grid control unit performs control computation having a predetermined frequency characteristic, with the deviation as an input and the power command value as an output. The frequency characteristic is defined such that a first control gain value in a first frequency range including direct current is set corresponding to a slope of the drooping characteristic and a second control gain value in a second frequency range including higher frequencies than the first frequency range is set to be lower than the first control gain value.

[0009] According to another aspect of the present disclosure, a control device of a grid system including a distribution grid to which a voltage source device is connected includes a deviation computation unit and a control computation unit. The deviation computation unit calculates a deviation between a state quantity of the distribution grid and a control target of the state quantity, based on an output of a detector provided in the distribution grid. The control computation unit generates a power command value for a power conversion device for inputting or outputting a power for changing the state quantity to or from the distribution grid. The control computation unit performs control computation having a predetermined frequency characteristic, with the deviation as an input and the power command value as an output, such that a drooping characteristic for compensating for the deviation calculated by the deviation computation unit is provided. The frequency characteristic is defined such that a first control gain value in a first frequency range including direct current and a target value of a grid frequency of the distribution grid is set corresponding to a slope of the drooping characteristic and a second control gain value in a second frequency range including higher frequencies than the first frequency range is set to be lower than the first control gain value.

ADVANTAGEOUS EFFECTS OF INVENTION

[0010] According to the present disclosure, even when the control gain value in the first frequency range including direct current is set to be high in order to ensure the slope of the drooping characteristic, the control gain in the second frequency range with higher frequencies can be reduced, so that grid stabilization control having a predetermined drooping characteristic can be implemented without impairing the control

stability.

BRIEF DESCRIPTION OF DRAWINGS

[0011] Fig. 1 is a block diagram illustrating a schematic configuration of a grid system according to a first embodiment.

Fig. 2 is a control block diagram of a V-Q control unit according to a comparative example.

Fig. 3 is a graph showing a drooping characteristic by V-Q control according to the comparative example.

Fig. 4 is a Bode plot showing a frequency characteristic of V-Q control according to the comparative example.

Fig. 5 is a Bode plot showing an example of a frequency characteristic of input/output response of V-Q control in a power conversion device alone.

Fig. 6 is an entire control block diagram in control of a power converter using the V-Q control unit according to the comparative example.

Fig. 7 is a Bode plot showing a frequency characteristic of the entire control block shown in Fig. 6.

Fig. 8 is a control block diagram of a V-Q control unit according to the first embodiment.

Fig. 9 is a Bode plot showing a frequency characteristic of the V-Q control unit according to the first embodiment.

Fig. 10 is a Bode plot showing a frequency characteristic in control of the power converter using the V-Q control unit according to the first embodiment.

Fig. 11 is a graph showing a drooping characteristic by V-Q control according to a modification of the first embodiment.

Fig. 12 is a control block diagram of the V-Q control unit according to a modification of the first embodiment.

Fig. 13 is a block diagram illustrating a first modification of a configuration of the grid system.

Fig. 14 is a block diagram illustrating a second modification of a configuration of the grid system.

Fig. 15 is a block diagram illustrating a third modification of a configuration of the grid system.

Fig. 16 is a block diagram illustrating a schematic configuration of a grid system according to a second embodiment.

Fig. 17 is a control block diagram of a f-P control unit according to a comparative example.

Fig. 18 is a graph showing a drooping characteristic by f-P control according to the comparative example.

Fig. 19 is a Bode plot showing a frequency characteristic of f-P control according to the comparative example.

Fig. 20 is a Bode plot showing an example of a frequency characteristic of input/output response of f-P control in a power conversion device alone.

Fig. 21 is an entire control block diagram in control of a power converter using the f-P control unit according to the comparative example.

Fig. 22 is a Bode plot showing a frequency characteristic of the entire control block shown in Fig. 21.

Fig. 23 is a control block diagram of the f-P control unit according to the second embodiment.

Fig. 24 is a Bode plot showing a frequency characteristic of the f-P control unit according to the second embodiment.

Fig. 25 is a Bode plot showing a frequency characteristic in control of the power converter using the f-P control unit according to the second embodiment.

Fig. 26 is a graph showing a drooping characteristic by f-P control according to a modification of the second embodiment.

Fig. 27 is a control block diagram of the f-P control unit according to a modification of the second embodiment.

DESCRIPTION OF EMBODIMENTS

[0012] Embodiments of the present disclosure will be described in detail below with reference to the drawings. In the following, like or corresponding parts in the drawings are denoted by like reference signs and a description thereof will basically not be repeated.

[0013] First Embodiment

In a first embodiment, reactive power control (V-Q control) for change of grid voltage will be described as grid stabilizing control.

[0014] As shown in Fig. 1, a grid system 100a according to the first embodiment includes a voltage source device 10, a distribution grid 40 including a transmission line, power conversion devices 50a, 50b, voltage measuring units 52a, 52b, current measuring units 54a, 54b, and grid control units 60a, 60b.

[0015] Voltage source device 10 is connected to distribution grid 40 to output an AC voltage

to distribution grid 40. It is conceivable that voltage source device 10 corresponds to a power grid or is a voltage source isolated from and independent of a power grid. Voltage source device 10 can include, for example, a power generation device such as a power generator, a combination of a power generation device and a load, or a large-capacity power storage device.

[0016] A consumer group 20 is connected to distribution grid 40. Consumer group 20 consumes power supplied from the distribution grid. Alternatively, in consumer group 20, the generated power by a photovoltaic generation device (not shown) or the like may reversely flow to distribution grid 40.

[0017] Distribution grid 40 has a distribution impedance corresponding to the length of the transmission line. In the example in Fig. 1, a distribution impedance 40xa exists between voltage source device 10 and a connection point to power conversion devices 50a, 50b on distribution grid 40, and a distribution impedance 40xb exists between the connection point and consumer group 20.

[0018] The distribution line impedance is characterized in that, in a power transmission line of the same kind, the distribution impedance increases as the wiring length increases. When a reactive power (current) flows through distribution grid 40, the grid voltage rises or lowers depending on the polarity (phase) of the reactive power. The amount of change of the grid voltage in this case is determined in accordance with the magnitude of inductance (wiring inductance) that is produced on the distribution line in the distribution impedance. In the following, for simplification of explanation, it is assumed that the influence of the interaction between active power and wiring inductance and between reactive power and wiring resistance on the grid voltage is small enough to be ignored.

[0019] Voltage measuring units 52a, 52b and current measuring units 54a, 54b are disposed for detecting a state of distribution grid 40. Voltage measuring units 52a, 52b measure an AC voltage (grid voltage) at a connection point to distribution grid 40. Similarly, current measuring units 54a, 54b measure an AC current (grid current) at a connection point to distribution grid 40. The measured grid voltage and grid current are input to grid control units 60a, 60b.

[0020] In the example in Fig. 1, voltage measuring units 52a, 52b and current measuring units 54a, 54b are installed in proximity to power conversion devices 50a, 50b, but they may be disposed at locations away from power conversion devices 50a, 50b. Alternatively, voltage measuring units 52a, 52b and current measuring units 54a, 54b may be disposed at a plurality of locations on distribution grid 40, and the grid voltages and grid currents measured

at a plurality of locations may be selectively input to grid control units 60a, 60b.

[0021] Power conversion devices 50a, 50b are configured to output a reactive power to distribution grid 40 in accordance with a power command value from grid control units 60a, 60b. As described above, in the first embodiment, V-Q control is described, and power conversion devices 50a, 50b can be configured using self-commutated or line-commutated reactive power compensating devices such as static synchronous compensators (STATCOMs) for injecting reactive powers Q_{xa} , Q_{xb} into distribution grid 40.

[0022] In the following, a reactive power in a current phase advance direction (that is, grid voltage rising direction) with respect to the phase of the grid voltage is represented by a positive value ($Q > 0$), while a reactive power in a current phase delay direction (that is, grid voltage lowering direction) is represented by a negative value ($Q < 0$). Power conversion devices 50a, 50b may be connected to a power storage device and/or a distributed power source (solar cell panel, etc.) for demand and supply adjusting means.

[0023] Grid control units 60a, 60b generate a power command value of power conversion devices 50a, 50b, based on a state of distribution grid 40 measured by voltage measuring units 52a, 52b and current measuring units 54a, 54b (specifically, grid voltage and/or grid current). In the first embodiment in which V-Q control is described, grid control units 60a, 60b generate a power command value Q_{ref} . According to the definition above, $Q_{ref} > 0$ is to specify output of a reactive power (Q_{xa} , $Q_{xb} > 0$) in the current phase advance direction (voltage rising direction), and $Q_{ref} < 0$ is to specify output of a reactive power (Q_{xa} , $Q_{xb} < 0$) in the current phase delay direction (voltage lowering direction).

