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(54) **ELECTRIC POWER STEERING DEVICE**

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(57) **ABSTRACT**

An electric power steering device including: a motor configured to generate a steering assist force; a current command value calculation unit configured to calculate a current command value to control driving current of the motor; a current control unit configured to output a first voltage command value, based on current deviation of a measured value of the driving current to the current command value; a first gain setting unit configured to set a first gain depending on rotational velocity of the motor; a disturbance voltage suppression unit configured to calculate a third voltage command value by adding output from a first delay element to a second voltage command value obtained by limiting the first voltage command value by the first gain and input the third voltage command value to the first delay element; and a driving circuit configured to drive the motor, based on the third voltage command value.

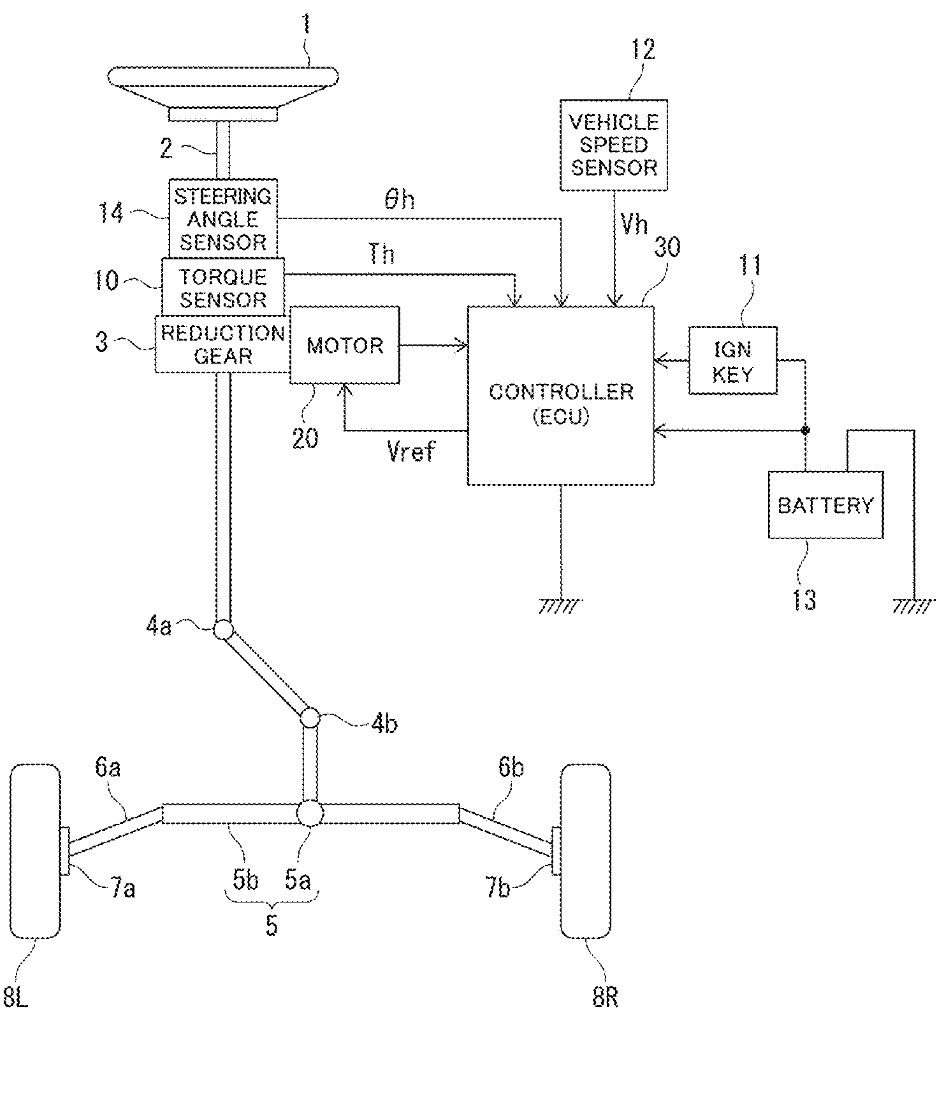


FIG. 1

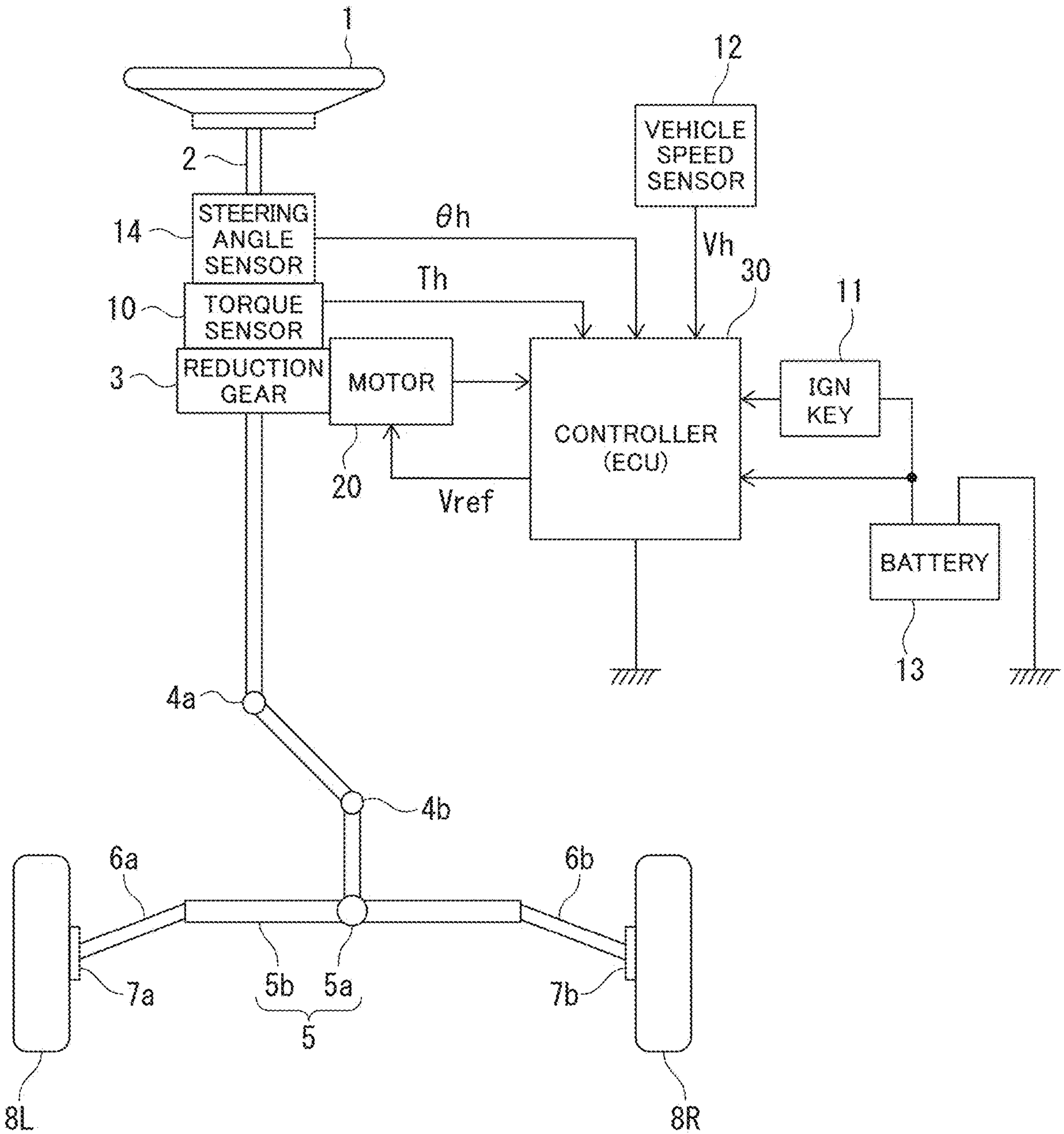
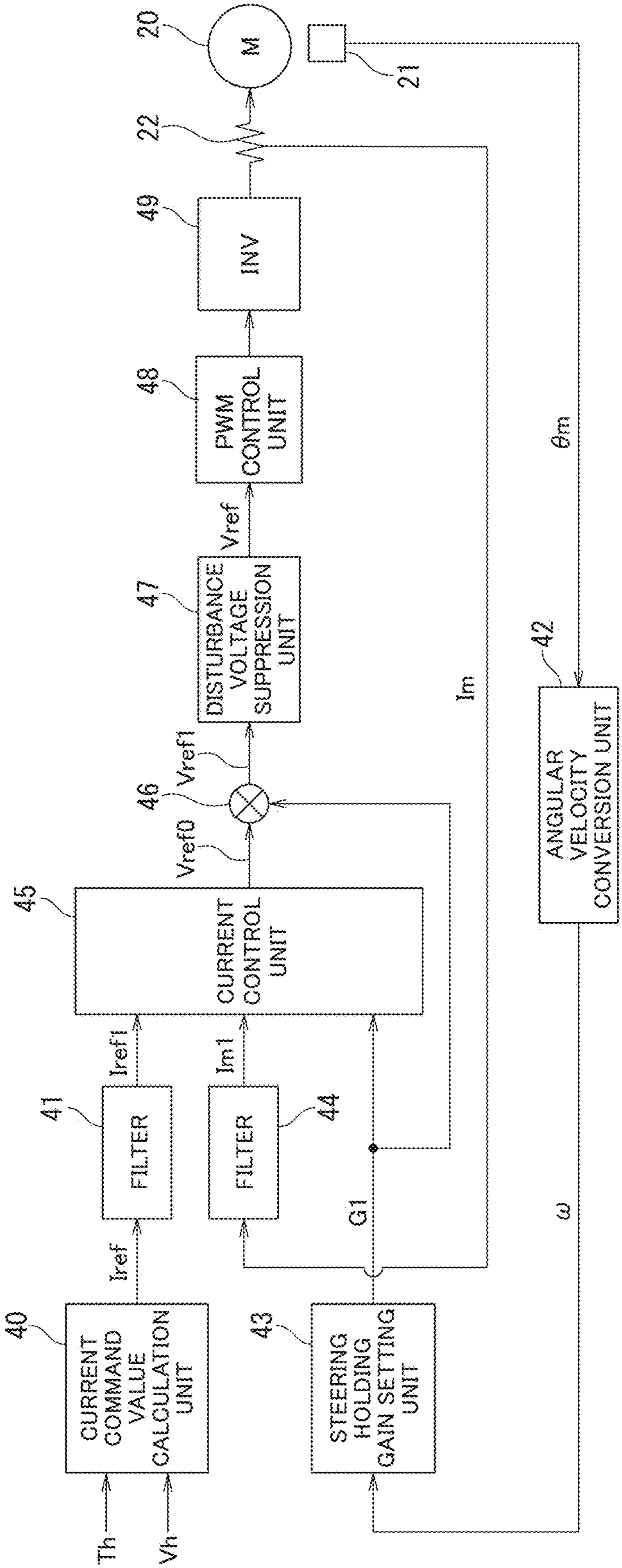

1
2
14
STEERING ANGLE SENSOR
10
TORQUE SENSOR
3
REDUCTION GEAR
MOTOR
20
θh
Th
Vref
12
VEHICLE SPEED SENSOR
Vh
30
CONTROLLER (ECU)
11
IGN KEY
BATTERY
13
4a
4b
6a
6b
7a
7b
5b
5a
5
8L
8R

