

DESCRIPTION

CONTROL SYSTEM

FIELD

[0001] Embodiments of the present invention relate to a control system.

BACKGROUND

[0002] In a rotational sensorless control device of a permanent magnet synchronous motor, estimation of the initial magnetic-pole position at the time of activation from an idle state is performed using saliency (for example, see Patent Literature 1). Hence, it is necessary to estimate the magnetic-pole direction.

As far as estimation of the magnetic-pole direction is concerned, an estimation method has been proposed in which magnetic saturation is put to use (for example, see Patent Literature 2 and Patent Literature 3).

CITATION LIST

Patent Literature

[0003] Patent Literature 1: Japanese Patent No. 3719910

Patent Literature 2: Japanese Patent No. 3401155

Patent Literature 3: Japanese Patent Application Laid-open No. 2008-079489

SUMMARY OF THE INVENTION

Problem to be Solved by the Invention

[0004] In the conventional estimation method mentioned above, the magnetic-pole direction is estimated by making use of the fact that the inductance in the direction of magnetic flux undergoes a monotonic decrease in reaction to

an increment in the current in the north pole direction.

Thus, the conventional technology could not be implemented in the case in which, in reaction to an increment in the current in the north pole direction, the inductance in the direction of magnetic flux does not undergo a monotonic decrease but has a local maximum point.

The present invention has been made in view of the foregoing, and it is an object of the present invention to implement a control system that enables estimation of the magnetic-pole direction even in an electrical motor in which, in reaction to an increment in the current in the north pole direction, the inductance in the direction of magnetic flux has a local maximum point.

Means for Solving Problem

[0005] A control system of an embodiment controls a synchronous motor including a magnet inside a rotor. The control system comprises: an inverter that outputs an alternating current for driving the synchronous motor; a gate command generating unit that generates a gate command for driving the inverter; a current detecting unit that detects a current value of the alternating current output from the inverter; a magnetic-pole position estimating unit that estimates a magnetic-pole position based on the current value detected by the current detecting unit; a control unit that instructs, upon determination of magnetic-pole polarity, the gate command generating unit to generate a gate command for polarity determination so that a d-axis component of the current value detected by the current detecting unit represents a predetermined value; and a magnetic-pole polarity determining unit that obtains, if the gate command for polarity determination is generated and based on the magnetic-pole position estimated by the

magnetic-pole position estimating unit, a first information indicating an inductance occurring due to a positive d-axis current and a second information indicating an inductance occurring due to a negative d-axis current, compares the first information and the second information, and determines one of the first information and the second information of a greater value to be the north pole.

BRIEF DESCRIPTION OF DRAWINGS

[0006] FIG. 1 is a block diagram illustrating an overall configuration a rotational control device of a permanent magnet synchronous motor according to a first embodiment.

FIG. 2 is a vertical cross-sectional view illustrating an overall configuration of the permanent magnet synchronous motor.

FIG. 3 is a diagram for explaining the well-known d-axis inductance characteristic in a permanent magnet synchronous motor.

FIG. 4 is a diagram for explaining the d-axis inductance characteristic in the permanent magnet synchronous motor according to the first embodiment.

FIG. 5 is a characteristic explanation diagram.

FIG. 6 is an explanatory diagram illustrating an example of another rotor having an identical characteristic to the characteristic illustrated in FIG. 4.

FIG. 7 is an explanatory diagram illustrating the relationship between a magnetic flux density (B) and a magnetic field intensity (H).

FIG. 8 is an explanatory diagram for explaining the operating principle according to the first embodiment.

FIG. 9 is an explanatory diagram illustrating the relationship between d-axis current and d-axis inductance in the state illustrated in FIG. 8.

FIG. 10 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in a rotor in the case in which the width of a magnetic-path-forming iron core is increased.

FIG. 11 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in a stator.

FIG. 12 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in the rotor in the case in which permanent magnets are inserted in vertical holes.

FIG. 13 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in the stator in the case in which permanent magnets are inserted in vertical holes.

FIG. 14 is an explanatory diagram for explaining the d-axis inductance increment and the d-axis inductance decrement according to the first embodiment.

FIG. 15 is an explanatory diagram for explaining the amount of change occurring in the d-axis inductance according to the first embodiment due to slot harmonics.

FIG. 16 is an explanatory diagram for explaining a magnetic-pole polarity determining operation according to the first embodiment.

FIG. 17A is an explanatory diagram for explaining γ -axis voltage changes equivalent to the d-axis in another example of the magnetic-pole polarity determining operation.

FIG. 17B is an explanatory diagram for explaining the γ -axis voltage changes equivalent to the d-axis in another example of the magnetic-pole polarity determining operation.

FIG. 18 is an explanatory diagram for explaining a magnetic-pole polarity determining operation according to a second embodiment.

FIG. 19 is a block diagram illustrating an overall configuration of a magnetic-pole polarity determining unit according to the third embodiment.

FIG. 20 is an explanatory diagram illustrating the relationship between a γ -axis current command and a γ -axis current.

DETAILED DESCRIPTION

[0007] Exemplary embodiments are described below in detail with reference to the accompanying drawings.

[1] First Embodiment

FIG. 1 is a block diagram illustrating an overall configuration a control device of a permanent magnet synchronous motor according to a first embodiment.

[0008] A motor drive device 100 mainly includes a current command generating unit 10, a current control unit 11, a high-frequency voltage superposing unit 12, a first coordinate converting unit 13, a triangular-wave PWM modulating unit 14, an inverter 15, a current detecting unit 16, a second coordinate converting unit 17, a magnetic-pole position estimating unit 18, and a magnetic-pole polarity determining unit 19.

[0009] In the configuration described above, the current command generating unit 10, the current control unit 11, the high-frequency voltage superposing unit 12, the first coordinate converting unit 13, the triangular-wave PWM modulating unit 14, the current detecting unit 16, the second coordinate converting unit 17, the magnetic-pole position estimating unit 18, and the magnetic-pole polarity determining unit 19 collectively function as an inverter control unit.

[0010] The current command generating unit 10 outputs a flux current command signal $i_{\gamma\text{ref}}$ and a torque current

command signal $i_{\delta\text{ref}}$. Moreover, the current that is output by the inverter 15 at the time of determining the magnetic-pole polarity is also controlled using the flux current command signal $i_{\gamma\text{ref}}$ and the torque current command signal $i_{\delta\text{ref}}$ output by the current command generating unit 10.