[0024] For example, as illustrated in Fig. 1, grid control units 60a, 60b can be configured based on a computer including a central processing unit (CPU) 151, a memory 152, and an input/output (I/O) circuit 153. CPU 51, memory 152, and I/O circuit 153 can exchange data with each other via a bus 155. A program is stored in advance in a partial area of memory 152, and CPU 151 executes the program to implement the functions of V-Q control described later and f-P control described in the second embodiment. I/O circuit 153 receives/outputs signals and data from/to the outside of grid control units 60a, 60b.

[0025] Alternatively, unlike the example in Fig. 1, at least a part of grid control units 60a, 60b may be configured using circuitry such as a field programmable gate array (FPGA) or an application specific integrated circuit (ASIC). At least a part of grid control units 60a, 60b may be configured with an analog circuit. In this way, the functions of V-Q control and f-P control described later can be implemented by at least one of software processing and hardware processing.

[0026] In the example in Fig. 1, power conversion device 50a and grid control unit 60a as well as power conversion device 50b and grid control unit 60b are configured with separate devices and connected through wired or wireless communication. However, grid control units 60a, 60b may be internal functions of power conversion devices 50a, 50b, and power conversion device 50a and grid control unit 60a as well as power conversion device 50b and grid control unit 60b may be configured as a single device.

[0027] The control of power conversion device 50a by grid control unit 60a and the control of power conversion device 50b by grid control unit 60b are common. In the following, therefore, grid stabilizing control using each of power conversion devices 50a, 50b by the corresponding one of grid control units 60a, 60b will be collectively described without the index a, b of each element.

[0028] First of all, the conventional V-Q control described in PTL 1 and the like will be described as a comparative example with reference to Fig. 2 to Fig. 7.

[0029] As shown in Fig. 2, a V-Q control unit 200# according to the comparative example is executed by an effective value calculator 202, a subtractor 204, a proportional control element 206, and a limiter 208. Effective value calculator 202 calculates a grid voltage effective value V_{rms} from a grid voltage V_{ac} measured by voltage measuring unit 52.

[0030] Subtractor 204 calculates a voltage deviation ΔV_{rms} by subtracting grid voltage V_{ac} calculated by effective value calculator 202 from grid voltage command value V_{rms}^* .

Proportional control element 206 outputs a multiplication value of voltage deviation ΔV_{rms} and a proportional gain K_{vq} . An output value of proportional control element 206 passes through limiter 208 whereby power command value Q_{ref} is generated.

[0031] Limiter 208 fixes $Q_{ref}=Q_{refup}$ when $K_{vq} \cdot \Delta V_{rms} > Q_{refup}$ and fixes $Q_{ref}=Q_{refdwn}$ when $K_{vq} \cdot \Delta V_{rms} < Q_{refdwn}$ ($Q_{refdwn} < 0$, $Q_{refup} > 0$). On the other hand, when $Q_{refdwn} \leq K_{vq} \cdot \Delta V_{rms} \leq Q_{refup}$, $Q_{ref}=K_{vq} \cdot \Delta V_{rms}$ is set.

[0032] Fig. 3 shows a drooping characteristic by V-Q control in accordance with the control block diagram in Fig. 2.

The horizontal axis in Fig. 3 shows voltage deviation ΔV_{rms} , and the vertical axis shows power command value Q_{ref} . When $\Delta V_{rms}=0$, that is, $V_{rms}=V_{rms}^*$, $Q_{ref}=0$. When $\Delta V_{rms} > 0$ (that is, $V_{rms}^* > V_{rms}$), power command value Q_{ref} is set ($Q_{ref} > 0$) such that a phase advance reactive power (the direction to rise the grid voltage) of a magnitude proportional to ΔV_{rms} is output from power conversion device 50 to distribution grid 40. On the other hand, when $\Delta V_{rms} < 0$ (that is, $V_{rms}^* < V_{rms}$), power command value Q_{ref} is set

($Q_{ref} < 0$) such that a phase delay reactive power (the direction to lower the grid voltage) of a magnitude proportional to ΔV_{rms} is output from power conversion device 50 to distribution grid 40.

[0033] Although power command value Q_{ref} is set to be limited in the range of $Q_{refdmn} \leq Q_{ref} \leq Q_{refup}$ by limiter 208 (Fig. 2), the limit values Q_{refup} , Q_{refdwn} can be determined in advance in accordance with a rated power or the like that can be output by power conversion device 50. Alternatively, in a case where power conversion device 50 can output both an active power and a reactive power, the limit values Q_{refup} , Q_{refdwn} may be variable in accordance with the output amount of active power. For example, in a case where the current amount that can be output by power conversion device 50 has a limit, a certain limit is imposed on the apparent power amount that can be output by power conversion device 50, and therefore the limit values Q_{refup} , Q_{refdwn} can be changed in accordance with the output amount of active power so that the apparent power output from power conversion device 50 is a predetermined limit value or lower. The limit values in this case can be set as desired according to the specifications and the like of power conversion device 50.

[0034] As shown in Fig. 3, the slope of a drooping characteristic is determined by proportional gain K_{vq} . For example, when a drooping characteristic is given from a not-shown higher-level control unit, proportional gain K_{vq} in Fig. 2 is determined by the slope of the specified drooping characteristic.

[0035] Fig. 4 shows a Bode plot schematically showing a frequency characteristic of input/output response of the control block diagram shown in Fig. 2. The horizontal axis in Fig. 4(a), (b) shows frequency, the vertical axis in Fig. 4(a) shows control gain, and the vertical axis in Fig. 4(b) shows phase.

[0036] As shown in Fig. 4(a), the gain is constantly maintained to proportional gain K_{vq} , irrespective of the frequency. As shown in Fig. 4(b), the phase is maintained at 0 [deg] for proportional control, irrespective of the frequency.

[0037] Fig. 5 shows an example of the frequency characteristic of input/output response of V-Q control in power conversion device 50 alone. In the actual operation of power conversion device 50, there is capability limitation such that a certain response frequency is the limit before power (current) in accordance with a certain power command value is settled and output after the power command value is set. For example, such a limit is caused by, for example, a control delay due to the capability (response speed) of power conversion device 50 itself and limitations in communication interval between power conversion device 50 and

grid control unit 60.

[0038] To schematically illustrate the limit in response capability, as shown in Fig. 5(a), it is assumed that the gain characteristic of V-Q control of power conversion device 50 alone has a frequency characteristic of a second order lag system. Here, suppose that the cut-off frequency at which the gain is half relative to the pass band, which corresponds to the break frequency in the frequency response of the second order lag system represented by the broken line in Fig. 5(a), is defined as an upper limit frequency f_c that can avoid the limit described above. Hereinafter, the upper limit frequency is also referred to as response frequency f_c of power conversion device 50. In the V-Q control of power conversion device 50 alone, the phase characteristic also changes from 0 [deg] to -180 [deg] in the vicinity of response frequency f_c , as shown in Fig. 5(b).

[0039] Fig. 6 shows the entire control block diagram in control of power conversion device 50 using V-Q control unit 200# (comparative example) in Fig. 2.

[0040] In entire control block 250 shown in Fig. 6, the block denoted by "PCS" corresponds to power conversion device 50. The power (in the first embodiment, reactive power Q_x) output from power conversion device 50 causes a change in grid voltage effective value V_{rms} in accordance with the magnitude (X) of impedance of distribution grid 40. Grid voltage effective value V_{rms} is input to V-Q control unit 200# shown in Fig. 2. V-Q control unit 200# controls power conversion device 50 so that reactive power Q_x proportional to voltage deviation ΔV_{rms} obtained by subtracting grid voltage effective value V_{rms} from grid voltage command value V_{rms}^* is output.

[0041] Fig. 7 shows a Bode plot schematically showing a frequency characteristic of entire control block 250 including V-Q control unit 200# and power conversion device 50 shown in Fig. 6. The horizontal axis in Fig. 7(a), (b) shows frequency, the vertical axis in Fig. 7(a) shows control gain, and the vertical axis in Fig. 7(b) shows phase.

[0042] As shown in Fig. 7(a), proportional gain K_{vq} defined according to the drooping characteristic from the higher level is determined, whereby the control gain is maintained at a constant value dependent on the proportional gain K_{vq} in a frequency range equal to or lower than response frequency f_c . On the other hand, as shown in Fig. 7(b), the phase changes from 0 [deg] to -180 [deg] in the vicinity of response frequency f_c , in the same manner as in Fig. 5(b).

[0043] As can be understood from Fig. 7(b), in the V-Q control of power conversion device 50 to which the V-Q control (Fig. 2) of the comparative example is applied, the control gain

is maintained at a constant value dependent on proportional gain K_{vq} , even in the vicinity of response frequency f_c .

[0044] Thus, when proportional gain K_{vq} is set to be too high by the drooping characteristic, the phase margin or gain margin of control decreases, which may deteriorate the control stability in the entire V-Q control shown in Fig. 6.