FIG. 2



20
M
21
22
49
INV
48
PWM CONTROL UNIT
Vref
47
DISTURBANCE VOLTAGE SUPPRESSION UNIT
Vref1
46
Vref0
45
CURRENT CONTROL UNIT
θm
Im
42
ANGULAR VELOCITY CONVERSION UNIT
41
FILTER
Iref1
Im1
44
FILTER
G1
Iref
40
CURRENT COMMAND VALUE CALCULATION UNIT
43
STEERING HOLDING GAIN SETTING UNIT
ω
Th
Vh

FIG. 3

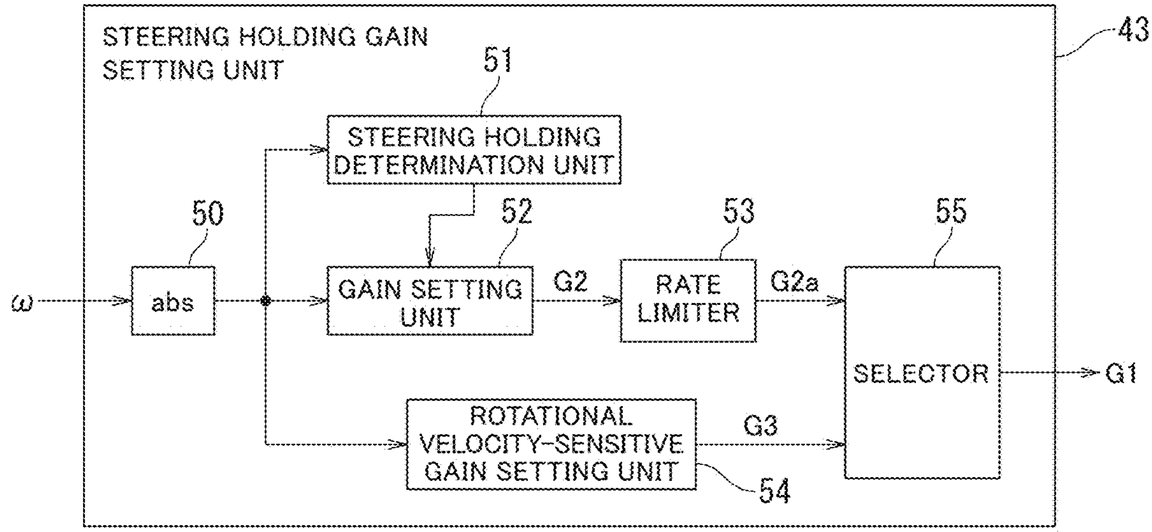


FIG. 4A

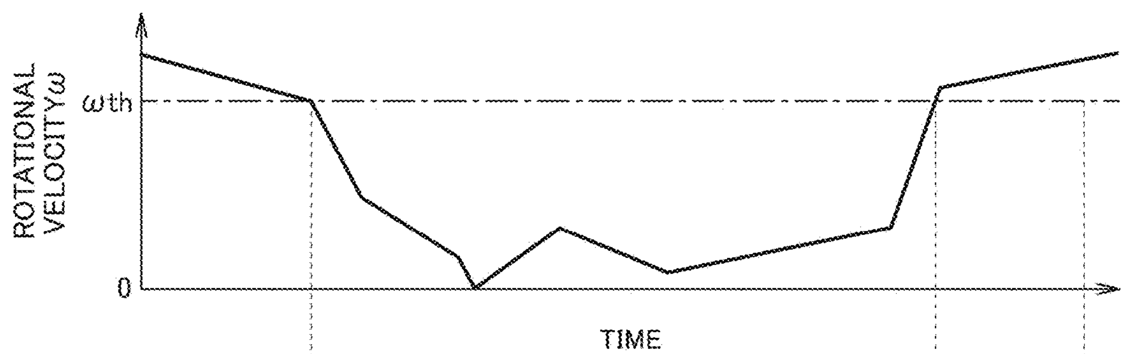