Based on the flux current command signal $i_{\gamma\text{ref}}$ and the torque current command signal $i_{\delta\text{ref}}$ input from the current command generating unit 10 as well as based on a flux current component signal i_{γ} and a torque current component signal i_{δ} , the current control unit 11 outputs fundamental-wave voltage command signals $v_{\gamma 0}$ and $v_{\delta 0}$.

The high-frequency voltage superposing unit 12 superposes high-frequency voltage command signals $v_{\gamma h}$ and $v_{\delta h}$ onto the fundamental-wave voltage command signals $v_{\gamma 0}$ and $v_{\delta 0}$, respectively, to generate voltage command signals v_{γ} and v_{δ} , respectively; and then outputs the voltage command signals v_{γ} and v_{δ} to the first coordinate converting unit 13.

[0011] The first coordinate converting unit 13 performs $\gamma\delta$ -to-UVW conversion with respect to the voltage command signals v_{γ} and v_{δ} based on a polarized magnetic-pole position θ_{est} ; generates voltage command signals v_u , v_v , and v_w ; and outputs the voltage command signals v_u , v_v , and v_w to the triangular-wave PWM modulating unit 14.

Based on the voltage command signals v_u , v_v , and v_w input thereto, the triangular-wave PWM modulating unit 14 generates a gate command signal (group) GC for the purpose of driving a switching transistor (for example, IGBT: Insulated Gate Bipolar Transistor) (not illustrated) that constitutes the inverter 15; and outputs the gate command signal GC to the inverter 15.

[0012] Based on the gate command signal GC, the inverter 15 generates a U-phase signal U, a V-phase signal V, and a W-phase signal W for the purpose of driving a permanent magnet synchronous motor (PMSM) 20. Then, based on the U-phase signal U, the V-phase signal V, and the W-phase signal W; the inverter 15 performs ON/OFF switching of a built-in switching element (for example, an IGBT) to convert alternate-current power into direct-current power and vice versa.

[0013] The current detecting unit 16 detects a U-phase current i_u , which flows to the permanent magnet synchronous motor 20 in response to the U-phase signal U, using a current sensor 16u and detects a W-phase current i_w , which flows to the permanent magnet synchronous motor 20 in response to the W-phase signal W, using a current sensor 16w; and then outputs the U-phase current i_u and the W-phase current i_w to the second coordinate converting unit 17. In the first embodiment, although the current values (the current response values) of two phases, namely, the U phase and the W phase are detected; it is also possible to have a configuration in which the current values of all three phases are detected.

[0014] The second coordinate converting unit 17 performs UVW-to- $\gamma\delta$ conversion with respect to the input U-phase current i_u and the input W-phase current i_w based on the polarized magnetic-pole position θ_{est} . Then, the second coordinate converting unit 17 outputs the flux current component signal i_γ and the torque current component signal i_δ , which are generated as a result of the UVW-to- $\gamma\delta$ conversion, to the magnetic-pole position estimating unit 18 and the current control unit 11.

The magnetic-pole position estimating unit 18 refers to

the current component signal i_y (a current response value) and the torque current component signal i_δ (a current response value), and estimates the magnetic-pole position of the permanent magnet synchronous motor 20.

[0015] As far as the technique of estimating the magnetic-pole position is concerned, the technique disclosed in, for example, Patent Literature 1 is implemented.

That is, the detected current is passed through a bandpass filter, and a value equivalent to a magnetic-pole position error is obtained by performing calculations. Then, the obtained value is input to a controller, and the angular velocity is estimated. Subsequently, the magnetic-pole position is estimated by integrating the estimated angular velocity. Alternatively, the magnetic-pole position can be calculated directly from the high-frequency current.

Thus, based on the flux current component signal i_y and the torque current component signal i_δ that are input, the magnetic-pole position estimating unit 18 estimates the magnetic-pole position and outputs a magnetic-pole position estimation signal θ_{est0} to the magnetic-pole polarity determining unit 19.

[0016] In the estimation of the magnetic-pole position, saliency of a rotor is put to use. For that reason, it is not possible to estimate the magnetic-pole direction. Thus, there is a possibility that a position in the direction displaced by 180° (deg) is obtained as the magnetic-pole position.

Hence, in the estimation of the magnetic-pole position, it is necessary to determine the magnetic-pole direction.

[0017] Based on the magnetic-pole position estimation signal θ_{est0} input thereto, the magnetic-pole polarity determining unit 19 generates the polarized magnetic-pole

position θ_{est} ; and outputs the polarized magnetic-pole position θ_{est} to the first coordinate converting unit 13 and the second coordinate converting unit 17. That is, the magnetic-pole polarity determining unit 19 determines the north pole and the south pole by making use of the magnetic saturation of the rotor iron core and, in the case in which the magnetic-pole position estimated by the magnetic-pole position estimating unit 18 is displaced by 180° (deg), outputs a value obtained by inverting the polarized magnetic-pole position θ_{est} corresponding to the magnetic-pole polarity by 180° (deg) from the magnetic-pole position estimation signal θ_{est0} .

[0018] Prior to the explanation of specific operations performed in the motor drive device 100, the explanation is given about a configuration of the permanent magnet synchronous motor 20 in which the first embodiment is implemented.

FIG. 2 is a vertical cross-sectional view illustrating an overall configuration of the permanent magnet synchronous motor.

The permanent magnet synchronous motor 20 includes a stator 21 and a rotor 22, and generates a torque for rotating the rotor 22 using the magnetic interactions that occur due to the magnetic field which is formed by a three-phase alternating current flowing to each excitation phase.

In the stator 21, stator teeth 23 and stator slots 24 are arranged in an alternating manner.

[0019] In the rotor 22, a plurality of vertical holes (air gaps) 26 is formed at predetermined positions of a rotor iron core 25 so as to isolate the magnetic poles. In each vertical hole 26, at least a single permanent magnet 27 is inserted and fixed to form a magnetic pole. Moreover, at

both sides of each permanent magnet 27, a magnetic-path-forming iron core 28 is disposed for the purpose of forming a local magnetic path that loops inside the rotor iron core 25.

[0020] Firstly, the explanation is given about the characteristic of the permanent magnet synchronous motor 20.

In the following explanation, it is assumed that, with the north pole direction of the magnetic poles treated as a d-axis, applying a positive current as a d-axis current means applying a current that flows in the direction of current in which the magnetic flux is strengthened by the relationship between the inductance of the magnetic-pole direction and the current.