[0045] When grid voltage variations are suppressed by power conversion device 50, stabilization of the grid voltage is emphasized, and the drooping characteristic is set such that a reactive power equivalent to the rated output of power conversion device 50 is output for a voltage variation as small as ± 1 (%) or lower of the grid voltage. Thus, proportional gain K_{vq} may be set to be large in order to ensure the slope of the drooping characteristic of V-Q control. Accordingly, control stability may be reduced as described above in the vicinity of response frequency f_c . Conversely, if control stability is emphasized and proportional gain K_{vq} is limited, the performance of grid voltage stabilizing control is limited.

[0046] In the present first embodiment, therefore, in entire control block 250 shown in Fig. 6, grid control unit 60 is configured such that V-Q control unit 200# according to the comparative example is replaced by V-Q control unit 200 shown in Fig. 8.

[0047] Entire control block 250 shown in Fig. 6 is simplified for the sake of brevity of the spirit of the present disclosure and described only by way of example. That is, it should be noted that the application of the present disclosure is not limited to the configuration using V-Q control unit 200 shown in Fig. 8, instead of V-Q control unit 200#, in entire control block 250 shown in Fig. 6.

[0048] As shown in Fig. 8, V-Q control unit 200 according to the first embodiment includes effective value calculator 202, subtractor 204, and limiter 208 similar to those in Fig. 2, and proportional control elements 211, 212, an integral control element 213, a subtractor 214, an adder 216, and a limiter 220.

[0049] Proportional control element 211 outputs a multiplication value of voltage deviation ΔV_{rms} and proportional gain K_p . Voltage deviation ΔV_{rms} is input to the (+) side of subtractor 214.

[0050] Integral control element 213 integrates the multiplication value of the output of subtractor 214 and the integral gain (K_p/T) (T : integral time). The integral value that is the output of integral control element 213 is multiplied by a gain ($1/K_{vq0}$) by proportional control element 212 and set as an input value A to the (-) side of subtractor 214. Limiter 220 has a function similar to that of limiter 208 and is provided for limiting the integral value by

integral control element 213 to within the above range of $Q_{refdown}$ to Q_{refup} .

[0051] Adder 216 adds the output value of proportional control element 211 (K_p) and the integral value by integral control element 213 (after passing through limiter 220). In V-Q control unit 200, the output value of adder 216 passes through limiter 208, whereby power command value Q_{ref} is generated. That is, power command value Q_{ref} is set so as to be limited within the range of $Q_{refdown} \leq Q_{ref} \leq Q_{refup}$.

[0052] In Fig. 8, when limiters 208, 220 are omitted, the control computation between input ΔV_{rms} and output Q_{ref} can be expressed by the following equation (1) using the input value A to subtractor 214.

$$[0053] (\Delta V_{rms} - A) \cdot (K_p / sT) + \Delta V_{rms} \cdot K_p = Q_{ref} \quad \dots (1)$$

For the input value A, the following equation (2) holds.

$$[0054] (\Delta V_{rms} - A) \cdot (K_p / sT) \cdot (1 / K_{vq0}) = A \quad \dots (2)$$

A system of equations (1) and (2) is solved for $(Q_{ref} / \Delta V_{rms})$ by eliminating the input value A to yield the following equation (3), which is also shown in Fig. 8, for the control computation in V-Q control unit 200.

[0055]

$$\frac{Q_{ref}}{\Delta V_{rms}} = K_p \cdot \left(1 + \frac{1}{\frac{K_p}{K_{vq0}} + sT} \right) \quad \dots (3)$$

[0056] In equation (3), it is understood that when $s \rightarrow 0$, that is, the frequency is brought closer to zero, $(Q_{ref} / \Delta V_{rms}) = K_p + K_{vq0}$. Conversely, it is understood that when $s \rightarrow \infty$, that is, the frequency is increased, $(Q_{ref} / \Delta V_{rms}) = K_p$. Therefore, with $K_p < K_{vq0}$, the gain in the high frequency range can be made lower than the gain in the low frequency range.

[0057] Fig. 9 shows a Bode plot schematically showing the frequency characteristic of input/output response of V-Q control unit 200 shown in Fig. 8, that is, the frequency characteristic of V-Q control according to the first embodiment. The horizontal axis in Fig. 9(a), (b) shows frequency, the vertical axis in Fig. 9(a) shows control gain, and the vertical axis in Fig. 9(b) shows phase, in the same manner as in Fig. 4.

[0058] As shown in Fig. 9, since the proportional control is dominant in the low frequency range ($s \rightarrow 0$), the control gain is a first gain value indicated by $K_{vq} = K_{p0} + K_p$ and the phase is 0 [deg] (no phase lag). On the other hand, when the frequency increases from the low frequency range, the influence of integral control increases, the control gain decreases from the first gain value, and the phase decreases toward -90 [deg]. Therefore, in the low

frequency range including direct current (0 [Hz]), the control gain can be set to the first gain value K_{vq} . That is, first gain value K_{vq} corresponds to an example of "first control gain value", and the low frequency range including direct current corresponds to an example of "first frequency range". It is preferable that the above low frequency range in which the control gain is set to first gain value K_{vq} includes a frequency indicated by a reciprocal of a target value (approximately a few tens of seconds to a few hundreds of seconds) of the settling time of the grid voltage control.

[0059] When the frequency further increases, the integral control is dominant in the frequency range, and the phase is -90 [deg]. Even in this frequency range, the control gain decreases with increase of frequency.

[0060] In the high frequency range ($s \rightarrow \infty$), the control gain decreases to K_p (second gain value), the proportional control is dominant again, and the phase is 0 [deg]. Broken line frequency f_{c0} that is the lower limit frequency where control gain $= K_p$ is determined depending on integral time T in integral control element 213.

[0061] In order to reduce the control gain at response frequency f_c of power conversion device 50 as illustrated in Fig. 5 and Fig. 7, it is preferable that integral time T is set so that $f_{c0} < f_c$. In this case, since the control gain value at response frequency f_c is K_p , second gain value K_p corresponds to an example of "second control gain value", and second gain value K_p is set.

[0062] Alternatively, if the control gain value at response frequency f_c is within a range sufficiently lower than the first gain value (K_{vq}), $f_{c0} > f_c$ can be permitted, and integral time T can be set so that, for example, broken line frequency f_{c0} is located within the range of $f_{c0} < 5 \cdot f_c$, as a minimum requirement. In this case, the control gain at response frequency f_c that is larger than gain K_p and smaller than gain K_{vq} corresponds to an example of "second gain value". In either case, it is understood that "second frequency range" in which the control gain value is set to "second gain value" includes response frequency f_c .

[0063] Gain K_{vq} (first gain value) in the low frequency range corresponds to the slope of the drooping characteristic similar to that in Fig. 3. Therefore, gains K_p and K_{vq0} in Fig. 8 are defined as a value in grid control unit 60 in association with the slope of the obtained drooping characteristic.

[0064] In grid control unit 60, the gain ($1/K_{vq0}$) of proportional control element 212 can be defined by setting $K_{vq0} = K_{vq} - K_p$ using the preset gain K_p and the slope K_{vq} of the drooping characteristic specified by the higher level. When $K_{vq} \gg K_p$, $K_{vq} \approx (K_{vq0} + K_p)$, and then in

grid control unit 60, $K_{vq0}=K_{vq}$ can be readily set using the slope K_{vq} of the drooping characteristic specified by the higher level as it is.

[0065] Fig. 10 shows the frequency characteristic of the entire control block including V-Q control unit 200 shown in Fig. 8 and power conversion device 50. Specifically, a Bode plot is shown to schematically illustrate the frequency characteristic when V-Q control unit 200 according to the first embodiment is applied instead of V-Q control unit 200# of the comparative example in entire control block 250 in Fig. 6. The horizontal axis in Fig. 10(a), (b) shows frequency, the vertical axis in Fig. 10(a) shows control gain, and the vertical axis in Fig. 10(b) shows phase, in the same manner as in Fig. 7.

[0066] As shown in Fig. 10(a), in the above low frequency range including direct current (0 [Hz]), the control gain is a value dependent on first gain value K_{vq} . Thus, a control gain equivalent to that in Fig. 7 for ensuring the slope (K_{vq}) of the drooping characteristic can be ensured. As a result, the drooping characteristic shown in Fig. 3 can be implemented similarly.

[0067] On the other hand, the control gain in the high frequency range including response frequency f_c decreases to a value dependent on second gain value K_p . As a result, in the frequency range in the vicinity of response frequency f_c of power conversion device 50 that is higher than broken line frequency f_{c0} shown in Fig. 9, the control gain is a value dependent on second gain value K_p and can be kept lower than a value dependent on first gain value K_{vq} in the low frequency range.

[0068] In the frequency range higher than response frequency f_c , the control gain decreases as the frequency increases. In particular, the control gain is 0 [dB] at gain crossover frequency f_{c1} determined in connection with the frequency characteristic of power conversion device 50 (Fig. 5), the characteristic of V-Q control unit 200, and impedance X of the distribution grid.