FIG. 4B

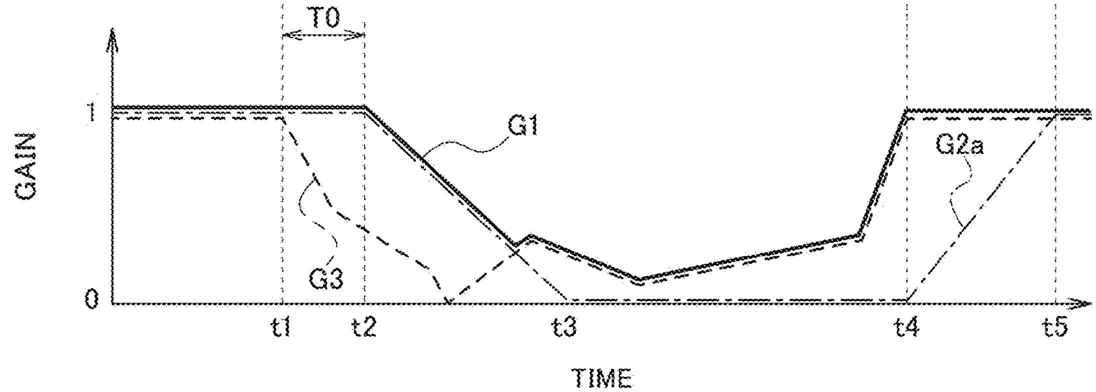


FIG. 5

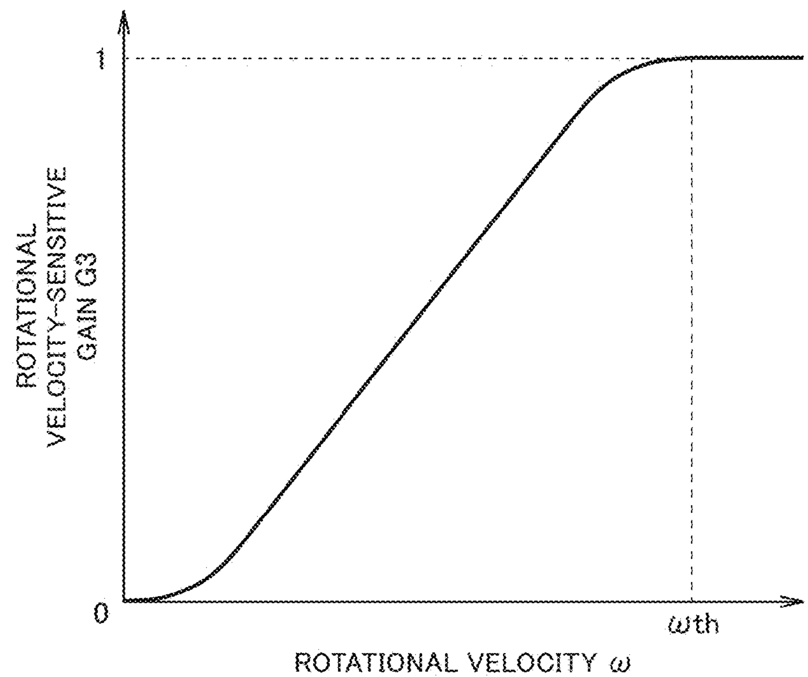

1
0
ROTATIONAL VELOCITY-SENSITIVE GAIN G3
ωth
ROTATIONAL VELOCITY ω

FIG. 6

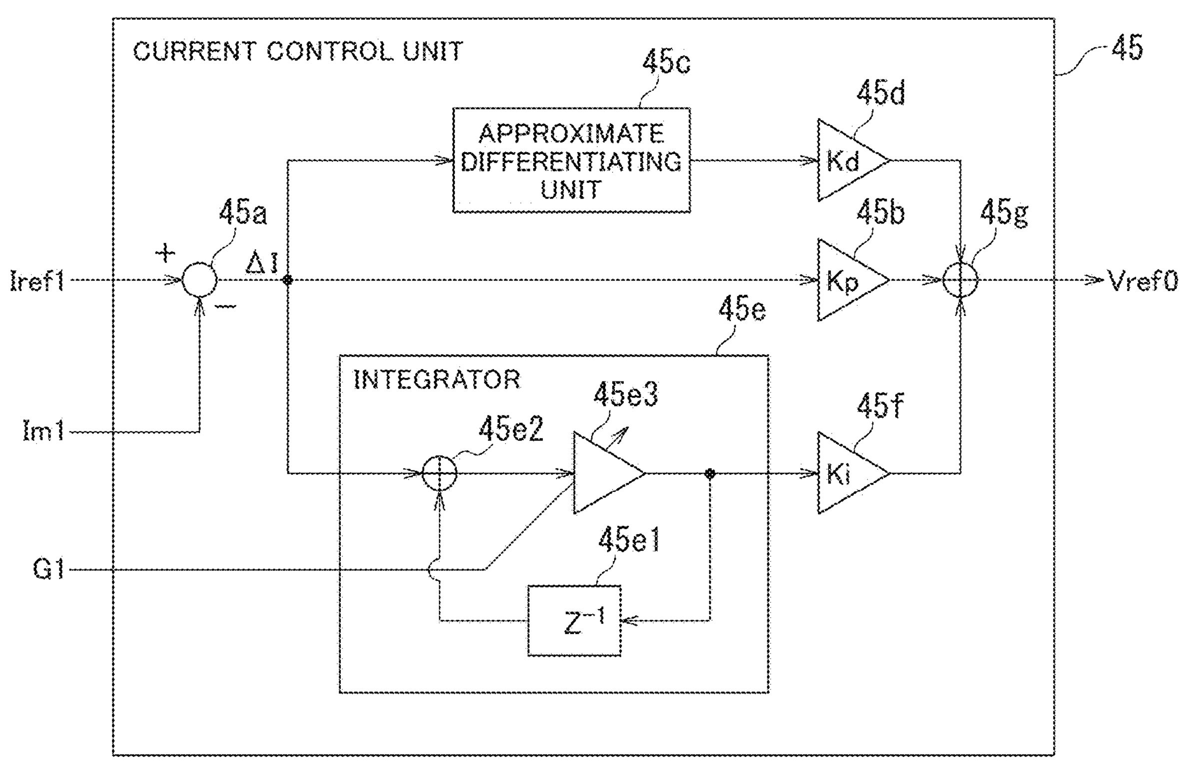

CURRENT CONTROL UNIT
45
45c
APPROXIMATE DIFFERENTIATING UNIT
45d
Kd
45a
45b
45g
+
−
ΔI
Iref1
Kp
Vref0
45e
Im1
INTEGRATOR
45e3
45e2
45f
Ki
G1
45e1
Z^{-1}