A magnetic path MW of the d-axis is as illustrated in FIG. 2, and it is assumed that a d-axis inductance L_d is defined using the equation given below from a change Δi_d in the current of the d-axis and a change $\Delta \phi_d$ in the magnetic flux of the d-axis.

[0021] [Expression 1]

$$L_d = \frac{\Delta \phi_d}{\Delta i_d}$$

[0022] FIG. 3 is a diagram for explaining the well-known d-axis inductance characteristic in a permanent magnet synchronous motor.

FIG. 4 is a diagram for explaining the d-axis inductance characteristic in the permanent magnet synchronous motor according to the first embodiment.

Generally, in an interior permanent magnet synchronous motor (IPMSM); as illustrated in FIG. 3, along with an increase in the d-axis current, the d-axis inductance L_d undergoes a monotonic decrease.

[0023] In contrast, in the permanent magnet synchronous motor according to the first embodiment, as illustrated in FIG. 4, the d-axis inductance has a local maximum point L_{dp} in the positive direction with respect to the d-axis current. When the d-axis current is increased to be greater than the local maximum point L_{dp} , the d-axis inductance L_d undergoes a monotonic decrease.

[0024] For example, as illustrated in FIG. 5, the rotor 22 of the permanent magnet synchronous motor includes a rotor iron core in which air gaps are formed so as to isolate the magnetic poles, and at least a single permanent magnet is disposed in each air gap so that the permanent magnet forms a magnetic pole. At that time, if a magnetic-path-forming iron core is disposed for the purpose of forming a local magnetic path that loops inside the rotor iron core, then the characteristic illustrated in FIG. 4 are exhibited.

[0025] Explained below is the reason for the exhibition of the characteristic as illustrated in FIG. 4.

FIG. 5 is a characteristic explanation diagram.

As illustrated in FIG. 5, a flux flows in a looping manner inside the rotor 22 along local magnetic paths MWL due to the magnetic flux, and magnetic saturation occurs in the magnetic-path-forming iron core 28 due to the magnetic flux. At that time, if a positive current is applied to the d-axis, the flux that loops the stator 21 increases but the flux that loops inside the rotor 22 decreases. For that reason, the magnetic saturation of the magnetic-path-forming iron core 28 is released, and the d-axis inductance L_d increases in a gradual manner.

[0026] If the d-axis current is further increased, then magnetic saturation occurs in the magnetic path of the stator iron core and the d-axis inductance L_d goes on

decreasing. As a result, the characteristic illustrated in FIG. 4 is exhibited.

[0027] FIG. 6 is an explanatory diagram illustrating an example of another rotor having an identical characteristic to the characteristic illustrated in FIG. 4.

In the arrangement of the permanent magnets 27 illustrated in FIG. 6 too, the magnetic-path-forming iron core 28 that segmentalizes the vertical holes (air gaps) 26 undergoes magnetic saturation due to the magnetic flux. Hence, the characteristic illustrated in FIG. 4 is exhibited in an identical manner.

[0028] FIG. 7 is an explanatory diagram illustrating the relationship between a magnetic flux density (B) and a magnetic field intensity (H).

Herein, as illustrated in FIG. 7, magnetic saturation points to a decrease in the increase of the magnetic flux density (B) to a level lower than the linear increase in reaction to an increase in the magnetic field intensity H.

[0029] Thus, in reaction to an increase in the magnetic field intensity H that accompanies an increase in the current, the increase in the magnetic flux density B decreases to a lower level than the linear increase. For that reason, the inductance becomes smaller.

The value of the d-axis inductance L_d at the local maximum point L_{dp} is decided in the following manner.

[0030] FIG. 8 is an explanatory diagram for explaining the operating principle according to the first embodiment.

FIG. 9 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in the state illustrated in FIG. 8.

Firstly, as illustrated in FIG. 8, an electrical motor is considered in which the rotor 22 has only the vertical holes (air gaps) 26 arranged at predetermined positions of

the rotor iron core 25 so as to isolate the magnetic poles, and does not have magnets disposed therein.

[0031] At that time, the d-axis inductance L_d exhibits the characteristic as illustrated in FIG. 9 due to the fact that, when the magnetic flux density B is increased, the magnetic-path-forming iron core 28 that segmentalizes the vertical holes (air gaps) 26 undergoes magnetic saturation.

That is, when the magnetic-path-forming iron core 28 that segmentalizes the vertical holes (air gaps) 26 undergoes magnetic saturation and when the flux increases to a certain level and above, then the d-axis inductance L_d stops undergoing a change.

[0032] FIG. 10 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in the rotor in the case in which the width of the magnetic-path-forming iron core 28 is increased.

When the width of the magnetic-path-forming iron core 28 that segmentalizes the vertical holes (air gaps) 26 is increased, the magnetic saturation does not occur easily. That leads to an increase in the area in which the d-axis inductance L_d is large as illustrated in FIG. 10.

[0033] FIG. 11 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in the stator.

As illustrated in FIG. 11, along with an increase in the current in the stator, magnetic saturation progresses in a gentle way and the d-axis inductance L_d goes on decreasing. Meanwhile, if there are no magnets disposed; then, as illustrated in FIG. 9 and FIG. 11, there is no difference in the d-axis inductance L_d regardless of whether a positive d-axis current i_d is applied or a negative d-axis current i_d is applied.

[0034] The following explanation is given about the

changes in the d-axis inductance L_d in the case in which permanent magnets are inserted as illustrated in FIG. 5.

FIG. 12 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in the rotor in the case in which permanent magnets are inserted in vertical holes.

[0035] When the permanent magnets 27 are inserted in the vertical holes 26, then a flux flows in a looping manner inside the rotor 22 along the local magnetic paths MWL due to the magnetic flux, and magnetic saturation occurs in the magnetic-path-forming iron core 28 that segmentalizes the vertical holes (air gaps) 26. When a positive d-axis current i_d is applied to the d-axis, the magnetic saturation eases up due to the d-axis current i_d .

[0036] For that reason, as far the characteristic is concerned, the characteristic illustrated in FIG. 9 is shifted to the positive direction of the d-axis current i_d as illustrated in FIG. 12. Herein, since the iron core of the magnetic path MW of the d-axis undergoes magnetic saturation in some degree, a local maximum point L_{dp1} ($<L_{dp0}$) drops to a lower value.