[0069] In this way, in the grid system to which the V-Q control according to the first embodiment is applied, a desired drooping characteristic can be imparted without impairing the control stability in the vicinity of response frequency f_c . That is, it is understood that the set drooping characteristic can be imparted without impairing the control stability.

[0070] In the first embodiment, voltage measuring units 52a, 52b and current measuring units 54a, 54b shown in Fig. 1 and the like correspond to an example of "detector" for detecting a state quantity of distribution grid 40, and grid control units 60a, 60b correspond to an example of "control device" of the grid system. In the first embodiment, grid voltage effective value V_{rms} corresponds to "state quantity" of distribution grid 40. Further, in the

control block diagram shown in Fig. 8, effective value calculator 202 and subtractor 204 of V-Q control unit 200 correspond to an example of "deviation computation unit", and the elements downstream of subtractor 204 of V-Q control unit 200 constitute an example of "control computation unit".

[0071] The configuration of V-Q control unit 200 shown in Fig. 8 is illustrated only by way of example, and the control computation by V-Q control unit 200 can be set as desired as long as the frequency characteristics in the low frequency range including direct current (0 [Hz]) and the high frequency range including response frequency f_c described with reference to Fig. 9, are implemented.

[0072] Modifications of First Embodiment

In a modification of the first embodiment, V-Q control in which a dead band is provided for a small change of grid voltage as in PTL 1 will be described.

[0073] Fig. 11 shows a drooping characteristic by V-Q control according to a modification of the first embodiment.

In Fig. 11 compared with Fig. 3, in a modification of the first embodiment, when a change of grid voltage effective value V_{rms} relative to grid voltage command value V_{rms}^* is small, for example, in the range of $V_{rmsdwn} \leq \Delta V_{rms} \leq V_{rmsup}$ ($V_{rmsdwn} < 0$, $V_{rmsup} > 0$), $Q_{ref}=0$ is set, and V-Q control is performed so that a reactive power is not injected from power conversion device 50 into distribution grid 40.

[0074] On the other hand, in the region of $\Delta V_{rms} > V_{rmsup}$, power command value Q_{ref} is set in accordance with the product of slope K_{vq} similar to that of Fig. 3 and voltage deviation ΔV_{rmsup} so that a phase advance reactive power (voltage rising direction) of a magnitude proportional to voltage deviation ΔV_{rmsu} ($\Delta V_{rmsu} = V_{rms}^* - V_{rms} - V_{rmsup}$) is injected into distribution grid 40 ($Q_{ref} = K_{vq} \cdot \Delta V_{rmsu}$).

[0075] In the region of $\Delta V_{rms} < V_{rmsdwn}$, power command value Q_{ref} is set in accordance with the product of slope K_{vq} similar to that of Fig. 3 and voltage deviation ΔV_{rmsd} so that a phase delay reactive power (voltage lowering direction) of a magnitude proportional to voltage deviation ΔV_{rmsd} ($\Delta V_{rmsd} = V_{rms}^* - V_{rms} - V_{rmsdwn}$) is injected into distribution grid 40 ($Q_{ref} = K_{vq} \cdot \Delta V_{rmsd}$).

[0076] That is, in the region of $\Delta V_{rms} > V_{rmsup}$ and the region of $\Delta V_{rms} < V_{rmsdwn}$, V-Q control is performed in accordance with the drooping characteristic having slope K_{vq} similar to that of Fig. 3.

[0077] Fig. 12 shows a control block diagram of the V-Q control unit according to a

modification of the first embodiment.

As shown in Fig. 12, a V-Q control unit 201 according to a modification of the first embodiment includes effective value calculator 202, subtractor 204, a V-Q control unit 200u on the voltage rising side, a V-Q control unit 200d on the voltage lowering side, correctors 217u, 217d, and an adder 235.

[0078] Corrector 217u calculates a corrected voltage deviation ΔV_{rmsu} by subtracting $V_{rmsup} (>0)$ in Fig. 11 from voltage deviation ΔV_{rms} from subtractor 204. As a result, in the region of $0 < \Delta V_{rms} < V_{rmsup}$, voltage deviation ΔV_{rms} is a positive value, whereas voltage deviation ΔV_{rmsu} is corrected to a negative value.

[0079] Similarly, corrector 217d calculates a corrected voltage deviation ΔV_{rmsd} by subtracting $V_{rmsdwn} (<0)$ in Fig. 11 from voltage deviation ΔV_{rms} from subtractor 204. As a result, in the region of $V_{rmsdwn} < \Delta V_{rms} < 0$, voltage deviation ΔV_{rms} is a negative value, whereas voltage deviation ΔV_{rmsd} is corrected to a positive value.

[0080] V-Q control unit 200u includes limiters 208u, 220u, proportional control elements 211u, 212u, an integral control element 213u, a subtractor 214u, and an adder 216u, which are connected in the same manner as limiters 208, 220, proportional control elements 211, 212, integral control element 213, subtractor 214, and adder 216 of V-Q control unit 200 in Fig. 8.

[0081] However, limiters 208u, 220u are configured to limit an output value to within the range of 0 to Q_{refu} ($Q_{refu} > 0$). That is, when a negative value is input to limiters 208u, 220u, an output value of limiters 208u, 220u is zero.

[0082] V-Q control unit 200u receives the corrected voltage deviation ΔV_{rmsu} and outputs Q_{refu} . Through the operation of limiters 208u, 220u described above, when voltage deviation $\Delta V_{rmsu} < 0$, that is, $\Delta V_{rms} < V_{rmsup}$, output value Q_{refu} of V-Q control unit 200u is 0.

[0083] On the other hand, when voltage deviation $\Delta V_{rmsu} \geq 0$, the output value Q_{refu} of V-Q control unit 200u is > 0 in accordance with voltage deviation ΔV_{rmsu} . The relation between voltage deviation ΔV_{rmsu} and output value Q_{refu} in this case is similar to the relation between voltage deviation ΔV_{rms} and power command value Q_{ref} in V-Q control unit 200 (Fig. 8).

[0084] Similarly, V-Q control unit 200d includes limiters 208d, 220d, proportional control elements 211d, 212d, an integral control element 213d, a subtractor 214d, and an adder 216d, which are connected in the same manner as limiters 208, 220, proportional control elements

211, 212, integral control element 213, subtractor 214, and adder 216 of V-Q control unit 200 in Fig. 8.

[0085] However, limiters 208d, 220d are configured to limit the output value to within the range of Q_{refdwn} to 0 ($Q_{refdwn} < 0$). That is, when a positive value is input to limiters 208u, 213u, an output value of limiters 208d, 220d is zero.

[0086] V-Q control unit 200d receives the corrected voltage deviation ΔV_{rmsd} and outputs Q_{refd} . Through the operation of limiters 208d, 220d, when voltage deviation $\Delta V_{rmsd} > 0$, that is, $\Delta V_{rms} > V_{rmsdwn}$, the output value Q_{refd} of V-Q control unit 200d is 0.

[0087] On the other hand, when voltage deviation $\Delta V_{rmsd} \leq 0$, output value Q_{refd} of V-Q control unit 200d is < 0 in accordance with voltage deviation ΔV_{rmsd} . The relation between voltage deviation ΔV_{rmsd} and output value Q_{refd} in this case is similar to the relation between voltage deviation ΔV_{rms} and power command value Q_{ref} in V-Q control unit 200 (Fig. 8).

[0088] Adder 235 adds output value Q_{refu} of V-Q control unit 200u and output value Q_{refd} of V-Q control unit 200d to generate power command value Q_{ref} . As described above, in the range of $V_{rmsdwn} \leq \Delta V_{rms} \leq V_{rmsup}$ shown in Fig. 11, $Q_{refu} = Q_{refd} = 0$ and therefore power command value $Q_{ref} = 0$ is set. As a result, the region in which a change of grid voltage relative to grid voltage command value V_{rms}^* is small, where $V_{rmsdwn} \leq \Delta V_{rms} \leq V_{rmsup}$, can be set as a dead band in which a reactive power is not injected into distribution grid 40.

[0089] On the other hand, in the outside of the dead band, power command value Q_{ref} can be set in such a manner that voltage deviation ΔV_{rms} is replaced by the corrected voltage deviation ΔV_{rmsu} or ΔV_{rmsd} in V-Q control unit 200 in Fig. 8.

[0090] In this way, in the system in which the V-Q control according to the modification of the first embodiment is applied, a dead band is provided in a region in which a change of grid voltage is small, and in the outside of the dead band, V-Q control can be performed in the same manner as in the first embodiment. Therefore, in addition to the effect by the V-Q control according to the first embodiment, control stability can be further improved in a region in which a change of grid voltage is small.

[0091] A modification of the configuration of the grid system will now be described.

In Fig. 1, a configuration example in which each of two power conversion devices 50a, 50b disposed in proximity to each other performs control (V-Q control) for providing a drooping characteristic has been described. However, only one of two power conversion devices 50a, 50b may perform V-Q control according to the first embodiment.

