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### MOTOR CONTROL DEVICE AND ELECTRIC POWER STEERING DEVICE

#### Abstract

The motor control device includes: a d-axis current command value calculation unit configured to set a first d-axis current command value for field-weakening; a first current limiting unit configured to calculate a first q-axis current command value by limiting a base q-axis current command value as to satisfy a condition of motor rated current; a second current limiting unit configured to calculate a second d-axis current command value and a second q-axis current command value by limiting the first d-axis current command value and the first q-axis current command value, respectively to satisfy and not exceed an allowable upper limit battery current; voltage command value calculation units configured to calculate voltage command values, based on the second d-axis current command value and the second q-axis current command value; and a voltage limiting unit configured to prevent saturation of a duty ratio by limiting the voltage command values.

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## **Background/Summary**

CROSS REFERENCE TO RELATED APPLICATIONS [0001] This application is a National Stage of International Application No. PCT/JP2024/017489 filed May 10, 2024, claiming priority based on Japanese Patent Application No. 2023-087133 filed May 26, 2023.

### **TECHNICAL FIELD**

[0002] The present invention relates to a motor control device and an electric power steering device.

### **BACKGROUND ART**

[0003] In a motor control device that controls an electric motor, control output sometimes needs to be corrected. For example, in a motor control device that is mounted on an electric power steering, correction is performed on control output in accordance with system requirements or customer requirements. In PTL 1 described below, a motor control device that, while avoiding duty saturation in PWM control of a motor (that is, a state in which a voltage command value exceeds a maximum voltage applicable to a drive circuit), limits d-axis current to an arbitrary value is proposed.

### **CITATION LIST**

Patent Literature

[0004] PTL 1: WO 2020/095479 A

### **SUMMARY OF INVENTION**

Technical Problem

[0005] In the motor control device in PTL 1 described above, problems in that the duty ratio saturates in a high load condition, the duty ratio is reduced in a high rotational velocity region, and the like have arisen.

[0006] The present invention has been made in consideration of the above-described circumstances, and an object of the present invention is to prevent saturation of a duty ratio in a high load condition and reduction in the duty ratio in a high rotational velocity region in association with correction of control output of a motor control device.

Solution to Problem

[0007] In order to achieve the above-described object, according to an aspect of the present invention, there is provided a motor control device including: a torque control unit configured to set a base q-axis current command value to control torque generated by a motor; a d-axis current command value calculation unit configured to set a first d-axis current command value for field-weakening, based on the base q-axis current command value and rotational velocity of the motor; a first current limiting unit disposed in a succeeding stage of the d-axis current command value calculation unit and configured to calculate a first q-axis current command value by limiting the base q-axis current command value according to the first d-axis current command value in such a way that driving current of the motor does not exceed a rated current of the motor; a second current limiting unit disposed in a succeeding stage of the first current limiting unit and configured to calculate a second d-axis current command value and a second q-axis current command value by limiting the first d-axis current command value and the first q-axis current command value, respectively in such a way that output current from a battery does not exceed a predetermined

allowable upper limit; a voltage command value calculation unit configured to calculate a first d-axis voltage command value and a first q-axis voltage command value, based on the second d-axis current command value and the second q-axis current command value; a voltage limiting unit configured to calculate a second d-axis voltage command value and a second q-axis voltage command value by limiting the first d-axis voltage command value and the first q-axis voltage command value, respectively in such a way as to prevent saturation of a duty ratio in PWM control based on the first d-axis voltage command value and the first q-axis voltage command value; and a drive circuit configured to drive the motor, based on the second d-axis voltage command value and the second q-axis voltage command value.

[0008] According to another aspect of the present invention, there is provided an electric power steering device including: the motor control device described above; and a motor controlled by the motor control device, wherein the electric power steering device provides a steering system of a vehicle with a steering assist force, using the motor.

#### Advantageous Effects of Invention

[0009] According to the present invention, it is possible to prevent saturation of a duty ratio in a high load condition and reduction in the duty ratio in a high rotational velocity region in association with correction of control output of a motor control device.

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## Description

### BRIEF DESCRIPTION OF DRAWINGS

[0010] FIG. 1 is a configuration diagram illustrative of an outline of an example of an electric power steering device of an embodiment;

[0011] FIG. 2 is a block diagram illustrative of an example of a functional configuration of a controller illustrated in FIG. 1;

[0012] FIG. 3 is a block diagram illustrative of an example of a functional configuration of a d-axis current command value calculation unit;

[0013] FIG. 4A is a diagram illustrative of a setting example of an example of a d-axis current upper limit that is set by a field current limiting unit, and FIG. 4B is a timing diagram of an example of limitation of a d-axis current command value;

[0014] FIG. 5 is a block diagram illustrative of an example of a functional configuration of a feedback (FB) control unit;

[0015] FIG. 6 is a block diagram illustrative of an example of a functional configuration of a voltage limiting unit;

[0016] FIG. 7 is a block diagram illustrative of an example of a functional configuration of a voltage upper limit setting unit;

[0017] FIGS. 8A and 8B are schematic diagrams of a first example and a second example of a setting example of a first determination gain, respectively, and FIGS. 8C and 8D are schematic diagrams of a first example and a second example of a setting example of a second determination gain, respectively;

[0018] FIG. 9 is a flowchart of an example of a motor control method of the embodiment; and

[0019] FIG. 10 is a configuration diagram illustrative of an outline of an example of a linear motion table device in which the motor control device of the present invention is used.

### DESCRIPTION OF EMBODIMENTS

[0020] Embodiments of the present invention will be described in detail with reference to the drawings. Note that the embodiments of the present invention to be described below indicate devices and methods to embody the technical idea of the present invention by way of example, and the technical idea of the present invention does not limit the constitution, arrangements, and the like of the constituent components to those described below. The technical idea of the present

invention can be subjected to a variety of alterations within the technical scope prescribed by the claims described in CLAIMS.

(Configuration)

[0021] FIG. 1 is a configuration diagram illustrative of an outline of an example of an electric power steering device of an embodiment. A steering shaft (steering wheel shaft) 2 of a steering wheel 1 is connected to steered wheels 8L and 8R by way of a reduction gear (worm gear) 3 that constitutes a speed reduction mechanism, universal joints 4a and 4b, a pinion rack mechanism 5, and tie rods 6a and 6b and further via hub units 7a and 7b.

[0022] The pinion rack mechanism 5 includes a pinion 5a that is coupled to a pinion shaft to which steering force is transmitted from the universal joint 4b and a rack 5b that meshes with the pinion 5a, and converts rotational motion transmitted to the pinion 5a to linear motion in the vehicle width direction by means of the rack 5b.

[0023] To the steering shaft 2, a torque sensor 10 configured to detect steering torque  $T_h$  is disposed. To the steering shaft 2, a steering angle sensor 14 configured to detect a steering angle  $\theta_h$  of the steering wheel 1 is also disposed.

[0024] A motor 20 configured to assist steering force of the steering wheel 1 is also connected to the steering shaft 2 via the reduction gear 3. To a controller 30 configured to control the electric power steering device (EPS), power is supplied from a battery 13 and an ignition key signal is also input by way of an ignition (IGN) key 11.

[0025] The motor 20 is a polyphase AC motor and is driven by vector control performed by the controller 30. In the present embodiment, a case where the motor 20 is a three-phase AC motor is described as an example.

[0026] The controller 30 is an electronic control unit (ECU) configured to perform calculation of a current command value of an assist control command, based on steering torque  $T_h$  detected by the torque sensor 10, vehicle speed  $V_h$  detected by a vehicle speed sensor 12, and a steering angle  $\theta_h$  detected by the steering angle sensor 14 and control current to be supplied to the motor 20 in accordance with a voltage command value  $V_{ref}$  obtained by performing compensation and the like on the calculated current command value.

[0027] Note that the steering angle sensor 14 is not an essential component and the steering angle  $\theta_h$  may be calculated by adding a torsion angle of a torsion bar in the torque sensor 10 to a rotation angle acquired from a rotation angle sensor configured to detect a rotation angle of the rotation shaft of the motor 20.

[0028] In addition, a turning angle of the steered wheels 8L and 8R may be used in place of the steering angle  $\theta_h$ . The turning angle may be detected by, for example, detecting a displacement amount of the rack 5b.

[0029] The controller 30 includes, for example, a computer including a processor and peripheral components, such as a storage device. The processor may be, for example, a central processing unit (CPU) or a micro-processing unit (MPU).

[0030] The storage device may include one of a semiconductor storage device, a magnetic storage device, and an optical storage device. The storage device may include registers, a cache memory, or a memory, such as a read only memory (ROM) and a random access memory (RAM), that is used as a main storage device.

[0031] Functions of the controller 30, which will be described below, are achieved by, for example, the processor of the controller 30 executing computer programs stored in the storage device.

[0032] Note that the controller 30 may be formed by use of dedicated hardware for executing each type of information processing that will be described below.

[0033] For example, the controller 30 may include functional logic circuits that are set in a general-purpose semiconductor integrated circuit. For example, the controller 30 may have a programmable logic device (PLD), such as a field-programmable gate array (FPGA), or the like.