[0037] FIG. 13 is an explanatory diagram illustrating the relationship between the d-axis current and the d-axis inductance in the stator in the case in which permanent magnets are inserted in vertical holes.

When the permanent magnets 27 are inserted in the vertical holes 26, magnetic saturation progresses due to the magnetic flux, and the characteristic of the d-axis inductance L_d illustrated in FIG. 11 gets shifted in the negative direction of the d-axis current i_d .

[0038] Meanwhile, the amount of shift of the d-axis current i_d in the positive direction as illustrated in FIG. 12 as well as the amount of shift of the d-axis current i_d

in the negative direction as illustrated in FIG. 13 is decided according to the interlinkage magnetic flux content of the d-axis.

With reference to FIG. 12, when the interlinkage magnetic flux content attributed to the permanent magnets 27 becomes equal to the interlinkage magnetic flux content generated due to the d-axis current i_d , the loop of the magnetic flux passes entirely through the stator 21. Consequently, the flux looping inside the rotor, that is, the flux passing through the magnetic-path-forming iron core 28, which segmentalizes the vertical holes (air gaps) 26, disappears and the magnetic saturation of the magnetic-path-forming iron core 28 is reduced to zero. Hence, the d-axis inductance L_d takes the local maximum value.

[0039] Meanwhile, with reference to FIG. 13, the shift in the negative direction occurs by an amount equal to the magnetic flux looping the stator at zero current.

Thus, the combined characteristics of the rotor and the stator appear as the overall characteristic.

[0040] FIG. 14 is an explanatory diagram for explaining the d-axis inductance increment and the d-axis inductance decrement according to the first embodiment.

FIG. 15 is an explanatory diagram for explaining the amount of change occurring in the d-axis inductance according to the first embodiment due to slot harmonics.

[0041] Meanwhile, in order to determine the magnetic-pole polarity in a stable manner, it is necessary to increase the difference between the d-axis inductances L_d . In order to increase the difference between the d-axis inductances L_d , the rotor 22 and the stator 21 can be designed in such a way that, when the d-axis current i_d is applied at which the d-axis inductance L_d of the rotor 22 is equal to the local maximum point, the increment in that d-axis inductance (ΔL_{dr}

illustrated in FIG. 14) is sufficiently larger than the decrement in the d-axis inductance L_d of the stator 21 (ΔL_{ds} illustrated in FIG. 14).

[0042] Particularly, if the difference between the d-axis inductance increment ΔL_{dr} and the d-axis inductance decrement ΔL_{ds} is set to be greater than the amount of change (ΔL_{dh} illustrated in FIG. 15) occurring in the d-axis inductance due to slot harmonics, then there is no change in rotational position of the rotor thereby making it possible to determine the magnetic-pole polarity in a stable manner.

[0043] Meanwhile, although explained later in the description of the operations performed by the magnetic-pole polarity determining unit 19; in order to make use of the d-axis inductance L_d , the changed portion of the d-axis current is put to use. As described earlier, the area having a large d-axis inductance near the local maximum point of the d-axis inductance is determined according to the width of the iron core that segmentalizes the air gaps as illustrated in FIG. 10. Thus, the width of the magnetic-path-forming iron core 28 can be decided in such a way that the d-axis inductance does not undergo a substantial change in reaction to the change in the d-axis current i_d made by the magnetic-pole polarity determining unit 19.

[0044] Given below is the explanation of the operations performed by the magnetic-pole polarity determining unit 19.

In the conventional technology, as illustrated in FIG. 3, the characteristic that is put to use indicates that, along with an increase in the d-axis current i_d , the d-axis inductance undergoes a monotonic decrease. For example, in

Patent Literature 2, both positive and negative biases are applied to the d-axis current, and the direction in which the amount of change in the high-frequency current (equivalent to the reciprocal of the d-axis inductance) is greater (i.e., the direction in which the d-axis inductance is smaller) at that time is determined to be the north pole.

In contrast, as illustrated in FIG. 4, the permanent magnet synchronous motor 20 according to the first embodiment has the local maximum point L_{dp} in the north pole direction.

[0045] FIG. 16 is an explanatory diagram for explaining a magnetic-pole polarity determining operation according to the first embodiment.

As illustrated in FIG. 16, when a positive d-axis current and a negative d-axis current having the same absolute value are applied to the d-axis, the current values (the current amplitudes) at which the inductances are equal are referred to as I_0 . Herein, a current satisfying $I_1 < I_0$ is applied to the positive and negative sides.

As a result, as illustrated in FIG. 16, the d-axis inductance on the north pole side becomes greater than the d-axis inductance on the south pole side. Hence, the magnetic-pole polarity determining unit 19 determines that the direction in which the d-axis inductance is greater points to the north pole. In this way, even in a permanent magnet synchronous motor in which, as illustrated in FIG. 4, the d-axis inductance L_d has the local maximum point in the positive direction with respect to the d-axis current and undergoes a monotonic decrease when the d-axis current is increased to be greater than the local maximum point, it becomes possible to perform magnetic-pole polarity determination.

[0046] In this case, if the conventional technology is put to use in which the d-axis inductance undergoes a monotonic decrease, it becomes necessary to increase the d-axis current i_d to a level equal to or greater than the current value I_0 . Hence, as compared to the conventional technology, it becomes possible to determine the polarity with a smaller current ($=I_1 < I_0$).

Thus, even if the polarity is to be determined at the time of activation, it becomes possible to reduce the current applied to the permanent magnet synchronous motor. That enables achieving reduction in the noise as well reduction in torque shocks while determining the polarity.

[0047] FIG. 20 is an explanatory diagram illustrating the relationship between a γ -axis current command and a γ -axis current.