[0092] However, in the configuration as shown in Fig. 1, a control error may be caused by a sensor error or the like, and an output share may become uneven between power conversion devices 50a and 50b. In this respect, a drooping characteristic is provided in both of power conversion devices 50a and 50b so that such an uneven output share can be suppressed.

[0093] Furthermore, a system configuration like a grid system 100b shown in Fig. 13 may be employed, in which the functions of grid control units 60a, 60b shown in Fig. 1 are integrated into grid control unit 60 provided in common to power conversion devices 50a, 50b. Grid control unit 60 may be integrated into an upper-level control unit that sets the slope of a drooping characteristic. In this case, the slope (K_{vq}) of the drooping characteristic set in grid control unit 60 is used to generate a command value of power conversion devices 50a, 50b for power control (V-Q control) according to the present embodiment.

[0094] Alternatively, in a grid system 100c shown in Fig. 14, power control (V-Q control) according to the present embodiment may be executed in power conversion devices 50a, 50b individually connected to separate locations on distribution grid 40.

[0095] Alternatively, in a grid system 100d shown in Fig. 15, power control (V-Q control) according to the present embodiment may be executed in power conversion devices 50a, 50b connected to different distribution grids 40a, 40b, respectively.

[0096] In Fig. 1 and Fig. 13 to Fig. 15, power control (V-Q control) by two power conversion devices 50a, 50b has been described, but one or three or more power conversion devices 50 may be connected to any locations on a distribution grid. That is, the power control according to the present embodiment can be executed in any number of power conversion devices 50 connected to a distribution grid.

[0097] Second Embodiment

In a second embodiment, active power control (f-P) for a change of grid frequency will be described as grid stabilizing control.

[0098] As shown in Fig. 16, a grid system 100e according to the second embodiment is configured in the same manner as grid system 100a (Fig. 1) and includes a voltage source device 10, a distribution grid 40 including a transmission line, power conversion devices 50a, 50b, voltage measuring units 52a, 52b, current measuring units 54a, 54b, and grid control units 60a, 60b.

[0099] In general, voltage source device 10 has a rotation element that stores kinetic energy of rotation motion, such as a rotor of a power generator. Thus, in voltage source device 10, when an instantaneous power balance is lost, the operation of keeping a power balance by changing kinetic energy of the rotation element is performed. For example, when consumed

power in consumer group 20 and the like is greater than the power that can be supplied by voltage source device 10, voltage source device 10 extracts part of the kinetic energy of the rotation element as power that can be supplied and supplies the power to consumer group 20. As a result, rotation kinetic energy of the rotation element decreases, so that the rotation speed of the rotation element decreases, and the change in rotation speed appears as a frequency change in grid voltage. Conversely, when the consumed power in consumer group 20 and the like is smaller than the power that can be supplied by voltage source device 10, the rotation speed of the rotation element increases, so that the change in rotation speed appears as a frequency change (increase) of the grid voltage.

[0100] Whether a frequency change occurs in this way depends on the balance between the supply capability of voltage source device 10 and the consumed power in consumers and the like. In the second embodiment, it is assumed that voltage source device 10 is characterized in that the grid frequency of distribution grid 40 changes in accordance with a power share.

[0101] In the second embodiment, power conversion devices 50a, 50b are configured to input/output active powers P_{xa} , P_{xb} to/from distribution grid 40 in accordance with a power command value from grid control units 60a, 60b. Power conversion devices 50a, 50b use an inverter or the like connected to demand and supply adjusting means including a power storage device (battery, etc.) such as a battery so that both of input and output of active power is possible.

[0102] In the second embodiment, grid control units 60a, 60b generate a power command value P_{ref} of active power, based on a state of distribution grid 40 measured by voltage measuring units 52a, 52b and current measuring units 54a, 54b (specifically, grid voltage and/or grid current).

[0103] In the following, it is assumed that the active power in a direction in which it is output from power conversion device 50 to distribution grid 40 is represented by a positive value, while the active power in a direction in which it is output from distribution grid 40 to power conversion device 50 is represented by a negative value. According to the above definition, $P_{ref} > 0$ is to specify an output of active power to distribution grid 40 (a direction to increase the frequency, P_{xa} , $P_{xb} > 0$), and $P_{ref} < 0$ is to specify outflow of active power from distribution grid 40 (a direction to decrease the frequency, P_{xa} , $P_{xb} < 0$). The other configuration of Fig. 16 is similar to that of Fig. 1 and will not be further elaborated.

[0104] The conventional f-P control described in PTL 1 and the like will be described as a comparative example with reference to Fig. 17 to Fig. 22.

[0105] As shown in Fig. 17, a P-Q control unit 300# according to the comparative example is

executed by a frequency calculator 302, a subtractor 304, a proportional control element 306, and a limiter 308. Frequency calculator 302 calculates a grid frequency f_s from the waveform of grid voltage V_{ac} measured by voltage measuring unit 52.

[0106] Subtractor 304 calculates a frequency deviation Δf_s by subtracting grid frequency f_s calculated by frequency calculator 302 from a grid frequency command value f_s^* that is a grid frequency control target. Proportional control element 306 outputs a multiplication value of frequency deviation Δf_s and proportional gain K_{fp} . An output value of proportional control element 306 passes through limiter 308 whereby power command value P_{ref} is generated.

[0107] Limiter 208 fixes $P_{ref}=P_{refup}$ when $K_{fp}\cdot\Delta f_s>P_{refup}$ and fixes $P_{ref}=P_{refdwn}$ when $K_{fp}\cdot\Delta f_s<P_{refdwn}$ ($P_{refdwn}<0$, $P_{refup}>0$). On the other hand, when $P_{refdwn}\leq K_{fp}\cdot\Delta f_s\leq P_{refup}$, $P_{ref}=K_{fp}\cdot\Delta f_s$ is set.

[0108] Thus, a drooping characteristic is provided by the P (proportional) control similar to the V-Q control according to the comparative example.

[0109] As shown in Fig. 18, power command value P_{ref} shown on the vertical axis is proportional to frequency deviation Δf_s shown on the horizontal axis, whereby a drooping characteristic determined by proportional gain K_{vq} is implemented. That is, proportional gain K_{fp} in Fig. 17 can be determined by the slope of the drooping characteristic given by a not-shown higher-level control unit.

[0110] With this drooping characteristic, when $\Delta f_s>0$ (that is, $f_s^*>f_s$), power command value P_{ref} is set ($P_{ref}>0$) such that an active power of a magnitude proportional to Δf_s is output from power conversion device 50 to distribution grid 40. On the other hand, when $\Delta f_s<0$ (that is, $f_s^*<f_s$), power command value P_{ref} is set ($P_{ref}<0$) such that an active power of a magnitude proportional to Δf_s is input from distribution grid 40 to power conversion device 50.

[0111] Power command value P_{ref} is set by limiter 308 (Fig. 17) to be limited to within the range of $P_{refdmn}\leq P_{ref}\leq P_{refup}$, and the limit values P_{refup} , P_{refdwn} can also be determined in advance in accordance with a rated power or the like that can be output by power conversion device 50. Alternatively, when power conversion device 50 can output both of an active power and a reactive power, the limit values P_{refup} , P_{refdwn} may be changed in accordance with the output amount of reactive power so that the apparent power does not exceed a certain limit value.

[0112] Fig. 19 shows a Bode plot similar to Fig. 4. As shown in Fig. 19(a), the gain is

constantly maintained to proportional gain K_{fp} , irrespective of the frequency. As shown in Fig. 19(b), the phase is maintained at 0 [deg] for proportional control, irrespective of the frequency.

[0113] Fig. 20 shows an example of the frequency characteristic of input/output response of f-P control in power conversion device 50 alone. Fig. 20 corresponds to the Bode plot shown in Fig. 5 in V-Q control.

[0114] As shown in Fig. 20(a), even in f-P control, upper limit frequency f_c similar to that described in Fig. 5(a) exists in the gain characteristic of power conversion device 50 alone, due to a delay time in the actual operation of power conversion device 50. Further, as shown in Fig. 20(b), in the phase characteristic, 0 [deg] changes to -180 [deg] in the vicinity of response frequency f_c , in the same manner as in Fig. 5(b).

[0115] Response frequency f_c in the first and second embodiments is denoted by the same reference sign, but actually, the value of response frequency f_c may be different between V-Q (first embodiment) and f-P control (second embodiment).

[0116] Fig. 21 shows the entire control block diagram, similar to Fig. 6, in control of power conversion device 50 using f-P control unit 300# (comparative example) in Fig. 17.

[0117] Grid frequency f_s is input to f-P control unit 300# shown in Fig. 17. The f-P control unit 300# controls power conversion device (PCS) 50 so that an active power P_x proportional to frequency deviation Δf_s obtained by subtracting grid frequency f_s from grid frequency command value f_s^* is output. The power output from power conversion device 50 (in the second embodiment, active power P_x) has grid frequency f_s changed in accordance with grid frequency-active power characteristic (K) in distribution grid 40.