[0034] Next, problems in a limiting function of control output to the motor 20 performed by the

controller **30** will be described. The limiting function of the control output to the motor **20** has been developed with the aims of (1) calculating the amount of field-weakening current to satisfy a requirement for following performance of a turning angle of the steered wheels with respect to steering of the steering wheel, (2) satisfying a system current upper limit and a battery current upper limit, and (3) preventing duty saturation.

[0035] However, in the motor control device in PTL 1 described above, the following problems 1 and 2 remain to be solved. [0036] (Problem 1) There are some cases where the duty saturation cannot be prevented in a high load condition. [0037] (Problem 2) There are some cases where a reduction in a duty ratio occurs in a high rotational velocity region.

[0038] Therefore, the motor control device in the embodiment aims at solving the problems 1 and 2.

[0039] Further, the motor control device in the embodiment also aims at solving, in addition to the problems 1 and 2, the following problems 3 and 4. [0040] (Problem 3) Since as described later, an integrator is used in feedback control of motor current in the motor control device in the embodiment, there is a risk that integrated values are excessively accumulated. [0041] (Problem 4) Due to a recent requirement for high output power, use of a motor having low inductance and inertia is widely accepted. Therefore, a counter measure against overcurrent caused by counter electromotive voltage at the time of high speed rotation needs to be taken.

[0042] In the present invention, means for solving the above-described problems 1 to 4 is provided based on the following principle.

[0043] It is considered that the duty saturation in a high load condition (problem 1) is caused by steady-state deviation or error due to transient characteristics in the feedback control of the motor current, an inappropriate position at which current limiting is performed, an attempt to apply limitation of a duty dimension in a current dimension, or the like. Thus, prevention of duty saturation is achieved by limiting a voltage command value.

[0044] It is considered that the reduction in the duty ratio in the high rotational velocity region (problem 2) is caused by excessively limiting a q-axis current command value. Thus, a limiting method of the q-axis current command value is reconsidered and the q-axis current command value is limited in a preferential manner.

[0045] Against the excessive accumulation of integrated values in the feedback control of motor current (problem 3), an anti-windup function is newly added.

[0046] As a counter measure against an overcurrent (problem 4), counter electromotive voltage is reduced by field-weakening by flowing as large a d-axis current command value as possible at the time of high speed rotation. To flow as large a d-axis current command value as possible, the q-axis current command value is limited in a preferential manner.

[0047] To achieve the above-described counter measures, the inventors of the present invention performed reconstruction and arrangement change of functional constituent elements of the controller **30**. FIG. 2 is a block diagram illustrative of an example of a functional configuration of the controller **30**. The controller **30** includes a torque control unit **40**, a d-axis current command value calculation unit **41**, an angular acceleration regulator **42**, a first current limiting unit **43**, a second current limiting unit **44**, a feedforward (FF) control unit **45**, a three-phase/two-phase conversion unit **46**, a feedback (FB) control unit **47**, a voltage limiting unit **48**, a two-phase/three-phase conversion unit **49**, a pulse width modulation (PWM) control unit **50**, and an inverter (INV) **51**.

[0048] The torque control unit **40** calculates a base q-axis current command value  $I_{qr0}$  that is a current command value to control torque generated by the motor **20**, based on at least the steering torque  $T_h$  and the vehicle speed  $V_h$ .

[0049] The d-axis current command value calculation unit **41** sets a first d-axis current command value  $I_{dr1}$  for field-weakening, based on the base q-axis current command value  $I_{qr0}$ , rotational velocity  $\omega_o$  of the motor **20**, power source voltage  $V_R$  supplied by the battery **13**.

[0050] FIG. 3 is a block diagram illustrative of an example of a functional configuration of the d-axis current command value calculation unit **41**. The d-axis current command value calculation unit **41** includes a current command value setting unit **41a**, a field current command value calculation unit **41b**, and a field current limiting unit **41c**.

[0051] The current command value setting unit **41a** sets a q-axis current command value  $I_{qt}$  used for calculation of a base d-axis current command value  $I_{dr0}$  in the field current command value calculation unit **41b** in the succeeding stage, based on the base q-axis current command value  $I_{qr0}$ , the rotational velocity  $\omega$ , the power source voltage  $V_R$ , and a past value  $I_{dz}$  of the d-axis current command value.

[0052] Herein, the current command value setting unit **41a** sets a q-axis current command value  $I_{qt}$  that is appropriate for the base d-axis current command value  $I_{dr0}$  to satisfy a condition of rated current of the motor **20** and a condition of allowable upper limit current of the battery **13**.

[0053] Note that as the past value  $I_{dz}$  of the d-axis current command value, a past value of a second d-axis current command value  $I_{dr2}$  that the second current limiting unit **44** calculates as described later (for example, a second d-axis current command value  $I_{dr2}$  that the second current limiting unit **44** calculated in the last control period) may be used.

[0054] In the following description, the condition of the rated current of the motor **20** and the condition of the allowable upper limit current of the battery **13** are sometimes referred to as “system current limitation” and “battery current limitation”, respectively.

[0055] Regarding the system current limitation, the current command value setting unit **41a** sets a limiting gain  $G_{q1}$  for the q-axis current command value in accordance with the equation (1) below in such a way that the d-axis current command value and the q-axis current command value are less than or equal to a system maximum current  $I_{max}$  (for example, the rated current of the motor).

[0056] Note that processing to prevent division by “0” is performed in a calculation process of the equation (1). In addition, limiter processing (limited to within 0 to 1) is performed lest a calculation result exceed 1.

$$[00001][\text{Math1}] \quad G_{q1} = \frac{\sqrt{(I_{max})^2 - (I_{dz})^2}}{I_{qr0}} \quad (1)$$

[0057] Regarding the battery current limitation, the current command value setting unit **41a** sets a limiting gain  $G_{q2}$  for the q-axis current command value in such a way that battery current  $I_{bat}$  output from the battery **13** becomes less than or equal to a predetermined allowable upper limit  $I_{batmax}$ . The current command value setting unit **41a** sets a limiting gain  $G_{d1}$  for the d-axis current command value in accordance with the equation (2) below in such a way that the battery current  $I_{bat}$  does not exceed the allowable upper limit  $I_{batmax}$  due to only the d-axis current command value. Note that in the equation (2), the processing to prevent division by “0” and the limiter processing are also performed.

$$[00002][\text{Math2}] \quad G_{d1} = \frac{\sqrt{6R(V_R \cdot \text{Math. } I_{batmax} - P_{loss})}}{3 \cdot \text{Math. } R \cdot \text{Math. } I_{dz}} \quad (2)$$

[0058] Note that the constant  $R$  denotes a resistance value of windings for respective phases of the motor **20** and  $P_{loss}$  denotes iron loss, loss due to friction, or the like. The current command value setting unit **41a** sets the limiting gain  $G_{q2}$  for the q-axis current command value in accordance with the equation (3) below, based on the limiting gain  $G_{d1}$  set in accordance with the equation (2). Note that the constant  $K_t$  denotes a torque constant of the motor **20**. Note that in the equation (3), the processing to prevent division by “0” and the limiter processing are also performed.

$$[00003][\text{Math3}] \quad G_{q2} = \frac{-K_t + \sqrt{(K_t)^2 - (3 \cdot \text{Math. } R \cdot \text{Math. } G_{d1} \cdot \text{Math. } I_{dz})^2 + 6R(V_R \cdot \text{Math. } I_{batmax} - P_{loss})}}{3R \cdot \text{Math. } I_{qr0}} \quad (3)$$

[0059] The current command value setting unit **41a** calculates the q-axis current command value  $I_{qt} = \min(G_{q1}, G_{q2}) \times I_{qr0}$  by multiplying the base q-axis current command value  $I_{qr0}$  by a smaller one of the limiting gains  $G_{q1}$  and  $G_{q2}$ .

[0060] The field current command value calculation unit **41b** calculates the base d-axis current

command value  $I_{dr0}$  that is a field current command value for field-weakening, based on the q-axis current command value  $I_{qt}$  set by the current command value setting unit **41a**, the rotational velocity  $\omega$ , and the power source voltage  $V_R$  in accordance with the equation (4) below. Note that a constant  $L$  denotes inductance per phase of the motor and a constant  $\psi$  denotes the number of flux linkages that is determined depending on the motor.

$$I_{d0} = -\frac{2}{R^2 + \frac{2}{L^2}} \frac{L}{R^2 + \frac{2}{L^2}} + \sqrt{\frac{V_R^2 / 3}{R^2 + \frac{2}{L^2}} - \left\{ I_{qt} + \frac{R}{R^2 + \frac{2}{L^2}} \right\}^2}$$

[0061] The field current limiting unit **41c** calculates the first d-axis current command value  $I_{dr1}$  by limiting the base d-axis current command value  $I_{dr0}$  to only a direction of the field-weakening current.

[0062] Although a limit value of the d-axis current command value is determined in consideration of balance between a requirement for the following performance of the turning angle with respect to steering of the steering wheel and operation noise, it is required to flow as large a d-axis current command value as possible to solve the above-described problem 4 (a counter measure against overcurrent) in the present embodiment.

[0063] Therefore, the field current limiting unit **41c** calculates the first d-axis current command value  $I_{dr1}$  by limiting the base d-axis current command value  $I_{dr0}$  to a value less than or equal to a d-axis current upper limit  $I_{dUL}$  and changes the d-axis current upper limit  $I_{dUL}$  according to the rotational velocity  $\omega$ .