More particularly, for example, as illustrated in FIG. 20(a), the current command generating unit 10 applies both positive and negative biases ($I_1 \leq I_0$) to a γ -axis current command corresponding to the d-axis. The δ -axis current command is assumed to be 0. At that time, due to voltage commands v_γ and v_δ that are generated by adding high-frequency voltages $v_{\gamma h}$ and $v_{\delta h}$ to voltage commands $v_{\gamma 0}$ and $v_{\delta 0}$ corresponding to a γ -axis current command, the γ -axis current flows as illustrated in FIG. 20(b). The amount of change in the high-frequency current at that time is equivalent to the reciprocal of the d-axis inductance. Thus, by comparing a high-frequency current change amount Δi_{hp} at the time of applying bias to the positive side and a high-frequency current change amount Δi_{hm} at the time of applying bias to the negative side, the direction in which the amount of change is greater (i.e., the direction in which the d-axis inductance is smaller) is determined to be

the south pole (with reference to FIG. 20, since $\Delta i_{hp} > \Delta i_{hm}$ is satisfied and the positive side becomes the south pole, the magnetic-pole polarity is reversed). Particularly, as illustrated in FIG. 16, if the d-axis current i_d during polarity determination is set, that is, if the current $I_1 = I_{dp}$ is satisfied; then the difference between the positive and negative inductances is maximized thereby making it possible to increase the SN ratio in the polarity determination.

[0048] Given below is the explanation of a modification example of the first embodiment.

In the modification example, in the motor drive device 100 illustrated in FIG. 1, the current control unit 11 and the high-frequency voltage superposing unit 12 are not disposed. Moreover, the configuration is such that the flux current component signal i_γ and the torque current component signal i_δ that are output by the second coordinate converting unit 17 at the time of generating the voltage command signals v_γ and v_δ , respectively, are not used. Instead, the current command generating unit 10 is configured to output the voltage command signals v_γ and v_δ .

FIG. 17A is an explanatory diagram for explaining the γ -axis voltage changes equivalent to the d-axis in another example of the magnetic-pole polarity determining operation.

FIG. 17B is an explanatory diagram for explaining the γ -axis voltage changes equivalent to the d-axis in another example of the magnetic-pole polarity determining operation.

As another example of polarity determination, when positive and negative fixed voltages are applied in the γ -axis direction as illustrated in FIG. 17A, the amplitude of the γ -axis voltage (equivalent to the reciprocal of the d-axis inductance) is checked and the

direction in which the amplitude is greater is determined to be the south pole as illustrated in FIG. 17B.

In this case, the voltage amplitude is determined in such a way that the current amplitude I_1 in the south pole direction satisfies $I_1 < I_0$. Particularly, if the voltage amplitude is determined in such a way that the current amplitude I_1 in the south pole direction is equal to I_0 , then the difference between the amplitudes of the d-axis current i_d is maximized thereby making it possible to increase the SN ratio.

[0049] Alternatively, the amplitude of the γ -axis voltage (equivalent to the reciprocal of the d-axis inductance) is checked in response to the application of a fixed voltage; and, if the amplitude is equal to or greater than a threshold value, it is determined to be the south pole. The voltage amplitude is decided in such a way that the current amplitude I_1 in the south pole direction satisfies $I_1 \leq I_0$. Particularly, if the voltage amplitude is determined in such a way that the current amplitude I_1 in the south pole direction is equal to I_0 , then the current amplitude is maximized thereby making it possible to increase the SN ratio.

[0050] Still alternatively, an alternating-voltage generating unit is disposed that superposes an alternating voltage having positive/negative symmetry to the γ -axis. Then, the amplitude in the positive direction and the amplitude in the negative direction of the γ -axis current i_γ , which is generated due to the alternating voltage, is detected; and the direction in which the current amplitude (equivalent to the reciprocal of the d-axis inductance) is greater is determined to be the south pole direction.

In this case, the voltage amplitude is decided in such

a way that the current amplitude I_1 in the south pole direction satisfies $I_1 \leq I_0$. Particularly, if the voltage amplitude is determined in such a way that the current amplitude I_1 in the south pole direction is equal to I_0 , then the difference between the current amplitudes is maximized thereby making it possible to increase the SN ratio.

[0051] Still alternatively, if the fact that the d-axis inductance on the north pole side increases in an area satisfying $i_d < i_0$, it becomes possible to determine the magnetic-pole direction in an identical manner.

[0052] In the explanation given above, the magnetic-pole position estimating unit 18 and the magnetic-pole polarity determining unit 19 are configured separately. However, alternatively, the magnetic-pole position estimating unit 18 and the magnetic-pole polarity determining unit 19 can also be configured in an integrated manner. For example, when the d-axis current having positive/negative symmetry is applied, according to a method in which the characteristic of magnetic saturation of differing in positivity and negativity only in the d-axis direction is used in estimating the magnetic-pole position, it becomes possible to perform magnetic-pole position estimation including magnetic-pole polarity determination. At that time, if the current amplitude is set to satisfy $I_1 \leq I_0$ and if the fact that the d-axis inductance on the north pole side increases is used, then it becomes possible to achieve the same effect as the effect achieved in the embodiment described above.

[0053] Meanwhile, the explanation given above is about sensorless control. However, alternatively, the explanation is applicable in an identical manner in estimating the initial magnetic-pole position of a pulse

generator.

[0054] [2] Second Embodiment

In a second embodiment, in a permanent magnet synchronous motor having the characteristic that the d-axis inductance has the local maximum point in the positive direction with respect to the d-axis current i_d and undergoes a monotonic decrease when the d-axis current is increased to be greater than the local maximum point; unlike in the first embodiment, polarity determination is performed by applying a current satisfying $I_1 > I_0$ to the positive and negative sides.

[0055] FIG. 18 is an explanatory diagram for explaining a magnetic-pole polarity determining operation according to the second embodiment.

As illustrated in FIG. 18, the d-axis inductance L_d decreases to a lower level on the north pole side than on the south pole side. Then, the magnetic-pole polarity determining unit 19 determines the direction in which the d-axis inductance is smaller to be the north pole.

In this case, unlike in the case of the first embodiment, more the increase in the d-axis current i_d , greater becomes the difference between the d-axis inductance L_d on the north pole side and the d-axis inductance L_d on the south pole side. The advantage thereof is that the adjustments become easier to perform and the SN ratio becomes easier to secure.

[0056] More particularly, for example, positive and negative biases ($I_1 > I_0$) are applied to the d-axis current, and the direction in which the amount of change in the high-frequency current (equivalent to the reciprocal of the d-axis inductance) is greater (i.e., the direction in which the d-axis inductance is smaller) at that time is determined to be the north pole.

[0057] Moreover, if the fact that the d-axis inductance on the south pole side increases in the area satisfying $i_d > I_0$ is used, then it becomes possible to determine the magnetic-pole direction in an identical manner.