FIG. 7

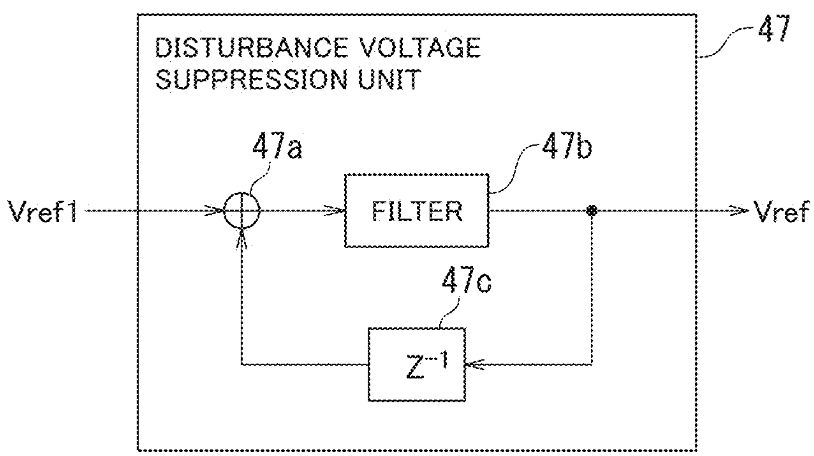

DISTURBANCE VOLTAGE SUPPRESSION UNIT
47
47a
47b
FILTER
Vref1
Vref
47c
Z⁻¹

FIG. 8

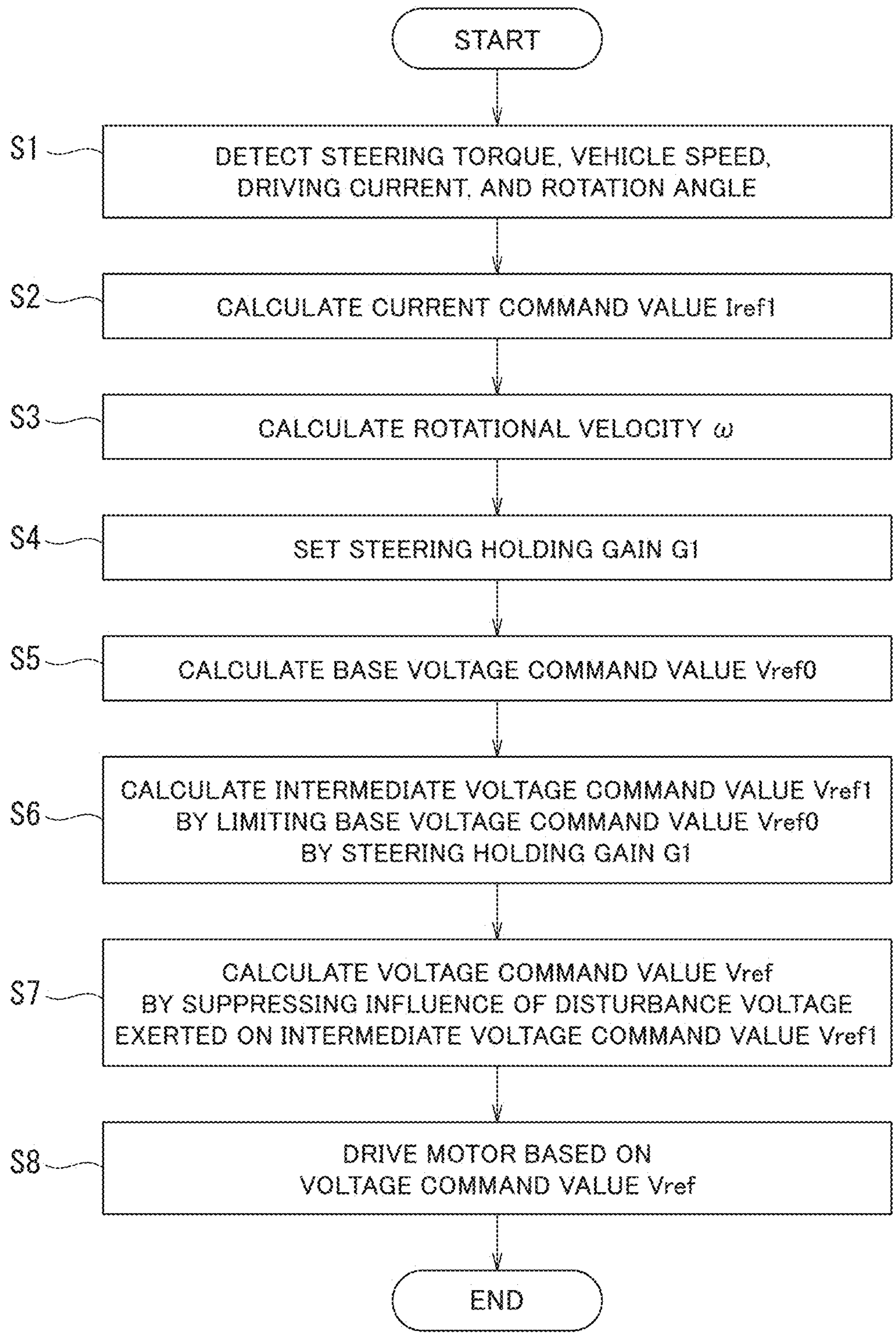

START
S1
DETECT STEERING TORQUE, VEHICLE SPEED, DRIVING CURRENT, AND ROTATION ANGLE
S2
CALCULATE CURRENT COMMAND VALUE Iref1
S3
CALCULATE ROTATIONAL VELOCITY ω
S4
SET STEERING HOLDING GAIN G1
S5
CALCULATE BASE VOLTAGE COMMAND VALUE Vref0
S6
CALCULATE INTERMEDIATE VOLTAGE COMMAND VALUE Vref1 BY LIMITING BASE VOLTAGE COMMAND VALUE Vref0 BY STEERING HOLDING GAIN G1
S7
CALCULATE VOLTAGE COMMAND VALUE Vref BY SUPPRESSING INFLUENCE OF DISTURBANCE VOLTAGE EXERTED ON INTERMEDIATE VOLTAGE COMMAND VALUE Vref1
S8
DRIVE MOTOR BASED ON VOLTAGE COMMAND VALUE Vref
END