[0064] FIG. 4A is a diagram illustrative of a setting example of an example of the d-axis current upper limit  $I_{dUL}$  that is set by the field current limiting unit **41c**. In a range where the rotational velocity  $\omega$  is less than a threshold value  $\omega_{th}$ , the d-axis current upper limit  $I_{dUL}$  is set to a first limit value  $I_{d1}$  that is comparatively small, and in a range where the rotational velocity  $\omega$  is greater than or equal to the threshold value  $\omega_{th}$ , the d-axis current upper limit  $I_{dUL}$  is set to a second limit value  $I_{d2}$  that is larger than the first limit value  $I_{d1}$ .

[0065] For example, the threshold value  $\omega_{th}$  may be set by converting a maximum steering angular velocity that is conceivable to be potentially generated at the time of emergency avoidance or the like to a rotational velocity of the motor **20**. Because of this configuration, quietness of operation noise at the time of regular steering and the following performance of the turning angle with respect to steering of the steering wheel at the time of emergency avoidance or the like can be balanced with each other.

[0066] The field current limiting unit **41c** may include a rate limiter configured to limit temporal change in the first d-axis current command value  $I_{dr1}$ .

[0067] FIG. 4B is a timing diagram of an example of the limitation of the first d-axis current command value  $I_{dr1}$ . When the base d-axis current command value  $I_{dr0}$  is input at time  $t_1$ , the first d-axis current command value  $I_{dr1}$  gradually increases with an increase rate limited by the rate limiter and reaches the first limit value  $I_{d1}$  at time  $t_2$ .

[0068] Subsequently, when the rotational velocity  $\omega$  of the motor **20** increases and exceeds the threshold value  $\omega_{th}$  at time  $t_3$ , the d-axis current upper limit  $I_{dUL}$  increases to the second limit value  $I_{d2}$ . As a result, the first d-axis current command value  $I_{dr1}$  gradually increases with the increase rate limited by the rate limiter and reaches the second limit value  $I_{d2}$  at time  $t_4$ .

[0069] FIG. 2 is now referred to. The angular acceleration regulator **42** sets a compensation value  $A_q$  of the q-axis current command value to suppress torque variation, based on the rotational velocity  $\omega$  of the motor **20**.

[0070] The first current limiting unit **43** calculates a first q-axis current command value  $I_{qr1}$  by compensating the base q-axis current command value  $I_{qr0}$  with the compensation value  $A_q$  and limiting a base q-axis current command value after compensation ( $I_{qr0} + A_q$ ) in such a way that driving current of the motor **20** does not exceed the system current limit.

[0071] Specifically, the first current limiting unit **43** sets a limiting gain  $G_{q3}$  in accordance with the equation (5) below. Note that in the equation (5), the processing to prevent division by “0” and the

limiter processing are also performed.

$$[00005][\text{Math5}] \quad G_{q3} = \frac{\sqrt{(I_{\max})^2 - (I_{dr1})^2}}{I_{qr0} + q} \quad (5)$$

[0072] The first current limiting unit **43** calculates the first q-axis current command value  $I_{qr1} = G_{q3} \times (I_{qr0} + \Delta q)$  by multiplying the base q-axis current command value  $(I_{qr0} + \Delta q)$  by the limiting gain  $G_{q3}$ .

[0073] The second current limiting unit **44** calculates the second d-axis current command value  $I_{dr2}$  and a second q-axis current command value  $I_{qr2}$  by limiting the first d-axis current command value  $I_{dr1}$  and the first q-axis current command value  $I_{qr1}$ , respectively in such a way that the battery current  $I_{bat}$  does not exceed the battery current limit.

[0074] Specifically, the second current limiting unit **44** sets a limiting gain  $G_{d2}$  for the d-axis current command value and a limiting gain  $G_{q4}$  for the q-axis current command value in accordance with the equations (6) and (7) below, respectively. Note that in the equations (6) and (7), the processing to prevent division by “0” and the limiter processing are also performed.

$$[00006][\text{Math6}] \quad G_{d2} = \frac{\sqrt{6R(VR \cdot \text{Math. } I_{bat\max} - P_{loss})}}{3 \cdot \text{Math. } R \cdot \text{Math. } I_{dr1} - K_t} \quad (6)$$

$$G_{q4} = \frac{\sqrt{(K_t)^2 - (3 \cdot \text{Math. } R \cdot \text{Math. } G_{d2} \cdot \text{Math. } I_{dr1})^2 + 6R(VR \cdot \text{Math. } I_{bat\max} - P_{loss})}}{3R \cdot \text{Math. } I_{qr1}} \quad (7)$$

[0075] The second current limiting unit **44** calculates the second d-axis current command value  $I_{dr2} = G_{d2} \times I_{dr1}$  by multiplying the first d-axis current command value  $I_{dr1}$  by the limiting gain  $G_{d2}$  and calculates the second q-axis current command value  $I_{qr2} = G_{q4} \times I_{qr1}$  by multiplying the first q-axis current command value  $I_{qr1}$  by the limiting gain  $G_{q4}$ .

[0076] The FF control unit **45** calculates a FF d-axis voltage command value  $V_{dff}$  and a FF q-axis voltage command value  $V_{qff}$  that are voltage command values to the motor **20**, by feedforward control based on the second d-axis current command value  $I_{dr2}$  and the second q-axis current command value  $I_{qr2}$ , respectively.

[0077] For example, the FF control unit **45** may calculate, as the FF d-axis voltage command value  $V_{dff}$  and the FF q-axis voltage command value  $V_{qff}$ , dq-axis non-interference voltage command values that cancel interference voltages interfering with each other between the d-axis and the q-axis.

[0078] In addition, for example, the FF control unit **45** may calculate feedforward outputs from a two-degree-of-freedom control configuration as the FF d-axis voltage command value  $V_{dff}$  and the FF q-axis voltage command value  $V_{qff}$ .

[0079] The FF d-axis voltage command value  $V_{dff}$  and the FF q-axis voltage command value  $V_{qff}$  are examples of a “first d-axis voltage command value” and a “first q-axis voltage command value” described in the claims, respectively.

[0080] The three-phase/two-phase conversion unit **46** converts detected values of three-phase currents of the motor **20** that are detected by a motor current detector **21** to d-axis current  $i_d$  and q-axis current  $i_q$ .

[0081] The FB control unit **47** calculates a FB d-axis voltage command value  $V_{dfb}$  that is a d-axis voltage command value to the motor **20**, by feedback control based on current deviation  $\Delta I_d$  of a detected value  $i_d$  of the d-axis current in the driving current of the motor **20** with respect to the second d-axis current command value  $I_{dr2}$ .

[0082] In addition, the FB control unit **47** calculates a FB q-axis voltage command value  $V_{qfb}$  that is a q-axis voltage command value to the motor **20**, by feedback control based on current deviation  $\Delta I_q$  of a detected value  $i_q$  of the q-axis current in the driving current of the motor **20** with respect to the second q-axis current command value  $I_{qr2}$ .

[0083] The FB d-axis voltage command value  $V_{dfb}$  and the FB q-axis voltage command value  $V_{qfb}$  are examples of the “first d-axis voltage command value” and the “first q-axis voltage



command value” described in the claims, respectively.

[0084] The FB control unit **47** calculates the FB d-axis voltage command value  $V_{dfb}$  and the FB q-axis voltage command value  $V_{qfb}$  by at least one of proportional control (P-control), integral control (I-control), and derivative control (D-control) based on the current deviations  $\Delta I_d$  and  $\Delta I_q$  or a combination of the foregoing.

[0085] FIG. 5 is a block diagram illustrative of an example of a functional configuration of the FB control unit **47** when the FB d-axis voltage command value  $V_{dfb}$  and the FB q-axis voltage command value  $V_{qfb}$  are calculated by proportional-integral-derivative (PID) control.

[0086] The FB control unit **47** includes a subtracter **47a**, gain multiplication units **47b**, **47d**, and **47f**, an approximate differentiating unit **47c**, an integrator **47e**, and an adder **47g**.

[0087] The subtracter **47a** calculates current deviation  $\Delta I_d = (I_{dr2} - i_d)$  of the detected value  $i_d$  of the d-axis current with respect to the second d-axis current command value  $I_{dr2}$  and current deviation  $\Delta I_q = (I_{qr2} - i_q)$  of a detected value  $i_q$  of the q-axis current with respect to the second q-axis current command value  $I_{qr2}$ .

[0088] The gain multiplication unit **47b** outputs a multiplication result of the current deviation  $\Delta I_d$  and a proportional gain  $K_p$  and a multiplication result of the current deviation  $\Delta I_q$  and the proportional gain  $K_p$  to the adder **47g**.

[0089] The approximate differentiating unit **47c** calculates differential values of the current deviations  $\Delta I_d$  and  $\Delta I_q$ . For example, the approximate differentiating unit **47c** may calculate the differential values by multiplying the current deviations  $\Delta I_d$  and  $\Delta I_q$  by a transfer function  $s/(Ts+1)$  that is obtained by combining a differential operation and a low-pass filter. The gain multiplication unit **47d** outputs a multiplication result of the differential value of the current deviation  $\Delta I_d$  and a differential gain  $K_d$  and a multiplication result of the differential value of the current deviation  $\Delta I_q$  and the differential gain  $K_d$  to the adder **47g**.