In the explanation given above, the magnetic-pole position estimating unit 18 and the magnetic-pole polarity determining unit 19 are configured separately. However, alternatively, the magnetic-pole position estimating unit 18 and the magnetic-pole polarity determining unit 19 can also be configured in an integrated manner. For example, when the d-axis current having positive/negative symmetry is applied, according to a method in which the characteristic of magnetic saturation of differing in positivity and negativity only in the d-axis direction is used in estimating the magnetic-pole position, it becomes possible to perform magnetic-pole position estimation including magnetic-pole polarity determination.

[0058] At that time, if the current amplitude is set to satisfy $I_1 > I_0$ and if the fact that the d-axis inductance on the south pole side increases, then it becomes possible to achieve the effect of the present invention.

Meanwhile, in the second embodiment too, the explanation is not limited to sensorless control, and is applicable in an identical manner in estimating the initial magnetic-pole position of a pulse generator.

[0059] [3] Third Embodiment

In each embodiment described above, the explanation is given only for a case in which the permanent magnet synchronous motor that is connected and to be controlled has the characteristic illustrated in FIG. 4. In contrast, in a third embodiment, it is made possible to select between a permanent magnet synchronous motor that is connected and to be controlled has the characteristic

illustrated in FIG. 3 and a permanent magnet synchronous motor that is connected and to be controlled has the characteristic illustrated in FIG. 4.

[0060] The following explanation is given only about a magnetic-pole polarity determining unit that is different than the first embodiment.

FIG. 19 is a block diagram illustrating an overall configuration of the magnetic-pole polarity determining unit according to the third embodiment.

A magnetic-pole polarity determining unit 19A according to the third embodiment is used in place of the magnetic-pole polarity determining unit 19 according to the first embodiment; and includes a polarity determining unit 41, a determination method selecting unit 42, and a polarity inverting unit 43 as illustrated in FIG. 19.

[0061] In the polarity determining unit 41 of the magnetic-pole polarity determining unit 19A, the direction in which the inductance becomes greater in reaction to the application of the positive current I_1 and the negative current I_1 to the d-axis is determined to be the south pole, and a polarity determination flag f_{dir} is set. More particularly, for example, both positive and negative biases are applied to the d-axis current, and the direction in which the amount of change in the high-frequency current (equivalent to the reciprocal of the d-axis inductance) is smaller (i.e., the direction in which the d-axis inductance is greater) at that time is determined to be the south pole.

[0062] In the determination method selecting unit 42, the motor that is connected is a permanent magnet synchronous motor in which, as illustrated in FIG. 4, the d-axis inductance has the local maximum point in the positive direction with respect to the d-axis current and undergoes a monotonic decrease when the d-axis current is

increased to be greater than the local maximum point; as well as inverts the polarity determination flag f_{dir} when $I_1 < I_0$ is satisfied.

[0063] As a result, the polarity inverting unit 43 refers to the f_{dir} and accordingly determines whether or not to invert the polarity. In the case of inverting the polarity, 180° (deg) is output to a polarity inversion command θ_{dir} ; the polarity of the magnetic-pole position estimation signal θ_{est0} is inverted; and is output as the polarized magnetic-pole position θ_{est} .

[0064] According to the third embodiment, regardless of whether a permanent magnet synchronous motor has the characteristic that the d-axis inductance undergoes a monotonic decrease along with an increase in the d-axis current as illustrated in FIG. 3 or whether a permanent magnet synchronous motor has the characteristic that the d-axis inductance has the local maximum point in the positive direction with respect to the d-axis current and undergoes a monotonic decrease when the d-axis current is increased to be greater than the local maximum point; if the user only performs the setting of the determination method selecting unit 42, it becomes possible to implement a magnetic-pole polarity determining device and eventually a motor control device capable of performing magnetic-pole polarity determination.

[0065] Meanwhile, in the third embodiment too, the explanation is not limited to sensorless control, and is applicable in an identical manner in estimating the initial magnetic-pole position of a pulse generator.

[0066] Other Aspects of Embodiments

[4.1] 1st Other Aspect

In a magnetic-pole polarity determining device

according to a 1st other aspect of the embodiments, the direction of current in which the magnetic flux is strengthened by the relationship between the inductance of the magnetic-pole direction and the current is treated as the positive direction, while the direction of current in which the magnetic flux is weakened is treated as the negative direction. The magnetic-pole polarity determining device determines the magnetic-pole polarity of a permanent magnet synchronous motor having the characteristic that, when a current in the positive direction is applied, the inductance of the magnetic-pole direction has the local maximum point and undergoes a monotonic decrease when a large current is applied in the positive direction with respect to the local maximum point. Moreover, the magnetic-pole polarity determining device includes a magnetic-pole polarity determining unit that, when a current is applied in the positive direction and the negative direction with an identical predetermined current value, determines the side on which the inductance of the magnetic-pole direction (i.e., the d-axis inductance) increases as the north pole side.

[0067] [4.2] 2nd Other Aspect

According to a 2nd other aspect of the embodiments, a magnetic-pole polarity determining device determines the magnetic-pole polarity of a permanent magnet synchronous motor in which a rotor has a rotor iron core with air gaps formed thereon so as to isolate the magnetic poles; at least a single permanent magnet is disposed in each air gap to form a magnetic pole; and a magnetic-path-forming iron core is disposed for the purpose of forming a local magnetic path that loops inside the rotor iron core. Moreover, in the magnetic-pole polarity determining device, the direction of current in which the magnetic flux is

strengthened by the relationship between the inductance of the magnetic-pole direction and the current is treated as the positive direction, while the direction of current in which the magnetic flux is weakened is treated as the negative direction. Furthermore, the magnetic-pole polarity determining device includes a magnetic-pole polarity determining unit that, when a current is applied in the positive direction and the negative direction with an identical predetermined current value, determines the side on which the inductance of the magnetic-pole direction (i.e., the d-axis inductance) increases as the north pole side.

[0068] [4.3] 3rd Other Aspect

According to a 3rd other aspect of the embodiments, in the first other aspect or the second other aspect, the predetermined current value (I_1) is set to such a current value that is smaller than a current value at which the inductance of the magnetic-pole direction again becomes equal in the positive direction and the negative direction when, while applying an identical current in the positive direction and the negative direction from the state of zero current, the current in the positive direction is increased to a current value greater than the current value equivalent to the local maximum point.

[0069] [4.4] 4th Other Aspect

According to a 4th aspect of the embodiments, in any one of the first other aspect to the third other aspect, the predetermined current value is either set to the current value equivalent to the local maximum point or set to a current value equivalent to the neighborhood of the local maximum point.