[0118] Fig. 22 shows a Bode plot schematically showing a frequency characteristic of an entire control block 350 including f-P control unit 300# and power conversion device 50 shown in Fig. 21.

[0119] As shown in Fig. 22(a), proportional gain K_{fp} defined in accordance with the drooping characteristic from the higher level is determined, whereby the control gain is maintained at a constant value dependent on the proportional gain K_{fp} in a frequency range equal to or lower than response frequency f_c . On the other hand, as shown in Fig. 22(b), the phase changes from 0 [deg] to -180 [deg] in the vicinity of response frequency f_c , in the same manner as in Fig. 20(b).

[0120] As can be understood from Fig. 22(b), in the f-P control of power conversion device 50 to which the f-P control (Fig. 17) of the comparative example is applied, the control gain

is maintained at a constant value dependent on proportional gain K_{fp} , even in the vicinity of response frequency f_c .

[0121] Thus, when proportional gain K_{fp} is set to be too high by the drooping characteristic, the phase margin or gain margin in control decreases, which may deteriorate the control stability in the entire f-P control shown in Fig. 21.

[0122] When grid frequency variations are suppressed by power conversion device 50, stabilization of grid frequency is emphasized, and the drooping characteristic is set such that a reactive power equivalent to the rated power of power conversion device 50 can be output for a small variation of grid frequency. Thus, proportional gain K_{fp} may be set to be large in order to ensure the slope of the drooping characteristic of f-P control. Accordingly, control stability may be reduced in the vicinity of response frequency f_c . Conversely, if control stability is emphasized and proportional gain K_{fp} is limited, the performance of grid frequency stabilizing control is limited.

[0123] In the present second embodiment, therefore, in entire control block 350 shown in Fig. 21, grid control unit 60 is configured such that f-P control unit 200# according to the comparative example is replaced by f-P control unit 300 shown in Fig. 23.

[0124] Entire control block 350 shown in Fig. 21 is also simplified as in Fig. 6 and illustrated only by way of example. That is, it should be noted that the application of the present disclosure is not limited to the configuration using f-P control unit 300 shown in Fig. 23, instead of f-P control unit 300#, in entire control block 350 shown in Fig. 21.

[0125] As shown in Fig. 23, f-P control unit 300 according to the second embodiment includes frequency calculator 302, subtractor 304, and limiter 308 similar to those in Fig. 17, and proportional control elements 311, 312, an integral control element 313, a subtractor 314, an adder 316, and a limiter 320.

[0126] Proportional control element 311 outputs a multiplication value of frequency deviation Δf_s and proportional gain K_p . Frequency deviation Δf_s is input to the (+) side of subtractor 314.

[0127] Integral control element 313 integrates the multiplication value of the output of subtractor 314 and the integral gain (K_p/T) (T : integral time). The integral value that is the output of integral control element 313 is multiplied by a gain ($1/K_{vq0}$) by proportional control element 312 and set as an input value B to the (-) side of subtractor 314. Limiter 320 has a function similar to that of limiter 308 and is provided for limiting the integral value by integral control element 313 to within the above range of P_{refdwn} to P_{refup} . In the second

embodiment, the signs of gain K_p and integral time T similar to those in the first embodiment are used for simplification of explanation, but actually, the actual values of gain K_p and integral time T are different between V-Q control and f-P control.

[0128] Adder 316 adds the output value of proportional control element 311 (K_p) and the integral value by integral control element 313 (after passing through limiter 320). In f-P control unit 300, the output value of adder 316 passes through limiter 308, whereby power command value P_{ref} is generated. That is, power command value P_{ref} is set so as to be limited within the range of $P_{refdown} \leq P_{ref} \leq P_{refup}$.

[0129] In Fig. 23, when limiters 308, 320 are omitted, the control computation between input Δf_s and output P_{ref} can be expressed by the following equation (4) using the input value B to subtractor 314.

$$[0130] (\Delta f_s - B) \cdot (K_p / sT) + \Delta f_s \cdot K_p = P_{ref} \quad \dots(4)$$

For the input value B , the following equation (5) holds.

$$[0131] (\Delta f_s - B) \cdot (K_p / sT) \cdot (1 / K_{fp0}) = B \quad \dots(5)$$

A system of equations (4) and (5) is solved for $(P_{ref} / \Delta f_s)$ by eliminating the input value A to yield the following equation (6), which is also shown in Fig. 23, for the control computation in f-P control unit 300.

[0132]

$$\frac{P_{ref}}{\Delta f_s} = K_p \cdot \left(1 + \frac{1}{\frac{K_p}{K_{fp0}} + sT} \right) \quad \dots(6)$$

[0133] In equation (6), it is understood that when $s \rightarrow 0$, that is, the frequency is brought closer to zero, $(P_{ref} / \Delta f_s) = K_p + K_{fp0}$. Conversely, it is understood that when $s \rightarrow \infty$, that is, the frequency is increased, $(P_{ref} / \Delta f_s) = K_p$. Therefore, with $K_p < K_{fp0}$, the gain in the high frequency range can be made lower than the gain in the low frequency range.

[0134] Fig. 24 shows a Bode plot schematically showing the frequency characteristic of input/output response of f-P control unit 300 shown in Fig. 23, that is, the frequency characteristic of f-P control according to the second embodiment. The horizontal axis in Fig. 24(a), (b) shows frequency, the vertical axis in Fig. 24(a) shows control gain, and the vertical axis in Fig. 24(b) shows phase, in the same manner as in Fig. 10 in the first embodiment.

[0135] As shown in Fig. 24, even in the f-P control in the second embodiment, the frequency characteristic similar to that in the V-Q control in the first embodiment can be obtained. Specifically, since the proportional control is dominant in the low frequency range ($s \rightarrow 0$), the

control gain is a first gain value indicated by $K_{fp}=K_{fp0}+K_p$ and the phase is 0 [deg] (no phase lag). Therefore, in the low frequency range including direct current (0 [Hz]), the control gain can be set to first gain value K_{fp} . That is, first gain value K_{fp} corresponds to an example of "first control gain value", and the low frequency range including direct current corresponds to an example of "first frequency range". It is preferable that the above low frequency range in which the control gain is set to first gain value K_{fp} includes a frequency indicated by a reciprocal of a target value (approximately a few tens of seconds to a few hundreds of seconds) of the settling time of the grid frequency control.

[0136] On the other hand, when the frequency increases from the low frequency range, the influence of integral control increases, the control gain decreases from the first gain value, and the phase decreases toward -90 [deg]. When the frequency further increases, the integral control is dominant in the frequency range, and the phase is -90 [deg]. Even in this frequency range, the control gain decreases with increase of frequency.

[0137] In the high frequency range ($s \rightarrow \infty$), the control gain decreases to K_p (second gain value), the proportional control is dominant again, and the phase is 0 [deg]. Broken line frequency f_{c0} that is the lower limit frequency where control gain= K_p is determined depending on integral time T in integral control element 313.

[0138] In order to reduce the control gain at response frequency f_c of power conversion device 50 as illustrated in Fig. 20 and Fig. 22, it is also preferable that integral time T is set so that $f_{c0} < f_c$, even in the second embodiment as in the first embodiment. In this case, since the control gain value at response frequency f_c is K_p , second gain value K_p corresponds to an example of "second control gain value", and second gain value K_p is set.

[0139] Alternatively, even in the second embodiment, if the control gain value in response frequency f_c is within a range sufficiently lower than the first gain value (K_{fp}), $f_{c0} > f_c$ can be permitted, and integral time T can be set so that, for example, broken line frequency f_{c0} is located within the range of $f_{c0} < 5 \cdot f_c$, as a minimum requirement. In this case, the control gain at response frequency f_c that is larger than gain K_p and smaller than gain K_{fp} corresponds to an example of "second gain value". In either case, it is understood that "second frequency range" in which the control gain value is set to "second gain value" includes response frequency f_c .

[0140] Gain K_{fp} (first gain value) in the low frequency range corresponds to the slope of the drooping characteristic similar to that in Fig. 3. Therefore, gains K_p and K_{fp0} in Fig. 23 are defined as a value in grid control unit 60 in association with the slope of the obtained

drooping characteristic. On the other hand, second gain value K_p can be preset in grid control unit 60, based on the characteristic of power conversion device 50 and the grid frequency-active power characteristic K (Fig. 21) in distribution grid 40.

[0141] In grid control unit 60, the gain ($1/K_{fp0}$) of proportional control element 312 can be defined by setting $K_{fp0}=K_{fp}-K_p$ using the preset gain K_p and the slope K_{fp} of the drooping characteristic specified by the higher level. When $K_{fp} \gg K_p$, $K_{fp} \approx (K_{fp0}+K_p)$, and then in grid control unit 60, $K_{fp0}=K_{fq}$ can be readily set using the slope K_{fp} of the drooping characteristic specified by the higher level as it is.