FIG. 9A

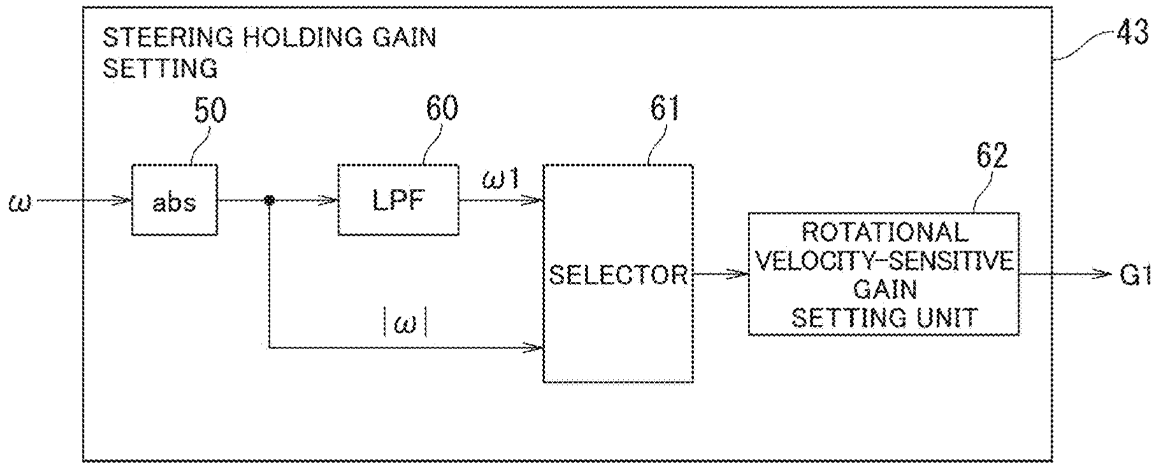
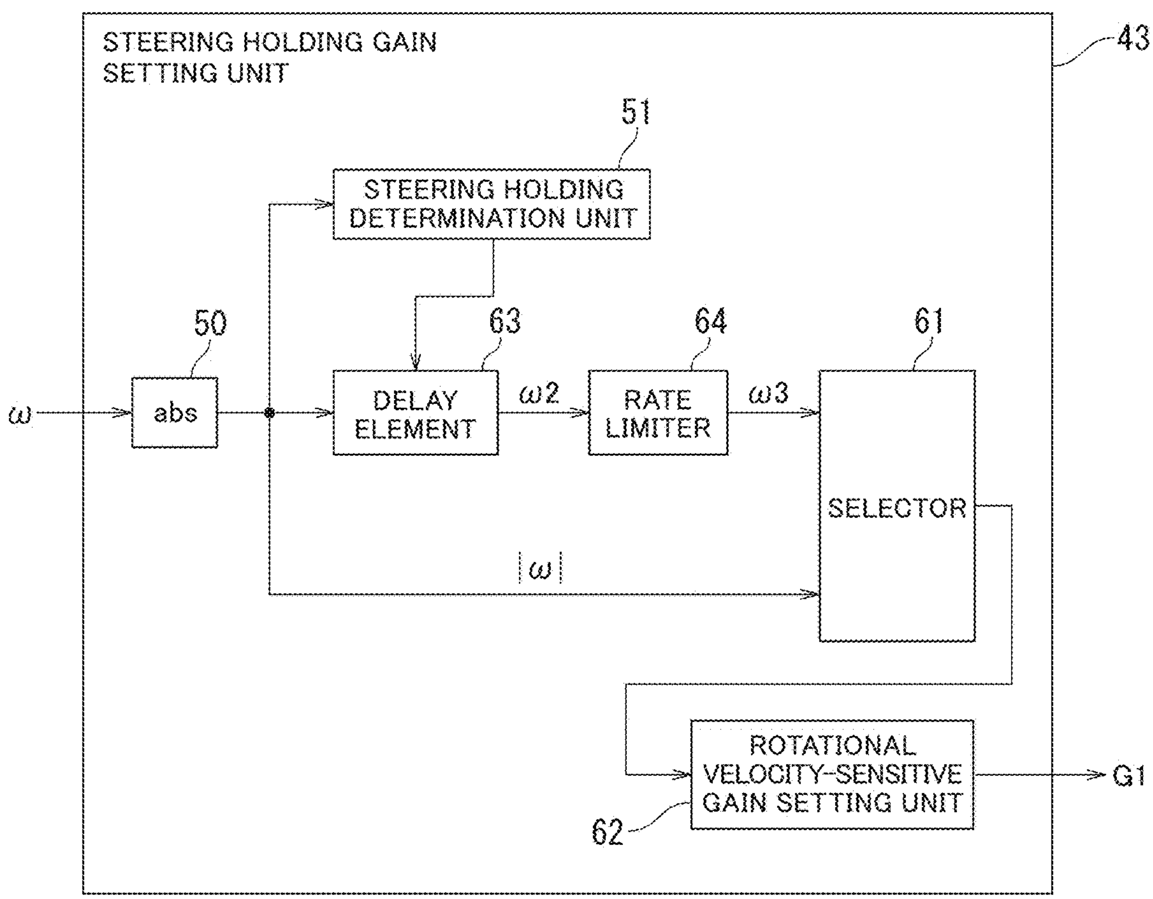

STEERING HOLDING GAIN
SETTING
43
50
60
61
62
ω
abs
LPF
ω1
SELECTOR
ROTATIONAL
VELOCITY-SENSITIVE
GAIN
SETTING UNIT
G1
|ω|

FIG. 9B


STEERING HOLDING GAIN
SETTING UNIT
43
51
STEERING HOLDING
DETERMINATION UNIT
50
63
64
61
ω
abs
DELAY
ELEMENT
ω2
RATE
LIMITER
ω3
SELECTOR
|ω|
ROTATIONAL
VELOCITY-SENSITIVE
GAIN SETTING UNIT
G1
62

ELECTRIC POWER STEERING DEVICE

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a National Stage of International Application No. PCT/JP2024/017490 filed May 10, 2024, claiming priority based on Japanese Patent Application No. 2023-082835 filed May 19, 2023.

TECHNICAL FIELD

[0002] The present invention relates to an electric power steering device.

BACKGROUND ART

[0003] An electric power steering device described in PTL 1 described below includes a steering assist motor configured to generate a steering assist force, sets a current command value, based on steering torque exerted on a steering shaft of a vehicle, and controls the steering assist motor, based on current deviation between a detected value of driving current of the steering assist motor and a current command value.

CITATION LIST

Patent Literature

[0004] PTL 1: JP 2010-47203 A

SUMMARY OF INVENTION

Technical Problem

[0005] In an electric power steering device that provides a steering assist force to a steering system of a vehicle, sound or vibration sometimes occurs due to noise included in a control signal. Since when the steering system is in a steering holding state in which a steering angle is barely changed, occurrence of sound or vibration is likely to stand out, it is preferable to suppress influence of noise. For example, arranging a noise reduction filter in a preceding stage or a succeeding stage of a feedback control device controlling driving current of a steering assist motor enables such influence of noise to be suppressed.