[0070] [4.5] 5th Other Aspect

According to a 5th aspect of the embodiments, in any

one of the first other aspect to the fourth other aspect, the predetermined current value is set in such a way that the difference in inductances of the magnetic-pole direction at the predetermined current value is equal to or greater than a predetermined difference.

[0071] [4.6] 6th Other Aspect

According to a 6th aspect of the embodiments, in any one of the first other aspect to the fifth other aspect, it is either possible to connect a permanent magnet synchronous motor having the characteristic that, when a large current is applied in the positive direction with respect to the local maximum point, the inductance of the magnetic-pole direction undergoes a monotonic decrease or possible to connect another type of permanent magnet synchronous motor having the characteristic that, when a current is applied in the positive direction, the inductance of the magnetic-pole direction undergoes a monotonic decrease as the current value increases. The magnetic-pole polarity determining device includes a polarity inverting unit that, when the other type of permanent magnet synchronous motor is connected, inverts the output of the magnetic-pole polarity determining unit.

[0072] [4.7] 7th Other Aspect

According to a 7th other aspect of the embodiments, in a magnetic-pole polarity determining device, the direction of current in which the magnetic flux is strengthened by the relationship between the inductance of the magnetic-pole direction and the current is treated as the positive direction, while the direction of current in which the magnetic flux is weakened is treated as the negative direction. The magnetic-pole polarity determining device determines the magnetic-pole polarity of a permanent magnet synchronous motor having the characteristic that, when a

current in the positive direction is applied, the inductance of the magnetic-pole direction has the local maximum point and undergoes a monotonic decrease when a large current is applied in the positive direction with respect to the local maximum point. Moreover, the magnetic-pole polarity determining device includes a magnetic-pole polarity determining unit that, when a current is applied in the positive direction and the negative direction with an identical predetermined current value, determines the side on which the inductance of the magnetic-pole direction decreases as the north pole side. Herein, the predetermined current value is set to such a current value that is greater than a current value at which the inductance of the magnetic-pole direction again becomes equal in the positive direction and the negative direction when, while applying an identical current in the positive direction and the negative direction from the state of zero current, the current in the positive direction is increased to a current value greater than the current value equivalent to the local maximum point.

[0073] [4.8] 8th Other Aspect

According to an 8th other aspect of the embodiments, in a magnetic-pole polarity determining device, the direction of current in which the magnetic flux is strengthened by the relationship between the inductance of the magnetic-pole direction and the current is treated as the positive direction, while the direction of current in which the magnetic flux is weakened is treated as the negative direction. The magnetic-pole polarity determining device determines the magnetic-pole polarity of a permanent magnet synchronous motor having the characteristic that, when a current in the positive direction is applied, the inductance of the magnetic-pole direction has the local

maximum point and undergoes a monotonic decrease when a large current is applied in the positive direction with respect to the local maximum point. Moreover, the magnetic-pole polarity determining device includes an alternating-voltage generating unit that superposes an alternating voltage having positive/negative symmetry to the magnetic-pole direction; and includes a magnetic-pole polarity determining unit that detects the amplitude in the positive direction and the amplitude in the negative direction of the current generated due to the alternating voltage and determines the direction in which the current amplitude is greater as the south pole direction.

[0074] [4.9] 9th Other Aspect

According to a 9th other aspect of the embodiments, in a permanent-magnet-synchronous-motor control device, the direction of current in which the magnetic flux is strengthened by the relationship between the inductance of the magnetic-pole direction and the current is treated as the positive direction, while the direction of current in which the magnetic flux is weakened is treated as the negative direction. The permanent-magnet-synchronous-motor control device controls a permanent magnet synchronous motor having the characteristic that, when a current in the positive direction is applied, the inductance of the magnetic-pole direction has the local maximum point and undergoes a monotonic decrease when a large current is applied in the positive direction with respect to the local maximum point. Moreover, the permanent-magnet-synchronous-motor control device includes a magnetic-pole polarity determining unit that, when a current is applied in the positive direction and the negative direction with an identical predetermined current value, determines the side on which the inductance of the magnetic-pole direction

increases as the north pole side; and includes an inverter control unit that generates a gate command signal based on the determination result of the magnetic-pole polarity determining unit and controls an inverter which drives the permanent magnet synchronous motor.

[0075] [4.10] 10th Other Aspect

According to a 10th other aspect of the embodiments, a permanent-magnet-synchronous-motor control device controls a permanent magnet synchronous motor in which a rotor has a rotor iron core with air gaps formed thereon so as to isolate the magnetic poles; at least a single permanent magnet is disposed in each air gap to form a magnetic pole; and a magnetic-path-forming iron core is disposed for the purpose of forming a local magnetic path that loops inside the rotor iron core. Moreover, in the a permanent-magnet-synchronous-motor control device, the direction of current in which the magnetic flux is strengthened by the relationship between the inductance of the magnetic-pole direction and the current is treated as the positive direction, while the direction of current in which the magnetic flux is weakened is treated as the negative direction. Furthermore, the permanent-magnet-synchronous-motor control device includes a magnetic-pole polarity determining unit that, when a current is applied in the positive direction and the negative direction with an identical predetermined current value, determines the side on which the inductance of the magnetic-pole direction increases as the north pole side; and includes an inverter control unit that generates a gate command signal based on the determination result of the magnetic-pole polarity determining unit and controls an inverter which drives the permanent magnet synchronous motor.

[0076] [4.11] 11th Other Aspect

According to an 11th aspect of the embodiments, in a magnetic-pole polarity determining device, the direction of current in which the magnetic flux is strengthened by the relationship between the inductance of the magnetic-pole direction and the current is treated as the positive direction, while the direction of current in which the magnetic flux is weakened is treated as the negative direction. The magnetic-pole polarity determining device determines the magnetic-pole polarity of a permanent magnet synchronous motor having the characteristic that, when a current in the positive direction is applied, the inductance of the magnetic-pole direction has the local maximum point and undergoes a monotonic decrease when a large current is applied in the positive direction with respect to the local maximum point. A magnetic-pole polarity determining method implemented in the magnetic-pole polarity determining device includes applying a current in the positive direction and the negative direction with an identical predetermined current value; and determining, when a current is applied with the predetermined current value, the side on which the inductance of the magnetic-pole direction increases as the north pole side.