[0142] Fig. 25 shows the frequency characteristic of the entire control block including f-P control unit 300 shown in Fig. 23 and power conversion device 50. Specifically, a Bode plot is shown to schematically illustrate the frequency characteristic when f-P control unit 300 according to the second embodiment is applied instead of f-P control unit 200# of the comparative example in entire control block 350 in Fig. 21. The horizontal axis in Fig. 25(a), (b) shows frequency, the vertical axis in Fig. 25(a) shows control gain, and the vertical axis in Fig. 25(b) shows phase, in the same manner as in Fig. 22.

[0143] As shown in Fig. 25(a), in the low frequency range including direct current (0 [Hz]), the control gain is a value dependent on first gain value K_{fp} . Thus, a control gain equivalent to that in Fig. 22 for ensuring the slope (K_{fp}) of the drooping characteristic can be ensured. As a result, the drooping characteristic shown in Fig. 18 can be implemented similarly.

[0144] On the other hand, the control gain in the high frequency range including response frequency f_c decreases to a value dependent on second gain value K_p . As a result, in the frequency range in the vicinity of response frequency f_c of power conversion device 50 that is higher than broken line frequency f_{c0} shown in Fig. 24, the control gain is a value dependent on second gain value K_p and can be kept lower than a value dependent on first gain value K_{vq} in the low frequency range.

[0145] In the frequency range higher than response frequency f_c , the control gain decreases as the frequency increases. In particular, the control gain is 0 [dB] at gain crossover frequency f_{c1} determined in connection with the frequency characteristic of power conversion device 50 (Fig. 20), the characteristic of f-P control unit 300, and the grid frequency-active power characteristic (K) of distribution grid 40.

[0146] In this way, in the grid system to which the f-P control according to the second embodiment is applied, a grid desired drooping characteristic can be imparted without impairing the control stability in the vicinity of response frequency f_c . That is, it is

understood that the set drooping characteristic can be imparted without impairing the control stability.

[0147] In the second embodiment, voltage measuring units 52a, 52b and current measuring units 54a, 54b shown in Fig. 16 correspond to an example of "detector" for detecting a state quantity of distribution grid 40, and grid control units 60a, 60b correspond to an example of "control device" of the grid system. In the second embodiment, grid frequency f_s corresponds to "state quantity" of distribution grid 40. Further, in the control block diagram shown in Fig. 23, frequency calculator 302 and subtractor 304 of f-P control unit 300 corresponds to an example of "deviation computation unit", and the elements downstream of subtractor 304 of f-P control unit 300 constitute an example of "control computation unit".

[0148] The configuration of f-P control unit 300 shown in Fig. 23 is illustrated only by way of example, and the control computation by f-P control unit 300 can be set as desired as long as the frequency characteristics in the low frequency range including a target value of the grid frequency and the high frequency range including response frequency f_c described with reference to Fig. 9 are implemented.

[0149] Modifications of Second Embodiment

In a modification of the second embodiment, f-P control in which a dead band is provided for a small change of grid frequency as in the modification of the first embodiment will be described.

[0150] Fig. 26 shows a drooping characteristic by f-P control according to a modification of the second embodiment.

In Fig. 26 compared with Fig. 18, in a modification of the second embodiment, when a change from grid frequency command value f_s^* that is a target value of the grid frequency is small, for example, in the range of $f_{s\text{dwn}} \leq \Delta f_s \leq f_{s\text{sup}}$ ($f_{s\text{dwn}} < 0$, $f_{s\text{sup}} > 0$), $P_{\text{ref}} = 0$ is set and f-P control is performed so that an active power is not input/output to/from power conversion device 50 to distribution grid 40.

[0151] On the other hand, in the region of $\Delta f_s > f_{s\text{sup}}$, power command value P_{ref} is set in accordance with the product of slope K_{fp} similar to that of Fig. 18 and frequency deviation Δf_{su} so that an active power of a magnitude proportional to frequency deviation Δf_{su} ($\Delta f_{\text{su}} = f_s^* - f_s - f_{s\text{sup}}$) is output from power conversion device 50 to distribution grid 40 ($P_{\text{ref}} = K_{\text{fp}} \cdot \Delta f_{\text{su}}$).

[0152] In the region of $\Delta f_s < f_{s\text{dwn}}$, power command value P_{ref} is set in accordance with the product of slope K_{fp} similar to that of Fig. 18 and frequency deviation Δf_{sd} so that an active

power of a magnitude proportional to frequency deviation Δf_{sd} ($\Delta f_{sd} = f_s^* - f_s - f_{sdwn}$) is input from distribution grid 40 to power conversion device 50 ($P_{ref} = K_{fp} \cdot \Delta f_{sd}$).

[0153] That is, in the region of $\Delta f_s > f_{sup}$ and the region of $\Delta f_s < f_{sdwn}$, f-P control is performed in accordance with the drooping characteristic having slope K_{vq} similar to that of Fig. 18.

[0154] Fig. 27 shows a control block diagram of the f-P control unit according to a modification of the second embodiment.

As shown in Fig. 27, f-P control unit 301 according to a modification of the second embodiment includes frequency calculator 302, subtractor 304, a f-P control unit 300u on the frequency rising side, a f-P control unit 300d on the frequency lowering side, correctors 317u, 317d, and an adder 335.

[0155] Corrector 317u calculates a corrected frequency deviation Δf_{su} by subtracting f_{sup} (>0) in Fig. 26 from frequency deviation Δf_s from subtractor 304. As a result, in the region of $0 < \Delta V_{rms} < f_{sup}$, frequency deviation Δf_s is a positive value, whereas frequency deviation Δf_{su} is corrected to a negative value.

[0156] Similarly, corrector 317d calculates a corrected frequency deviation Δf_{sd} by subtracting f_{sdwn} (<0) in Fig. 26 from frequency deviation Δf_s from subtractor 304. As a result, in the region of $f_{sdwn} < \Delta f_s < 0$, frequency deviation Δf_s is a negative value, whereas frequency deviation Δf_{sd} is corrected to a positive value.

[0157] f-P control unit 300u includes limiters 308u, 320u, proportional control elements 311u, 312u, an integral control element 313u, a subtractor 314u, and an adder 316u, which are connected in the same manner as limiters 308, 320, proportional control elements 311, 312, integral control element 313, subtractor 314, and adder 316 of V-Q control unit 300 in Fig. 23.

[0158] However, limiters 308u, 320u are configured to limit an output value to within the range of 0 to P_{refu} ($P_{refu} > 0$). That is, when a negative value is input to limiters 308u, 320u, an output value of limiters 308u, 320u is zero.

[0159] f-P control unit 300u receives the corrected frequency deviation Δf_{su} and outputs P_{refu} . Through the operation of limiters 308u, 320u described above, when frequency deviation $\Delta f_{su} < 0$, that is, $\Delta f_s < f_{sup}$, output value P_{refu} of f-P control unit 200u is 0.

[0160] On the other hand, when voltage deviation $\Delta f_{su} \geq 0$, the output value P_{refu} of f-P control unit 200u is >0 in accordance with frequency deviation Δf_{su} . The relation between frequency deviation Δf_{su} and output value P_{refu} in this case is similar to the relation between

frequency deviation Δf_s and power command value P_{ref} in f-P control unit 300 (Fig. 23).

[0161] Similarly, f-P control unit 300d includes limiters 308d, 320d, proportional control elements 311d, 312d, an integral control element 313d, a subtractor 314d, and an adder 316d, which are connected in the same manner as limiter 308, 320, proportional control elements 311, 312, integral control element 313, subtractor 314, and adder 316 of f-P control unit 300 in Fig. 13.

[0162] However, limiters 308d, 320d are configured to limit the output value to within the range of P_{refdwn} to 0 ($P_{refdwn} < 0$). That is, when a positive value is input to limiters 308u, 320u, an output value of limiters 308d, 320d is zero.

[0163] f-P control unit 300d receives the corrected frequency deviation Δf_{sd} and outputs P_{refd} . Through the operation of limiters 308d, 320d described above, when frequency deviation $\Delta f_{sd} > 0$, that is, $\Delta f_s > f_{sdwn}$, output value P_{refd} of f-P control unit 300d is 0.

[0164] On the other hand, when frequency $\Delta f_{sd} \leq 0$, output value P_{refd} of f-P control unit 300d is < 0 in accordance with frequency deviation Δf_{sd} . The relation between frequency deviation Δf_{sd} and output value P_{refd} in this case is similar to the relation between frequency deviation Δf_s and power command value P_{ref} in f-P control unit 300 (Fig. 23).