[0006] On the other hand, a high responsiveness of control is required for the electric power steering device at the time of regular steering. When a noise reduction filter as described above is installed, switching of filter characteristics is required to be performed between at the time of regular steering and in the steering holding state. As a result, control becomes complex and time and effort required for adaptation of filter characteristics increase.

[0007] The present invention has been made in consideration of the above-described circumstances, and an object of the present invention is to easily achieve at the same time both responsiveness of control of an electric power steering device at the time of regular steering and suppression of influence of noise while a steering system is in the steering holding state.

Solution to Problem

[0008] In order to achieve the above-described object, according to an aspect of the present invention, there is provided an electric power steering device including: a motor configured to generate a steering assist force to be provided to a steering system of a vehicle; a current command value calculation unit configured to calculate a current command value to control driving current of the motor; a current control unit configured to output a first voltage command value, based on current deviation of a measured value of driving current of the motor with respect to the current command value; a first gain setting unit configured to set a first gain depending on rotational velocity of the motor; a disturbance voltage suppression unit configured to calculate a third voltage command value by adding output from a first delay element to a second voltage command value obtained by limiting the first voltage command value by the first gain and also input the third voltage command value to the first delay element; and a driving circuit configured to drive the motor, based on the third voltage command value.

Advantageous Effects of Invention

[0009] According to the present invention, it is possible to easily achieve at the same time both responsiveness of control of an electric power steering device at the time of regular steering and suppression of influence of noise while a steering system is in the steering holding state.

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 steering holding gain setting unit;
[0013] FIGS. **4**A and **4**B are explanatory diagrams of operation examples of the steering holding gain setting unit;
[0014] FIG. **5** is a schematic diagram of an example of characteristics of a rotational velocity-sensitive gain;
[0015] FIG. **6** is a block diagram illustrative of an example of a functional configuration of a current control unit;
[0016] FIG. **7** is a block diagram illustrative of an example of a functional configuration of a disturbance voltage suppression unit;
[0017] FIG. **8** is a flowchart of an example of a control method of the electric power steering device of the embodiment; and
[0018] FIGS. **9**A and **9**B are block diagrams illustrative of examples of functional configurations of steering holding gain setting units of variations.

DESCRIPTION OF EMBODIMENTS

[0019] 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

[0020] 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 **8**L and **8**R by way of a reduction gear (worm gear) **3** that constitutes a speed reduction mechanism, universal joints **4***a* and **4***b*, a pinion rack mechanism **5**, and tie rods **6***a* and **6***b* and further via hub units **7***a* and **7***b*.

[0021] The pinion rack mechanism **5** includes a pinion **5***a* that is coupled to a pinion shaft to which steering force is transmitted from the universal joint **4***b* and a rack **5***b* that meshes with the pinion **5***a*, and converts rotational motion transmitted to the pinion **5***a* to linear motion in the vehicle width direction by means of the rack **5***b*.

[0022] To the steering shaft **2**, a torque sensor **10** configured to detect steering torque Th is disposed. To the steering shaft **2**, a steering angle sensor **14** configured to detect a steering angle Oh of the steering wheel **1** is also disposed.

[0023] 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 (EPS) device, power is supplied from a battery **13** and an ignition key signal is also input by way of an ignition (IGN) key **11**.

[0024] Note that means for providing a steering assist force is not limited to a motor, and various types of actuators can be used.

[0025] 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 Th detected by the torque sensor **10**, vehicle speed Vh detected by a vehicle speed sensor **12**, and a steering angle θh detected by the steering angle sensor **14** and control current to be supplied to the motor **20** in accordance with a voltage command value Vref obtained by performing compensation and the like on the calculated current command value.

[0026] Note that the steering angle sensor **14** is not an essential component and the steering angle θh 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**.

[0027] In addition, a turning angle of the steered wheels **8**L and **8**R may be used in place of the steering angle θh. The turning angle may be detected by, for example, detecting a displacement amount of the rack **5***b*.

[0028] 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).

[0029] 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.

[0030] 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.

[0031] 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.

[0032] 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.

[0033] Next, with reference to FIG. **2**, an example of a functional configuration of a steering assist function performed by the controller **30** will be described. The controller **30** includes a current command value calculation unit **40**, filters **41** and **44**, an angular velocity conversion unit **42**, a steering holding gain setting unit **43**, a current control unit **45**, a voltage command value limiting unit **46**, a disturbance voltage suppression unit **47**, a pulse width modulation (PWM) control unit **48**, and an inverter (INV) **49**.

[0034] The current command value calculation unit **40** calculates, based on at least the steering torque Th and the vehicle speed Vh, a base current command value Iref that is a current command value to control driving current of the motor **20**.

[0035] The filter **41** outputs a current command value Iref**1** obtained by reducing noise included in the base current command value Iref by performing filter processing on the base current command value Iref. The filter **41** may be, for example, a low-pass filter.

[0036] The angular velocity conversion unit **42** acquires a rotation angle θm from a rotation angle sensor **21** configured to detect a rotation angle of a rotation shaft of the motor **20**. The angular velocity conversion unit **42** calculates rotational velocity ω of the motor **20**, based on temporal change in the rotation angle θm.

[0037] The steering holding gain setting unit **43** sets a steering holding gain G**1**, based on the rotational velocity ω of the motor **20** and outputs the steering holding gain G**1** to the current control unit **45** and the voltage command value limiting unit **46**. The steering holding gain G**1** is an example of a "first gain" described in the claims.

[0038] FIG. **3** is a block diagram illustrative of an example of a functional configuration of the steering holding gain setting unit **43**. The steering holding gain setting unit **43** includes an absolute value calculation unit (abs) **50**, a steering holding determination unit **51**, a gain setting unit **52**, a rate limiter **53**, a rotational velocity-sensitive gain setting unit **54**, and a selector **55**.