[0090] The integrator **47e** calculates integrated values of the current deviations  $\Delta I_d$  and  $\Delta I_q$ . The gain multiplication unit **47f** outputs a multiplication result of the integrated value of the current deviation  $\Delta I_d$  and an integral gain  $K_i$  and a multiplication result of the integrated value of the current deviation  $\Delta I_q$  and the integral gain  $K_i$  to the adder **47g**.

[0091] The adder **47g** outputs a sum of the multiplication result of the current deviation  $\Delta I_d$  and the proportional gain  $K_p$ , the multiplication result of the differential value of the current deviation  $\Delta I_d$  and the differential gain  $K_d$ , and the multiplication result of the integrated value of the current deviation  $\Delta I_d$  and the integral gain  $K_i$ , as the FB d-axis voltage command value  $V_{dfb}$ .

[0092] In addition, the adder **47g** outputs a sum of the multiplication result of the current deviation  $\Delta I_q$  and the proportional gain  $K_p$ , the multiplication result of the differential value of the current deviation  $\Delta I_q$  and the differential gain  $K_d$ , and the multiplication result of the integrated value of the current deviation  $\Delta I_q$  and the integral gain  $K_i$ , as the FB q-axis voltage command value  $V_{qfb}$ .

[0093] The integrator **47e** includes a delay element **47e1**, an adder **47e2**, and a gain multiplication unit **47e3**.

[0094] The delay element **47e1** delays an integral component of the current deviation  $\Delta I_d$  and an integral component of the current deviation  $\Delta I_q$ , the integral components being output from the integrator **47e**, and subsequently inputs the delayed integral components to the adder **47e2**. That is, the delay element **47e1** inputs past values (last values) of the outputs from the integrator **47e** to the adder **47e2**.

[0095] The adder **47e2** outputs a sum of the current deviation  $\Delta I_d$  and an output from the delay element **47e1** and a sum of the current deviation  $\Delta I_q$  and the other output from the delay element **47e1**. Specifically, the adder **47e2** outputs a sum obtained by adding the current deviation  $\Delta I_d$  to a past value of the integral component of the current deviation  $\Delta I_d$ . In addition, the adder **47e2** outputs a sum obtained by adding the current deviation  $\Delta I_q$  to a past value of the integral component of the current deviation  $\Delta I_q$ .

[0096] The gain multiplication unit **47e3** calculates multiplication results obtained by multiplying

respective outputs from the adder **47e2** by a voltage limiting gain  $G_v$  that the voltage limiting unit **48** sets and that will be described later, as outputs of the integrator **47e** (that is, integral components of the current deviations  $\Delta I_d$  and  $\Delta I_q$ ) and outputs the multiplication results to the gain multiplication unit **47f** and also inputs the multiplication results to the delay element **47e1**. [0097] Since multiplying the outputs from the adder **47e2** by the voltage limiting gain  $G_v$  enables integrated values in the integrator **47e** to be reduced, the anti-windup function of integrated values can be achieved.

[0098] For example, as described later, setting the voltage limiting gain  $G_v$  to a value less than a value “1” enables accumulation of integrated values by the integrator **47e** to be suppressed. In addition, for example, setting the voltage limiting gain  $G_v$  to a value “0” enables integrated values by the integrator **47e** to be reset to “0”.

[0099] FIG. 2 is now referred to. The voltage limiting unit **48** calculates a second d-axis voltage command value  $V_d$  and a second q-axis voltage command value  $V_q$  by limiting the FF d-axis voltage command value  $V_{dff}$ , the FB d-axis voltage command value  $V_{dfb}$ , the FF q-axis voltage command value  $V_{qff}$ , and the FB q-axis voltage command value  $V_{qfb}$  in such a way as to prevent the duty ratio from saturating in the PWM control based on the voltage command values  $V_{dff}$ ,  $V_{dfb}$ ,  $V_{qff}$ , and  $V_{qfb}$ .

[0100] FIG. 6 is a block diagram illustrative of an example of a functional configuration of the voltage limiting unit **48**. The voltage limiting unit **48** includes a voltage upper limit setting unit **48a**, a disturbance voltage suppression unit **48b**, a voltage limiting gain setting unit **48c**, a limiter **48d**, a multiplier **48e**, and an adder **48f**.

[0101] The voltage upper limit setting unit **48a** sets a voltage upper limit  $VDutyMax$  that is an upper limit of a voltage command value that prevents duty saturation from occurring. Since directions in which dead time of the inverter **51** acts on the upper limit are different between at the time of power running of the motor **20** and at the time of regeneration of the motor **20**, the voltage upper limit setting unit **48a** sets a voltage upper limit  $VDutyMax$  at the time of power running in accordance with the equation (8) below and sets a voltage upper limit  $VDutyMax$  at the time of regeneration in accordance with the equation (9) below.

$$[00007][Math7] \quad VDutyMax = \frac{VR}{\sqrt{3}} \cdot Math. \frac{(DutyMaxRate - \frac{2 \cdot Math. DeadTime}{PWMTime})}{VR \{DutyConvFactor\}} \quad (8)$$

$$VDutyMax = \frac{VR}{\sqrt{3}} \cdot Math. \frac{(DutyMaxRate + \frac{2 \cdot Math. DeadTime}{PWMTime})}{VR DutyConvFactor} \quad (9)$$

[0102] Since superimposing a third-order harmonic on a three-phase voltage command values of the motor **20** causes voltage use efficiency to be improved, the upper limit of the voltage command value can be increased to  $\frac{2}{3}$  times of the power source voltage  $VR$ . A range of 0 to 100% of the duty ratio in the PWM control corresponds to a range from a lower limit of negative-side voltage to an upper limit of positive-side voltage of applied voltage. Thus, in the above-described equations (8) and (9), the power source voltage  $VR$  is multiplied by a coefficient of  $\frac{1}{3}$  that is equivalent to the upper limit of one side of the positive side and the negative side.

[0103] In addition, a voltage command value equivalent to a reduction  $(2 \times DeadTime / PWMTime)$  due to dead time  $DeadTime$  of the inverter **51** is subtracted or added depending on whether the motor **20** is in a power running state or a regeneration state. Note that  $PWMTime$  denotes a PWM period of the PWM control unit **50**. Since an actual value of the dead time  $DeadTime$  often deviates from a design value, a dead time compensation value that is appropriately set may be subtracted or added depending on whether the motor **20** is in the power running state or the regeneration state.

[0104] In addition, a rate (gradient) of change in terminal voltage of the motor **20** with respect to change in the duty ratio is reduced due to the dead time compensation. To compensate for the reduction, computation formulae in the above-described equations (8) and (9) are multiplied by an inverse of a conversion factor  $VRDutyConvFactor$ . Since the conversion factor  $VRDutyConvFactor$  acts in a direction in which the voltage command value is reduced in converting to a duty ratio, a

voltage command value equivalent to the reduction is compensated for by increasing the voltage upper limit  $V_{DutyMax}$ .

[0105] In addition, a constant  $DutyMaxRate$  is set by subtracting quantization error due to calculation in a later stage and a margin for securing current detection precision from a value “1” (that is,  $DutyMaxRate = 100\% - \text{quantization error} - \text{margin}$ ).

[0106] FIG. 7 is a block diagram illustrative of an example of a functional configuration of the voltage upper limit setting unit **48a**. The voltage upper limit setting unit **48a** includes a first gain setting unit **48a1**, a second gain setting unit **48a2**, a selector **48a3**, multipliers **48a4**, **48a6**, and **48a7**, and a subtracter **48a5**.

[0107] The first gain setting unit **48a1** determines whether the motor **20** is in the power running state or the regeneration state, based on the battery current  $I_{bat}$  and outputs a first determination gain  $G1$  that indicates a determination result. The first determination gain  $G1$  has a value “1” when the motor **20** is in the power running state, and the first determination gain  $G1$  has a value “-1” when the motor **20** is in the regeneration state.

[0108] FIG. 8A is a schematic diagram of a first example of a setting example of the first determination gain  $G1$ . For example, the first determination gain  $G1$  may be set to the value “-1” when the battery current  $I_{bat}$  is less than or equal to a value  $I1$  that is smaller than the value “0”, be set to the value “1” when the battery current  $I_{bat}$  is greater than or equal to the value “0”, and gradually increase linearly or gradually increase nonlinearly from the value “-1” to the value “1” as the battery current  $I_{bat}$  increases when the battery current  $I_{bat}$  falls within a range from the value  $I1$  to the value “0”.

[0109] A battery current  $I_{bat}$  at which the first determination gain  $G1$  is set to the value “1” may be set to a value  $I2$  that is smaller than “0” by providing a margin to the battery current  $I_{bat}$ . FIG. 8B is a schematic diagram of a second example of the setting example of the first determination gain  $G1$ . The reason why the first determination gain  $G1$  is set in accordance with the second example is that a sign of the first determination gain  $G1$  being erroneously set causes duty saturation to occur.