[0165] Adder 335 adds output value P_{refu} of f-P control unit 300u and output value P_{refd} of f-P control unit 300d to generate power command value P_{ref} . As described above, in the range of $f_{sdwn} \leq \Delta f_s \leq f_{sup}$ shown in Fig. 26, $P_{refu} = P_{refd} = 0$ and therefore power command value $P_{ref} = 0$ is set. As a result, the region in which a change of grid frequency is small, where $f_{sdwn} \leq \Delta f_s \leq f_{sup}$, can be set as a dead band in which an active power is not input/output to/from distribution grid 40.

[0166] On the other hand, in the outside of the dead band, in f-P control unit 300 in Fig. 23, power command value P_{ref} can be set in such a manner that frequency deviation Δf_s is replaced by the corrected frequency deviation Δf_{su} or Δf_{sd} .

[0167] In this way, in the system in which the f-P control according to the modification of the second embodiment is applied, a dead band is provided in a region in which a change of grid frequency is small, and in the outside of the dead band, f-P control can be performed in the same manner as in the second embodiment. Therefore, in addition to the effect by the f-P control according to the second embodiment, control stability can be further improved in a region in which a change of grid frequency is small.

[0168] In the second embodiment and the modification thereof, the configuration of the grid system can also be changed as appropriate in the same manner as described in the first

embodiment with reference to Fig. 13 to Fig. 15.

[0169] Power conversion devices 50a, 50b shown in Fig. 1, Fig. 16 and the like can be operated so that both of active power and reactive power are output, for example using a self-commutated inverter connected to demand and supply adjusting means such as a power storage device. In this case, power conversion device 50 (50a, 50b) may perform grid stabilizing control according to the present embodiment so that an AC power in which a reactive power in accordance with power command value Q_{ref} for V-Q control according to the first embodiment and an active power in accordance with power command value P_{ref} for f-P control according to the second embodiment are combined is output to distribution grid 40. In this case, in each of power conversion devices 50a, 50b, V-Q control and f-P control can be performed simultaneously in parallel.

[0170] Embodiments disclosed here should be understood as being illustrative rather than being limitative in all respects. The technical scope of the present disclosure is shown not in the foregoing description but in the claims, and it is intended that all modifications that come within the meaning and range of equivalence to the claims are embraced here.

REFERENCE SIGNS LIST

[0171] 10 voltage source device, 20 consumer group, 40, 40a, 40b distribution grid, 40xa, 40xb distribution impedance, 50a, 50b power conversion device, 52a, 52b voltage measuring unit, 54a, 54b current measuring unit, 60, 60a, 60b grid control unit, 100a to 100e grid system, 200, 200d, 200u, 201 V-Q control unit, 300, 300d, 300u, 301 f-P control unit, 202 effective value calculator, 206, 211, 211d, 211u, 212, 212d, 212u, 306, 311, 311d, 311u, 312, 312d, 312u proportional control element, 208, 208d, 208u, 213u, 220, 220d, 220u, 308, 308d, 308u, 320, 320d, 320u limiter, 213, 213d, 213u, 313, 313d, 313u integral control element, 216, 216d, 216u, 235, 316, 316d, 316u, 335 adder, 217d, 217u, 317d, 317u corrector, 250, 350 entire control block, 302 frequency calculator, P_{ref} , Q_{ref} power command value, P_{xa} , P_{xb} active power, Q_{xa} , Q_{xb} reactive power, T integral time, V_{rms} grid voltage command value, V_{rms}^* grid voltage effective value, f comparative example, f_c response frequency (power conversion device), f_{c0} broken line frequency, f_{c1} gain crossover frequency, f_s grid frequency, f_s^* grid frequency command value.

CLAIMS

[Claim 1] A grid system comprising:
a distribution grid to which a voltage source device is connected;
a detector to detect a state quantity of the distribution grid;
a power conversion device to input or output a power for changing the state quantity to or from the distribution grid; and
a grid control unit to calculate a power command value for the power conversion device from a deviation between the state quantity obtained from an output of the detector and a control target of the state quantity such that a drooping characteristic for compensating for the deviation is provided, wherein
the grid control unit performs control computation having a predetermined frequency characteristic, with the deviation as an input and the power command value as an output, and
the frequency characteristic is defined such that a first control gain value in a first frequency range including direct current is set corresponding to a slope of the drooping characteristic and a second control gain value in a second frequency range including higher frequencies than the first frequency range is set to be lower than the first control gain value.

[Claim 2] The grid system according to claim 1, wherein
the state quantity is a grid voltage effective value of the distribution grid, and
the grid control unit calculates the power command value such that the power conversion device outputs, to the distribution grid, a reactive power in a current phase advance direction or a current phase delay direction in accordance with the deviation of the grid voltage effective value and the control target value.

[Claim 3] The grid system according to claim 2, wherein when an absolute value of the deviation is smaller than a reference value, the grid control unit calculates the power command value such that the reactive power output from the power conversion device to the distribution grid becomes zero.

[Claim 4] The grid system according to claim 2 or 3, wherein
the power conversion device is connected to a power storage element and capable of

inputting/outputting an active power and the reactive power to/from the distribution grid, and the grid control unit generates the power command value to limit an output amount of the reactive power in accordance with an input/output amount of the active power by charging/discharging of the power storage element, such that an apparent power input/output to/from the power conversion device is equal to or lower than a limit value.

[Claim 5] The grid system according to claim 1, wherein the state quantity is a grid frequency of the distribution grid, and the grid control unit calculates the power command value such that the power conversion device inputs/outputs an active power to/from the distribution grid in accordance with the deviation of the grid frequency and the control target.

[Claim 6] The grid system according to claim 5, wherein when an absolute value of the deviation is smaller than a reference value, the grid control unit calculates the power command value such that the active power input/output between the power conversion device and the distribution grid becomes zero.

[Claim 7] The grid system according to any one of claims 1 to 6, wherein the second frequency range includes a response frequency of the power conversion device.

[Claim 8] A control device of a grid system including a distribution grid to which a voltage source device is connected, the control device comprising:

a deviation computation unit to calculate a deviation between a state quantity of the distribution grid and a control target of the state quantity, based on an output of a detector provided in the distribution grid; and

a control computation unit to generate a power command value for a power conversion device for inputting or outputting a power for changing the state quantity to or from the distribution grid, wherein

the control computation unit performs control computation having a predetermined frequency characteristic, with the deviation as an input and the power command value as an output, such that a drooping characteristic for compensating for the deviation calculated by the deviation computation unit is provided, and

the frequency characteristic is defined such that a first control gain value in a first frequency range including direct current is set corresponding to a slope of the drooping characteristic and a second control gain value in a second frequency range including higher frequencies than the first frequency range is set to be lower than the first control gain value.

[Claim 9] The control device according to claim 8, wherein
the state quantity is a grid voltage effective value of the distribution grid, and
the control computation unit calculates the power command value such that the power conversion device outputs, to the distribution grid, a reactive power in a current phase advance direction or a current phase delay direction in accordance with the deviation of the grid voltage effective value and the control target value.

[Claim 10] The control device according to claim 9, wherein when an absolute value of the deviation is smaller than a reference value, the control computation unit calculates the power command value such that the reactive power output from the power conversion device to the distribution grid becomes zero.

[Claim 11] The control device according to claim 8, wherein
the state quantity is a grid frequency of the distribution grid, and
the control computation unit calculates the power command value such that the power conversion device inputs/outputs an active power to/from the distribution grid in accordance with the deviation of the grid frequency and the control target.

[Claim 12] The control device according to claim 11, wherein when an absolute value of the deviation is smaller than a reference value, the control computation unit calculates the power command value such that the active power input/output between the power conversion device and the distribution grid becomes zero.

[Claim 13] The control device according to any one of claims 8 to 12, wherein the second frequency range includes a response frequency of the power conversion device.

[Claim 14] The grid system according to any one of claims 1 to 7, wherein

the frequency characteristic is defined such that (i) a third frequency range in which a phase lag is 90 degrees is provided between the first frequency range and the second frequency range, and (ii) the phase lag approaches 0 degrees with increase of a frequency in a frequency range including higher frequencies than the third frequency range.

[Claim 15] The grid system according to any one of claims 1 to 7, wherein the frequency characteristic is defined such that (i) a third frequency range in which a control gain decreases with increase of a frequency is provided between the first frequency range and the second frequency range, and (ii) the second frequency range includes a frequency range in which the control gain is constantly maintained with increase of the frequency.

[Claim 16] The control device according to any one of claims 8 to 13, wherein the frequency characteristic is defined such that (i) a third frequency range in which a phase lag is 90 degrees is provided between the first frequency range and the second frequency range, and (ii) the phase lag approaches 0 degrees with increase of a frequency in a frequency range including higher frequencies than the third frequency range.

[Claim 17] The control device according to any one of claims 8 to 13, wherein the frequency characteristic is defined such that (i) a third frequency range in which a control gain decreases with increase of a frequency is provided between the first frequency range and the second frequency range, and (ii) the second frequency range includes a frequency range in which the control gain is constantly maintained with increase of the frequency.