[0077] [4.12] 12th Other Aspect

According to a 12th aspect of the embodiments, a magnetic-pole polarity determining device determines the magnetic-pole polarity of a permanent magnet synchronous motor in which a rotor has a rotor iron core with air gaps formed thereon so as to isolate the magnetic poles; at least a single permanent magnet is disposed in each air gap to form a magnetic pole; and a magnetic-path-forming iron core is disposed for the purpose of forming a local magnetic path that loops inside the rotor iron core.

Moreover, in the magnetic-pole polarity determining device, the direction of current in which the magnetic flux is strengthened by the relationship between the inductance of the magnetic-pole direction and the current is treated as the positive direction, while the direction of current in which the magnetic flux is weakened is treated as the negative direction. The magnetic-pole polarity determining device executed by the magnetic-pole polarity determining device includes applying a current in the positive direction and the negative direction with an identical predetermined current value and determining, when a current is applied with the predetermined current value, the side on which the inductance of the magnetic-pole direction increases as the north pole side.

[0078] Meanwhile, although the invention has been described with respect to specific embodiments for a complete and clear disclosure, the appended claims are not to be thus limited but are to be construed as embodying all modifications and alternative constructions that may occur to one skilled in the art that fairly fall within the basic teaching herein set forth.

CLAIMS

1. A control system for controlling a synchronous motor having a magnet in a rotor, the control system comprising:

an inverter configured to output an AC current for driving the synchronous motor;

a gate command generating unit configured to generate a gate command for controlling the inverter;

a current detecting unit configured to detect the AC current output by the inverter;

a magnetic pole position estimating unit configured to estimate a magnetic pole position based on the AC current detected by the current detecting unit and generate an estimation signal;

a current command generating unit configured to generate a current command and an estimation command for controlling the inverter to output the AC current with a predetermined level, wherein the estimation command is generated when estimating the magnetic pole position; and

a magnetic polarity determination unit configured to calculate based on the estimation signal, first data indicating an inductance value based on a positive d-axis current and second data indicating an inductance value based on a negative d-axis current, compare the first data and the second data, and determine one of the first data and the second data having a larger value as indicating an N-pole direction;

wherein the synchronous motor has a characteristic that:

i) a d-axis inductance has a local maximum point within a range in which the positive d-axis current increases when the positive d-axis current is supplied to a stator,

ii) a d-axis inductance in magnetic flux direction

monotonically decreases when the positive d-axis current is increased beyond the local maximum point, and

iii) the value of the local maximum point is greater than a value of the d-axis inductance when the negative d-axis current is supplied to the stator.

2. The control system according to Claim 1, wherein the gate command for polarity determination is a command indicating that the d-axis obtained from the d-axis current corresponding to the current value represents the local maximum value or the neighborhood of the local maximum value.

3. The control system according to Claim 1, wherein the rotor includes a plurality of magnet portions made of two magnets, and the two magnets of each of the magnet portions are disposed across the d-axis so that the distance therebetween is shortest at a portion closest to the center of the rotor and longest at a portion furthest to the center of the rotor.

4. The control system according to Claim 1, wherein the rotor includes a plurality of magnet portions made of three magnets, one of the three magnets of each of the magnet portions is disposed astride the d-axis, and the other two of the three magnets are disposed across the d-axis so that the distance therebetween is shortest at a portion closest to the center of the rotor and longest at a portion furthest to the center of the rotor.

5. The control system of claim 1, wherein the gate command generating unit comprises:

a high-frequency voltage superposition unit configured

to superimpose first voltage command signals with fundamental voltage command signals to generate second voltage command signals;

a coordinate converting unit configured to convert the second voltage command signals to third voltage command signals based on the estimated magnetic pole position; and

a modulation unit configured to generate the gate command based on the third voltage command signals.

6. A control system for controlling a synchronous motor having a magnet in a rotor, the control system comprising:

an inverter configured to output an AC current for driving the synchronous motor;

a gate command generating unit configured to generate a gate command for controlling the inverter;

a current detecting unit configured to detect the AC current output by the inverter;

a magnetic pole position estimating unit configured to estimate a magnetic pole position based on the AC current detected by the current detecting unit and generate an estimation signal;

a current command generating unit configured to generate a current command and an estimation command for controlling the inverter to output the AC current with a predetermined level, wherein the estimation command is generated when estimating the magnetic pole position; and

a magnetic polarity determination unit configured to calculate, based on the estimation signal, first data indicating an inductance value based on a positive d-axis current and second data indicating an inductance value based on a negative d-axis current, compare the first data and the second data, and determine one of the first data and the second data having a smaller value as indicating an N-pole

direction,

wherein the estimation command controls the inverter to output an AC current larger value than a first AC current that causes an inductance value to be a maximum value and a second AC current that causes the same inductance value when outputting a positive second AC current and a negative second AC current;

wherein the synchronous motor has a characteristic that:

i) a d-axis inductance has a local maximum point within a range in which the positive d-axis current increases when the positive d-axis current is supplied to a stator,

ii) a d-axis inductance in magnetic flux direction monotonically decreases when the positive d-axis current is increased beyond the local maximum point, and

iii) the value of the local maximum point is greater than a value of the d-axis inductance when the negative d-axis current is supplied to the stator.

7. A control system for controlling a synchronous motor having a magnet in a rotor, the control system comprising:

an inverter configured to output an AC current for driving the synchronous motor;

a gate command generating unit configured to generate a gate command for driving the inverter;

a current detecting unit configured to detect the AC current output by the inverter;

a magnetic pole position estimating unit configured to estimate a magnetic pole position based on the AC current detected by the current detecting unit and generate an estimation signal;

an AC voltage generating unit configured to generate an AC voltage to be superimposed on a d-axis component of the

AC current output by the inverter; and

a magnetic polarity determination unit configured to determine an S-pole direction based on an amplitude of the d-axis component on which the AC voltage generated by the AC voltage generating unit is superimposed;

wherein the synchronous motor has a characteristic that:

i) a d-axis inductance has a local maximum point within a range in which a positive d-axis current increases when the positive d-axis current is supplied to a stator,

ii) a d-axis inductance in magnetic flux direction monotonically decreases when the positive d-axis current is increased beyond the local maximum point, and

iii) the value of the local maximum point is greater than a value of the d-axis inductance when a negative d-axis current is supplied to the stator.