[0110] For example, the value **12** that is greater than the value  $I1$  and less than the value “0” is set, and the first determination gain  $G1$  may be set to the value “1” when the battery current  $I_{bat}$  is greater than or equal to the value **12** and gradually increase linearly or gradually increase nonlinearly from the value “-1” to the value “1” as the battery current  $I_{bat}$  increases when the battery current  $I_{bat}$  falls within a range from the value  $I1$  to the value **12**.

[0111] FIG. 7 is now referred to. The second gain setting unit **48a2** determines whether or not the duty ratio is close to an upper limit, based on the voltage limiting gain  $G_v$ , which will be described later, and outputs a second determination gain  $G2$  that indicates a determination result. The second determination gain  $G2$  has the value “1” when the duty ratio is close to the upper limit, and the second determination gain  $G2$  has the value “-1” when the duty ratio is not close to the upper limit.

[0112] FIG. 8C is a schematic diagram of a first example of a setting example of the second determination gain  $G2$ . For example, the second determination gain  $G2$  may be set to the value “-1” when the voltage limiting gain  $G_v$  is less than or equal to a value  $G_{v1}$  that is smaller than the value “1”, be set to the value “1” when the voltage limiting gain  $G_v$  is greater than or equal to the value “1”, and gradually increase linearly or gradually increase nonlinearly from the value “-1” to the value “1” as the voltage limiting gain  $G_v$  increases when the voltage limiting gain  $G_v$  falls within a range from the value  $G_{v1}$  to the value “1”.

[0113] A voltage limiting gain  $G_v$  at which the second determination gain  $G2$  is set to the value “1” may be set to a value  $G_{v2}$  that is smaller than “1” by providing a margin to the voltage limiting gain  $G_v$ . FIG. 8D is a schematic diagram of a second example of the setting example of the second determination gain  $G2$ . The reason why the second determination gain  $G2$  is set in accordance with the second example is that a sign of the second determination gain  $G2$  being erroneously set causes duty saturation to occur.

[0114] For example, the value  $G_{v2}$  that is greater than the value  $G_{v1}$  and less than the value “1” is

set, and the second determination gain G2 may be set to the value “1” when the voltage limiting gain Gv is greater than or equal to the value Gv2 and gradually increase linearly or gradually increase nonlinearly from the value “-1” to the value “1” as the voltage limiting gain Gv increases when the voltage limiting gain Gv falls within a range from the value Gv1 to the value Gv2.

[0115] FIG. 7 is now referred to. The selector **48a3** outputs a larger one of the first determination gain G1 and the second determination gain G2 to the multiplier **48a4**. The multipliers **48a4**, **48a6**, and **48a7** and the subtractor **48a5** calculate the voltage upper limit VDutyMax in accordance with the computation formulae in the above-described equations (8) and (9).

[0116] FIG. 6 is now referred to. The disturbance voltage suppression unit **48b** is disposed in the succeeding stage of the FB control unit **47** and functions as a voltage disturbance observer that suppresses influence exerted on the FB d-axis voltage command value Vdfb and the FB q-axis voltage command value Vqfb by counter electromotive voltage or other disturbance voltage.

[0117] The disturbance voltage suppression unit **48b** includes a delay element **48b1**, an adder **48b2**, a filter **48b3**, and a multiplier **48b4**. The delay element **48b1** is an example of a “first delay element” and a “second delay element” described in the claims.

[0118] The delay element **48b1** delays a d-axis voltage command value (Gv×Vdobs) and a q-axis voltage command value (Gv×Vqobs) that are output from the disturbance voltage suppression unit **48b** and subsequently inputs the delayed d-axis voltage command value and q-axis voltage command value to the adder **48b2**. That is, the delay element **48b1** inputs past values (last values) of the d-axis voltage command value (Gv×Vdobs) and the q-axis voltage command value (Gv×Vqobs) to the adder **48b2**. The adder **48b2** outputs a sum obtained by adding the FB d-axis voltage command value Vdfb to the past value of the d-axis voltage command value (Gv×Vdobs). In addition, the adder **48b2** outputs a sum obtained by adding the FB q-axis voltage command value Vqfb to the past value of the q-axis voltage command value (Gv×Vqobs).

[0119] The filter **48b3** calculates the d-axis voltage command value Vdobs and the q-axis voltage command value Vqobs that are obtained by applying filter processing for noise reduction to the outputs from the adder **48b2**, as outputs from the voltage disturbance observer.

[0120] Specifically, the filter **48b3** calculates the d-axis voltage command value Vdobs by applying the filter processing to the sum of the past value of the d-axis voltage command value (Gv×Vdobs) and the FB d-axis voltage command value Vdfb. In addition, the filter **48b3** calculates the q-axis voltage command value Vqobs by applying the filter processing to the sum of the past value of the q-axis voltage command value (Gv×Vqobs) and the FB q-axis voltage command value Vqfb. For example, the filter **48b3** may be a low-pass filter.

[0121] The voltage limiting gain setting unit **48c** sets the voltage limiting gain Gv to limit the voltage command values to values less than or equal to the voltage upper limit VDutyMax, based on the outputs Vdobs and Vqobs from the voltage disturbance observer, the FF d-axis voltage command value Vdff, the FF q-axis voltage command value Vqff, and the voltage upper limit VDutyMax.

[0122] Specifically, the voltage limiting gain setting unit **48c** calculates the voltage limiting gain Gv, using a ratio of the voltage upper limit VDutyMax to a resultant vector of a sum of the d-axis voltage command values and the q-axis voltage command values (the equation (10) below). The limiter **48d** limits an upper limit and a lower limit of the voltage limiting gain Gv to “1” and “0”, respectively.

[00008][Math8] 
$$Gv = \frac{VDutyMax}{\sqrt{(Vdobs + Vdff)^2 + (Vqobs + Vqff)^2}} \quad (10)$$

[0123] The multiplier **48b4** in the disturbance voltage suppression unit **48b** multiplies each of the outputs Vdobs and Vqobs from the voltage disturbance observer by the voltage limiting gain Gv, and inputs the multiplication results (Gv×Vdobs) and (Gv×Vqobs) to the delay element **48b1** and also outputs the multiplication results (Gv×Vdobs) and (Gv×Vqobs) to the adder **48b2**.

[0124] The multiplier **48e** multiplies each of the FF d-axis voltage command value Vdff and the FF

q-axis voltage command value  $V_{qff}$  by the voltage limiting gain  $G_v$  and outputs the multiplication results ( $G_v \times V_{dff}$ ) and ( $G_v \times V_{qff}$ ) to the adder **48f**.

[0125] The adder **48f** calculates a sum of the multiplication results ( $G_v \times V_{dobs}$ ) and ( $G_v \times V_{dff}$ ) as the second d-axis voltage command value  $V_d = G_v \times (V_{dobs} + V_{dff})$  and calculates a sum of the multiplication results ( $G_v \times V_{qobs}$ ) and ( $G_v \times V_{qff}$ ) as the second q-axis voltage command value  $V_q = G_v \times (V_{qobs} + V_{qff})$ .

[0126] As described above, multiplying the voltage command values by the voltage limiting gain  $G_v$  and thereby limiting the voltage command values enable the duty ratio to be prevented from being saturated at 100% in the PWM control based on the second d-axis voltage command value  $V_d$  and the second q-axis voltage command value  $V_q$ .

[0127] FIG. **2** is now referred to. The two-phase/three-phase conversion unit **49** converts the second d-axis voltage command value  $V_d$  and the second q-axis voltage command value  $V_q$  to three-phase voltage command values.

[0128] The three-phase voltage command values are input to the PWM control unit **50**, and further, the motor **20** is PWM-driven by the inverter **51**. Driving currents of the motor **20** are detected by the motor current detector **21**, converted to the d-axis current  $i_d$  and the q-axis current  $i_q$  by the three-phase/two-phase conversion unit **46**, and fed back to the subtracter **47a** in the FB control unit **47**.

(Action)

[0129] The d-axis current command value calculation unit **41** calculates the base d-axis current command value  $I_{dr0}$ , based on the above-described equation (4). Since nominal values are set as the constants  $R$  and  $L$  in the equation, error due to variation in physical parameters, temperature change, or the like occurs. In addition, error also occurs in a detected value of the rotational velocity  $\omega$  of the motor **20** due to delay, noise, or the like. Thus, it is difficult to completely prevent duty saturation by limiting the d-axis current command value.

[0130] Therefore, in the present embodiment, prevention of duty saturation is performed in the voltage limiting unit **48** in a later stage, and calculation of an optimum d-axis current command value is attempted in the d-axis current command value calculation unit **41**.

[0131] Although in the present embodiment, duty saturation is not taken into consideration in the d-axis current command value calculation unit **41** as described above, when a d-axis current command value calculated in accordance with the above-described equation (4) is used without change, there is a risk that the d-axis current command value is calculated as an excessive value. Thus, what influence each input parameter exerts on the d-axis current command value is examined based on the above-described equation (4). It is revealed from the above-described equation (4) that to cause the d-axis current command value to increase in the negative direction (to intensify the field-weakening control), it is only necessary that the rotational velocity  $\omega$  of the motor increases, the power source voltage  $V_R$  is reduced, or the q-axis current command value  $I_{qt}$  increases.

[0132] Next, influence when the q-axis current command value  $I_{qt}$  that is used when the base d-axis current command value  $I_{dr0}$  is to be calculated and the second q-axis current command value  $I_{qr2}$  that is actually used for calculation of a voltage command value deviate from each other is examined.

[0133] When the second q-axis current command value  $I_{qr2}$  deviates in a direction in which the second q-axis current command value  $I_{qr2}$  increases, duty saturation occurs since the d-axis current command value becomes insufficient. As a cause of this phenomenon, a case where the output  $A_q$  from the angular acceleration regulator **42** is added to the base q-axis current command value  $I_{qr0}$  is conceivable. However, it is conjectured that while the output  $A_q$  from the angular acceleration regulator steeply changes, the d-axis current command value cannot follow such a rapid change since the d-axis current command value is limited by the rate limiter and the like. Thus, a period during which the second q-axis current command value  $I_{qr2}$  deviates in the direction in which the second q-axis current command value  $I_{qr2}$  increases is short and influence of the deviation is

limited. Therefore, a case where the second q-axis current command value  $I_{qr2}$  deviates in the direction in which the second q-axis current command value  $I_{qr2}$  increases is not taken into consideration.

[0134] When the second q-axis current command value  $I_{qr2}$  deviates in a direction in which the second q-axis current command value  $I_{qr2}$  decreases, the base d-axis current command value  $I_{dr0}$  becomes excessive and it becomes impossible to use the duty ratio to an upper limit. As a cause of this phenomenon, a case where the q-axis current command value is limited in a later stage is conceivable. The limitation of the q-axis current command value in a later stage is the system current limitation using the limiting gain  $G_{q3}$  expressed by the above-described equation (5) and the battery current limitation using the limiting gain  $G_{q4}$  expressed by the above-described equation (7).

[0135] Therefore, by calculating a q-axis current command value  $I_{qt}$  to which the above-described limitations are applied by the above-described equations (1) and (3) in the current command value setting unit **41a** and using the calculated q-axis current command value  $I_{qt}$  in the calculation of the base d-axis current command value  $I_{dr0}$ , an optimum q-axis current command value is calculated.

[0136] In addition, the voltage limiting unit **48** calculates the voltage limiting gain  $G_v$  to perform voltage limitation and multiplies a voltage command value by the calculated voltage limiting gain  $G_v$ . Since when a voltage command value is multiplied by the voltage limiting gain  $G_v$  in the disturbance voltage suppression unit **48b**, which functions as the voltage disturbance observer, an upper limit of the integrator that constitutes the voltage disturbance observer can be limited, the voltage limiting gain  $G_v$  essentially functions as the anti-windup function.

[0137] Note that in the voltage limiting unit **48**, the d-axis voltage command value and the q-axis voltage command value are limited by multiplying the d-axis voltage command value and the q-axis voltage command value by gains having the same value (the voltage limiting gain  $G_v$ ). This is because since the voltage disturbance observer includes an integrator, there is a risk that when the q-axis is limited in a preferential manner, the d-axis voltage command value continues to increase to an upper limit even though the resultant vector of the sum of the d-axis voltage command value and the q-axis voltage command value is limited at an upper limit, the q-axis voltage command value is rapidly limited in accordance with the increase in the d-axis voltage command value, and the rapid limitation leads to a sudden change in the output.

[0138] In addition, regarding the setting of the voltage upper limit  $VDutyMax$  by the voltage upper limit setting unit **48a**, the dead time acts in such a manner as to decrease the duty at the time of power running and to increase the duty at the time of regeneration.

[0139] The above-described equation (8) is a calculation formula of the voltage upper limit  $VDutyMax$  at the time of power running, and when switching of a direction in which the dead time acts at the time of regeneration is not taken into consideration, there is a risk that deviation occurs in the upper limit of the duty ratio. Thus, in the present embodiment, whether the motor **20** is performing the power running or the regeneration is determined, and a sign of a voltage command value equivalent to a reduction due to the dead time is switched.

[0140] However, since simply switching the sign causes the duty ratio to suddenly change, there is a risk that overcurrent or operation noise occurs. Thus, the battery current  $I_{bat}$  is used as a determination condition of the regeneration and the voltage limiting gain  $G_v$  is also used as a determination condition of the duty, and the determination gains  $G_1$  and  $G_2$  are calculated based on the battery current  $I_{bat}$  and the voltage limiting gain  $G_v$ . However, since it is difficult to determine which one of the determination conditions is satisfied, fade switching between the two determination gains  $G_1$  and  $G_2$  is achieved by switching the sign, based on the maximum value between the determination gains  $G_1$  and  $G_2$ .

[0141] In addition, the FB control unit **47** includes the anti-windup function of integrated values in the integrator **47e**. In general, the anti-windup function is aimed at preventing integrated values from being excessively accumulated when output from a controller including an integrator is

limited due to some reason.

[0142] In a general configuration of the anti-windup function, by performing some processing on a difference value between outputs before and after limitation and feeding back the processed value, an upper limit of an integrated value is limited.

[0143] In the present embodiment, the output from the FB control unit **47** hardly exceeds a voltage upper limit, and on most occasions, the output from the disturbance voltage suppression unit (voltage disturbance observer) **48b** disposed in the succeeding stage exceeds the voltage upper limit. Therefore, the general configuration of the anti-windup cannot be used without change.

[0144] In addition, even in a state in which a voltage command value is limited by a voltage upper limit, a ratio of the output from the FB control unit **47** to the output from the disturbance voltage suppression unit **48b** can preferably be changed (for example, since in a situation in which the rotational velocity  $\omega$  of the motor **20** decreases and torque increases, the counter electromotive voltage decreases and the q-axis current increases, it is preferable that a ratio of the output from the FB control unit **47** increase and a ratio of the output from the disturbance voltage suppression unit **48b** decrease).

[0145] Thus, in the present embodiment, an integrated value of the integrator **47e** in the FB control unit **47** and the outputs  $V_{dobs}$  and  $V_{qobs}$  from the voltage disturbance observer in the disturbance voltage suppression unit **48b** are multiplied by gains having the same value (the voltage limiting gain  $G_v$ ) and limited, and a load is equally divided between the FB control unit **47** and the disturbance voltage suppression unit **48b**.

(Operation)

[0146] FIG. **9** is a flowchart of an example of a motor control method of the embodiment.

[0147] In step **S1**, the torque sensor **10**, the vehicle speed sensor **12**, and the motor current detector **21** detect the steering torque  $T_h$ , the vehicle speed  $V_h$ , and the driving current of the motor **20**, respectively. In addition, a voltage sensor and a current sensor detect the power source voltage  $V_R$  and the battery current  $I_{bat}$  supplied by the battery **13**, respectively.

[0148] In step **S2**, the torque control unit **40** calculates the base q-axis current command value  $I_{qr0}$ , based on at least the steering torque  $T_h$  and the vehicle speed  $V_h$ .

[0149] In step **S3**, the d-axis current command value calculation unit **41** sets the first d-axis current command value  $I_{dr1}$ , based on the base q-axis current command value  $I_{qr0}$ , the power source voltage  $V_R$ , and the rotational velocity  $\omega$  of the motor **20**.

[0150] In step **S4**, the first current limiting unit **43** calculates the first q-axis current command value  $I_{qr1}$  by limiting the base q-axis current command value  $I_{qr0}$ , based on the rated current of the motor **20**.

[0151] In step **S5**, the second current limiting unit **44** calculates the second d-axis current command value  $I_{dr2}$  and the second q-axis current command value  $I_{qr2}$  by limiting the first d-axis current command value  $I_{dr1}$  and the first q-axis current command value  $I_{qr1}$ , based on battery upper limit current  $I_{batmax}$ , respectively.

[0152] In step **S6**, the FF control unit **45** calculates the FF d-axis voltage command value  $V_{dff}$  and the FF q-axis voltage command value  $V_{qff}$ . The FB control unit **47** calculates the FB d-axis voltage command value  $V_{dfb}$  and the FB q-axis voltage command value  $V_{qfb}$ .

[0153] In step **S7**, the voltage upper limit setting unit **48a** sets the voltage upper limit  $V_{DutyMax}$ .

[0154] In step **S8**, the voltage limiting gain setting unit **48c** sets the voltage limiting gain  $G_v$ , based on the voltage upper limit  $V_{DutyMax}$ .

[0155] In step **S9**, the voltage limiting unit **48** calculates the second d-axis voltage command value  $V_d$  and the second q-axis voltage command value  $V_q$  by limiting the FF d-axis voltage command value  $V_{dff}$ , the FF q-axis voltage command value  $V_{qff}$ , the FB d-axis voltage command value  $V_{dfb}$ , and the FB q-axis voltage command value  $V_{qfb}$ , using the voltage limiting gain  $G_v$ .

[0156] In step **S10**, the PWM control unit **50** and the inverter **51** drive the motor **20**, based on the second d-axis voltage command value  $V_d$  and the second q-axis voltage command value  $V_q$ .

Subsequently, the process terminates.

(Variations)

[0157] The motor control device according to the present invention is not limited to the above-described embodiment, and various modification can be made without departing from the spirit and scope of the present invention.

[0158] For example, although in the above-described embodiment, as an application example of the motor control device according to the present invention, the electric power steering device including the motor control device was described as an example, a scope of application of the motor control device according to the present invention is not limited to the electric power steering device and is applicable to various types of mechanical devices using a motor control device.

[0159] FIG. **10** is a configuration diagram illustrative of an outline of an example of a linear motion table device in which the motor control device of the present invention is used.

[0160] The linear motion table device includes a feed screw device, a table **71**, two linear guides (linear motion guide devices), and a base **74**.

[0161] The feed screw device includes a screw shaft **70**, a nut **76**, and a motor **77**, and the screw shaft **70** is inserted into the nut **76**. A feed screw mechanism in the feed screw device is a ball screw in which a spiral groove of the screw shaft **70** and a spiral groove of the nut **76** come into point contact with each other via balls (rolling elements). The motor **77** is coupled to one end in the axial direction of the screw shaft **70**.

[0162] Each of the two linear guides includes a guide rail **72**, two sliders (mobile units) **73**, and a plurality of rolling elements. In each linear guide, the guide rail **72** and each of the sliders **73** have raceway surfaces that form rolling paths for the rolling elements at positions facing each other. Both raceway surfaces extend in the longitudinal direction of the guide rail **72**, and the sliders **73** linearly move along the guide rail **72** via the rolling elements rolling in the rolling paths while being loaded.

[0163] The linear guides are arranged at both ends in a direction perpendicular to a movement direction Y of the table **71** on the base **74**, and the feed screw device is arranged between the two linear guides. The guide rails **72** and the screw shaft **70** are arranged in parallel with the movement direction Y of the table **71**.

[0164] In the arrangement, the guide rails **72** are fixed to the base **74**. Rolling bearings are attached at both ends in the axial direction of the screw shaft **70**, a housing **75** is fixed to an outer ring of each of the rolling bearings, and each of the housing **75** is fixed to the base **74**. Because of this configuration, the screw shaft **70** is rotatably supported with respect to the base **74**.

[0165] The table **71** is arranged above the two sliders **73** of each of the linear guides and the nut **76** of the feed screw device, and is directly fixed to the sliders **73** and is fixed to the nut **76** via a bracket. That is, the two sliders **73** of each of the linear guides and the nut **76** of the feed screw device are fixed to one surface of the table **71**.

[0166] In the linear motion table, when the motor **77** is driven and the feed screw device is operated, the screw shaft **70** rotates and the nut **76** linearly moves by the ball screw mechanism. In association with this movement, the table **71** linearly moves while being guided by the linear guides.

[0167] A controller **78** sets current command values to drive the motor **77** and, by performing the same processing as the processing performed by the controller **30** of the above-described embodiment, calculates voltage control command values  $V_{ref}$  from the current command values and controls currents to be supplied to the motor **20**.

(Advantageous Effects of Embodiment)

[0168] (1) A motor control device includes: a torque control unit configured to set a base q-axis current command value to control torque generated by a motor; a d-axis current command value calculation unit configured to set a first d-axis current command value for field-weakening, based on the base q-axis current command value and rotational velocity of the motor; a first current



limiting unit disposed in a succeeding stage of the d-axis current command value calculation unit and configured to calculate a first q-axis current command value by limiting the base q-axis current command value according to the first d-axis current command value in such a way that driving current of the motor does not exceed a rated current of the motor; a second current limiting unit disposed in a succeeding stage of the first current limiting unit and configured to calculate a second d-axis current command value and a second q-axis current command value by limiting the first d-axis current command value and the first q-axis current command value, respectively in such a way that output current from a battery does not exceed a predetermined allowable upper limit; a voltage command value calculation unit configured to calculate a first d-axis voltage command value and a first q-axis voltage command value, based on the second d-axis current command value and the second q-axis current command value; a voltage limiting unit configured to calculate a second d-axis voltage command value and a second q-axis voltage command value by limiting the first d-axis voltage command value and the first q-axis voltage command value, respectively in such a way as to prevent saturation of a duty ratio in PWM control based on the first d-axis voltage command value and the first q-axis voltage command value; and a drive circuit configured to drive the motor, based on the second d-axis voltage command value and the second q-axis voltage command value. Because of this configuration, the motor control device of the embodiment is capable of preventing the saturation of the duty ratio in a high load condition and reduction in the duty ratio in a high rotational velocity region.

[0169] (2) The d-axis current command value calculation unit may calculate the first d-axis current command value according to a q-axis current command value obtained by limiting the base q-axis current command value in such a way that driving current of the motor does not exceed a rated current of the motor, based on a past value of the second d-axis current command value.

[0170] Because of this configuration, even when the q-axis current command value that is used for calculation of a voltage command value is limited based on the rated current of the motor, deviation of the q-axis current command value that is used for calculation of the first d-axis current command value from the q-axis command value that is used for calculation of a voltage command value can be reduced. As a result, it is possible to prevent an excessive first d-axis current command value from being calculated and the duty ratio from being limited to a value lower than an upper limit.

[0171] (3) The d-axis current command value calculation unit may calculate the first d-axis current command value according to a q-axis current command value obtained by limiting the base q-axis current command value in such a way that output current from the battery does not exceed the allowable upper limit, based on a past value of the second d-axis current command value.

[0172] Because of this configuration, even when the q-axis current command value that is used for calculation of a voltage command value is limited based on the upper limit current of the battery, deviation of the q-axis current command value that is used for calculation of the first d-axis current command value from the q-axis command value that is used for calculation of a voltage command value can be reduced. As a result, it is possible to prevent an excessive first d-axis current command value from being calculated and the duty ratio from being limited to a value lower than an upper limit.

[0173] (4) The d-axis current command value calculation unit may limit an upper limit of the first d-axis current command value, based on rotational velocity of the motor.

[0174] Because of this configuration, operation noise and a counter measure against overcurrent can be balanced.

[0175] (5) The voltage limiting unit may include a voltage upper limit setting unit configured to set a voltage upper limit, the voltage upper limit being an upper limit of applied voltage to the motor, and a voltage limiting gain setting unit configured to set a voltage limiting gain according to the voltage upper limit and calculate a second d-axis voltage command value and a second q-axis voltage command value by limiting the first d-axis voltage command value and the first q-axis voltage command value, respectively according to the voltage limiting gain.

[0176] Because of this configuration, the motor control device is capable of preventing saturation of the duty ratio in a high load condition.

[0177] (6) The voltage upper limit setting unit may set a voltage upper limit, based on at least one of a voltage equivalent to use efficiency improvement achieved by superimposing a third-order harmonic on polyphase voltage command values of the motor, the motor being a polyphase motor, a voltage drop due to dead time, and a reduction in a ratio of motor terminal voltage to a duty ratio due to dead time compensation.

[0178] Because of this configuration, the voltage upper limit to limit the voltage command value can be appropriately set.

[0179] (7) The voltage limiting unit may include a disturbance voltage suppression unit configured to output a first multiplication result obtained by multiplying a sum of the first d-axis voltage command value and output from a first delay element by the voltage limiting gain and a second multiplication result obtained by multiplying a sum of the first q-axis voltage command value and output from a second delay element by the voltage limiting gain and also input the first multiplication result and the second multiplication result to the first delay element and the second delay element, respectively and output the second d-axis voltage command value including the first multiplication result and the second q-axis voltage command value including the second multiplication result.

[0180] Because of this configuration, the voltage command value can be limited based on the voltage limiting gain. In addition, influence that the disturbance voltage exerts on the first d-axis voltage command value and the first q-axis voltage command value can be prevented.

[0181] (8) The voltage limiting gain setting unit may set the voltage limiting gain, based on the voltage upper limit, the sum of the first d-axis voltage command value and output from the first delay element and the sum of the first q-axis voltage command value and output from the second delay element.

[0182] Because of this configuration, the voltage limiting gain can be calculated using a ratio of the voltage upper limit to a resultant vector of a sum of the d-axis voltage command value and the q-axis voltage command value.

[0183] (9) The voltage command value calculation unit may output the first d-axis voltage command value and the first q-axis voltage command value including a d-axis integral component, the d-axis integral component being an integral component of deviation of a detected value of d-axis current in driving current of the motor from the second d-axis current command value, and a q-axis integral component, the q-axis integral component being an integral component of deviation of a detected value of q-axis current in driving current of the motor from the second q-axis current command value, respectively and suppress the d-axis integral component and the q-axis integral component, based on the voltage limiting gain.

[0184] Because of this configuration, in the voltage command value calculation unit configured to calculate a voltage command value through integral control, an anti-windup function of integrated values can be achieved.

[0185] (10) The first d-axis voltage command value may include a feedforward d-axis voltage command value calculated by feedforward control based on the second d-axis current command value and a feedback d-axis voltage command value calculated by feedback control based on deviation of a detected value of d-axis current in driving current of the motor from the second d-axis current command value. In addition, the first q-axis voltage command value may include a feedforward q-axis voltage command value calculated by feedforward control based on the second q-axis current command value and a feedback q-axis voltage command value calculated by feedback control based on deviation of a detected value of the q-axis current in driving current of the motor from the second q-axis current command value.

[0186] The disturbance voltage suppression unit may output the first multiplication result obtained by multiplying a sum of the feedback d-axis voltage command value and output from the first delay

element by the voltage limiting gain and the second multiplication result obtained by multiplying a sum of the feedback q-axis voltage command value and output from the second delay element by the voltage limiting gain and also input the first multiplication result and the second multiplication result to the first delay element and the second delay element, respectively.

[0187] The voltage limiting gain setting unit may set the voltage limiting gain, based on the voltage upper limit, a sum of the feedback d-axis voltage command value, output from the first delay element, and the feedforward d-axis voltage command value and a sum of the feedback q-axis voltage command value, output from the second delay element, and the feedforward q-axis voltage command value.

[0188] The voltage limiting unit may output the second d-axis voltage command value including a third multiplication result obtained by multiplying the feedforward d-axis voltage command value by the voltage limiting gain and the first multiplication result and also output the second q-axis voltage command value including a fourth multiplication result obtained by multiplying the feedforward q-axis voltage command value by the voltage limiting gain and the second multiplication result.

[0189] Because of this configuration, improvement in responsiveness by the feedforward control and prevention of influence of disturbance by the feedback control can be achieved. In addition, the voltage command value can be limited based on the voltage limiting gain. Further, influence that the disturbance voltage exerts on the feedback d-axis voltage command value and the feedback q-axis voltage command value can be prevented. Furthermore, the voltage limiting gain can be calculated using a ratio of the voltage upper limit to a resultant vector of the sum of the d-axis voltage command value and the q-axis voltage command value.

REFERENCE SIGNS LIST

[0190] **1** Steering wheel [0191] **2** Steering shaft [0192] **3** Reduction gear [0193] **4a, 4b** Universal joint [0194] **5** Pinion rack mechanism [0195] **5a** Pinion [0196] **5b** Rack [0197] **6a, 6b** Tie rod [0198] **7a, 7b** Hub unit [0199] **8L, 8R** Steered wheel [0200] **10** Torque sensor [0201] **11** Ignition key [0202] **12** Vehicle speed sensor [0203] **13** Battery [0204] **14** Steering angle sensor [0205] **20, 77** Motor [0206] **21** Motor current detector [0207] **30** Controller [0208] **40** Torque control unit [0209] **41** d-axis current command value calculation unit [0210] **41a** Current command value setting unit [0211] **41b** Field current command value calculation unit [0212] **41c** Field current limiting unit [0213] **42** Angular acceleration regulator [0214] **43** First current limiting unit [0215] **44** Second current limiting unit [0216] **45** Feedforward control unit [0217] **46** Three-phase/two-phase conversion unit [0218] **47** Feedback control unit [0219] **47a, 48a5** Subtractor [0220] **47b, 47d, 47e3, 47f** Gain multiplication unit [0221] **47c** Approximate differentiating unit [0222] **47e** Integrator [0223] **47e1, 48b1** Delay element [0224] **47e2, 47g, 48b2, 48f** Adder [0225] **48** Voltage limiting unit [0226] **48a** Voltage upper limit setting unit [0227] **48a1** First gain setting unit [0228] **48a2** Second gain setting unit [0229] **48a3** Selector [0230] **48a4, 48a6, 48a7, 48b4, 48e** Multiplier [0231] **48b** Disturbance voltage suppression unit [0232] **48b3** Filter [0233] **48c** Voltage limiting gain setting unit [0234] **48d** Limiter [0235] **49** Two-phase/three-phase conversion unit [0236] **50** PWM control unit [0237] **51** Inverter [0238] **70** Screw shaft [0239] **71** Table [0240] **72** Guide rail [0241] **73** Slider [0242] **74** Base [0243] **75** Housing [0244] **76** Nut

## Claims

**1.** A motor control device comprising: a torque control unit configured to set a base q-axis current command value to control torque generated by a motor; a d-axis current command value calculation unit configured to set a first d-axis current command value for field-weakening, based on the base q-axis current command value and rotational velocity of the motor; a first current limiting unit disposed in a succeeding stage of the d-axis current command value calculation unit and configured to calculate a first q-axis current command value by limiting the base q-axis current

command value according to the first d-axis current command value in such a way that driving current of the motor does not exceed a rated current of the motor; a second current limiting unit disposed in a succeeding stage of the first current limiting unit and configured to calculate a second d-axis current command value and a second q-axis current command value by limiting the first d-axis current command value and the first q-axis current command value, respectively in such a way that output current from a battery does not exceed a predetermined allowable upper limit; a voltage command value calculation unit configured to calculate a first d-axis voltage command value and a first q-axis voltage command value, based on the second d-axis current command value and the second q-axis current command value; a voltage limiting unit configured to calculate a second d-axis voltage command value and a second q-axis voltage command value by limiting the first d-axis voltage command value and the first q-axis voltage command value, respectively in such a way as to prevent saturation of a duty ratio in PWM control based on the first d-axis voltage command value and the first q-axis voltage command value; and a drive circuit configured to drive the motor, based on the second d-axis voltage command value and the second q-axis voltage command value.

2. The motor control device according to claim 1, wherein the d-axis current command value calculation unit calculates the first d-axis current command value according to a q-axis current command value obtained by limiting the base q-axis current command value in such a way that driving current of the motor does not exceed a rated current of the motor, based on a past value of the second d-axis current command value.

3. The motor control device according to claim 1, wherein the d-axis current command value calculation unit calculates the first d-axis current command value according to a q-axis current command value obtained by limiting the base q-axis current command value in such a way that output current from the battery does not exceed the allowable upper limit, based on a past value of the second d-axis current command value.

4. The motor control device according to claim 1, wherein the d-axis current command value calculation unit limits an upper limit of the first d-axis current command value, based on rotational velocity of the motor.

5. The motor control device according to claim 1, wherein the voltage limiting unit includes: a voltage upper limit setting unit configured to set a voltage upper limit, the voltage upper limit being an upper limit of applied voltage to the motor; and a voltage limiting gain setting unit configured to set a voltage limiting gain according to the voltage upper limit, and calculates a second d-axis voltage command value and a second q-axis voltage command value by limiting the first d-axis voltage command value and the first q-axis voltage command value, respectively according to the voltage limiting gain.

6. The motor control device according to claim 5, wherein the voltage upper limit setting unit sets a voltage upper limit, based on at least one of a voltage equivalent to use efficiency improvement achieved by superimposing a third-order harmonic on polyphase voltage command values of the motor, the motor being a polyphase motor, a voltage drop due to dead time, and a reduction in a ratio of motor terminal voltage to a duty ratio due to dead time compensation.

7. The motor control device according to claim 5, wherein the voltage limiting unit: includes a disturbance voltage suppression unit configured to output a first multiplication result obtained by multiplying a sum of the first d-axis voltage command value and output from a first delay element by the voltage limiting gain and a second multiplication result obtained by multiplying a sum of the first q-axis voltage command value and output from a second delay element by the voltage limiting gain and also input the first multiplication result and the second multiplication result to the first delay element and the second delay element, respectively; and outputs the second d-axis voltage command value including the first multiplication result and the second q-axis voltage command value including the second multiplication result.

8. The motor control device according to claim 7, wherein the voltage limiting gain setting unit sets

the voltage limiting gain, based on the voltage upper limit, the sum of the first d-axis voltage command value and output from the first delay element and the sum of the first q-axis voltage command value and output from the second delay element.

**9.** The motor control device according to claim 7, wherein the voltage command value calculation unit outputs the first d-axis voltage command value and the first q-axis voltage command value including a d-axis integral component, the d-axis integral component being an integral component of deviation of a detected value of d-axis current in driving current of the motor from the second d-axis current command value, and a q-axis integral component, the q-axis integral component being an integral component of deviation of a detected value of q-axis current in driving current of the motor from the second q-axis current command value, respectively and suppresses the d-axis integral component and the q-axis integral component, based on the voltage limiting gain.

**10.** The motor control device according to claim 7, wherein the first d-axis voltage command value includes a feedforward d-axis voltage command value calculated by feedforward control based on the second d-axis current command value and a feedback d-axis voltage command value calculated by feedback control based on deviation of a detected value of d-axis current in driving current of the motor from the second d-axis current command value, the first q-axis voltage command value includes a feedforward q-axis voltage command value calculated by feedforward control based on the second q-axis current command value and a feedback q-axis voltage command value calculated by feedback control based on deviation of a detected value of q-axis current in driving current of the motor from the second q-axis current command value, the disturbance voltage suppression unit: outputs the first multiplication result obtained by multiplying a sum of the feedback d-axis voltage command value and output from the first delay element by the voltage limiting gain and the second multiplication result obtained by multiplying a sum of the feedback q-axis voltage command value and output from the second delay element by the voltage limiting gain; and inputs the first multiplication result and the second multiplication result to the first delay element and the second delay element, respectively, the voltage limiting gain setting unit sets the voltage limiting gain, based on the voltage upper limit, a sum of the feedback d-axis voltage command value, output from the first delay element, and the feedforward d-axis voltage command value, and a sum of the feedback q-axis voltage command value, output from the second delay element, and the feedforward q-axis voltage command value, and the voltage limiting unit outputs the second d-axis voltage command value including a third multiplication result obtained by multiplying the feedforward d-axis voltage command value by the voltage limiting gain and the first multiplication result and also outputs the second q-axis voltage command value including a fourth multiplication result obtained by multiplying the feedforward q-axis voltage command value by the voltage limiting gain and the second multiplication result.

**11.** An electric power steering device comprising: the motor control device according to claim 1; and a motor controlled by the motor control device, wherein the electric power steering device provides a steering system of a vehicle with a steering assist force, using the motor.

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