[0039] The absolute value calculation unit **50** calculates an absolute value $|\omega|$ of the rotational velocity of the motor **20**.

[0040] The steering holding determination unit **51** determines whether or not a steering system of the vehicle is in a steering holding state, based on the absolute value $|\omega|$ of the rotational velocity of the motor **20**.

[0041] The steering holding state is a state in which the steering angle θh of the steering wheel **1** or the steering shaft **2** is barely changed. For example, the steering holding determination unit **51** may determine that the steering system is in the steering holding state when the absolute value $|\omega|$ of the rotational velocity of the motor **20** is less than a determination threshold value ωth, and may determine that the steering system is not in the steering holding state when the absolute value $|\omega|$ is greater than or equal to the determination threshold value ωth. The steering holding gain setting unit **43** may calculate the rotational velocity ω, using the steering angle Oh in place of the rotation angle θm of the motor **20**.

[0042] The gain setting unit **52** sets a steering holding determination-dependent gain G**2** depending on a determination result of the steering holding determination unit **51**. The steering holding determination-dependent gain G**2** is an example of a "second gain" described in the claims.

[0043] For example, the gain setting unit **52** may set a smaller steering holding determination-dependent gain G**2** when the steering system is determined to be in the steering holding state than when the steering system is determined not to be in the steering holding state. That is, the gain setting unit **52** may set the steering holding determination-dependent gain G**2** to a first value G**21** when the steering system is determined to be in the steering holding state and may set the steering holding determination-dependent gain G**2** to a second value G**22** that is larger than the first value G**21** when the steering system is determined not to be in the steering holding state. For example, the gain setting unit **52** sets the steering holding determination-dependent gain G**2** to a value "0" when the steering system is determined to be in the steering holding state and sets the steering holding determination-dependent gain G**2** to a value "1" when the steering system is determined not to be in the steering holding state.

[0044] In addition, when a state of the steering system changes from a state in which the steering system is determined not to be in the steering holding state to a state in which the steering system is determined to be in the steering holding state, the gain setting unit **52** may delay change in the steering holding determination-dependent gain G**2** with respect to the change in the state of the steering system. In addition, when the state of the steering system changes from the state in which the steering system is determined to be in the steering holding state to the state in which the steering system is determined not to be in the steering holding state, the gain setting unit **52** may change the steering holding determination-dependent gain G**2** immediately after the state of the steering system changes.

[0045] For example, at a time point when a predetermined delay time T**0** has elapsed since a time point when the state of the steering system changed from the state in which the steering system is determined not to be in the steering holding state to the state in which the steering system is determined to be in the steering holding state, the gain setting unit **52** may change the steering holding determination-dependent gain G**2** from the second value G**22** to the first value G**21**. In addition, the gain setting unit **52** may change the steering holding determination-dependent gain G**2** from the first value G**21** to the second value G**22** immediately after the state of the steering system changes from the state in which the steering system is determined to be in the steering holding state to the state in which the steering system is determined not to be in the steering holding state.

[0046] The rate limiter **53** limits a change rate of the steering holding determination-dependent gain G**2**. For example, the rate limiter **53** limits the change rate in such a way that an absolute value of the change rate of the steering holding determination-dependent gain G**2** is less than or equal to a predetermined upper limit. The rate limiter **53** inputs a steering holding determination-dependent gain G**2***a* the change rate of which is limited to the selector **55**.

[0047] With reference to FIGS. **4**A and **4**B, an example of the steering holding determination-dependent gain G**2***a* will be described. FIG. **4**A is a timing diagram of temporal change in the rotational velocity ω of the motor **20**. A dashed-dotted line in FIG. **4**B is a timing diagram of temporal change in the steering holding determination-dependent gain G**2***a*.

[0048] Since in a period before time t**1**, the rotational velocity ω of the motor **20** is greater than or equal to the determination threshold value ωth, the steering holding determination unit **51** determines that the steering system is not in the steering holding state. Thus, the gain setting unit **52** sets the steering holding determination-dependent gain G**2** to the value "1". As a result, the steering holding determination-dependent gain G**2***a* is also set to the value "1".

[0049] When the rotational velocity ω changes to less than the determination threshold value ωth at time t**1**, the steering holding determination unit **51** determines that the steering system is in the steering holding state. The gain setting unit **52** maintains the steering holding determination-dependent gain G**2** at the value "1" until time t**2** at which the predetermined delay time T**0** has elapsed since time t**1** is reached, and changes the steering holding determination-dependent gain G**2** to the value "0" at time t**2**. The steering holding determination-dependent gain G**2***a* the change rate of which is limited starts to decrease from time t**2**, decreases at a limited change rate, and reaches the value "0" at time t**3**.

[0050] When the rotational velocity ω changes to greater than or equal to the determination threshold value ωth at time t**4**, the steering holding determination unit **51** determines that the steering system is not in the steering holding state. The gain setting unit **52** immediately sets the steering holding determination-dependent gain G**2** to the value "1". The steering holding determination-dependent gain G**2***a* the change rate of which is limited starts to increase from time t**4**, increases at a limited change rate, and reaches the value "1" at time t**5**.

[0051] Since the gain setting unit **52** changes the steering holding determination-dependent gain G**2** from the value "1" to the value "0" after the delay time T**0** has elapsed in this way, the steering holding determination-dependent gain G**2***a* changes in a delayed manner with respect to change in the rotational velocity of the motor **20**. In addition, since the rate limiter **53** limits the change rate of the steering holding determination-dependent gain G**2***a*, the steering holding determination-dependent gain G**2***a* changes in a delayed manner with respect to change in the rotational velocity of the motor **20**. Therefore, the steering holding determination-dependent gain G**2***a* is an example of a "first component changing in a delayed manner with respect to change in rotational velocity of the motor" described in the claims.

[0052] FIG. **3** is now referred to. The rotational velocity-sensitive gain setting unit **54** sets a rotational velocity-sensitive gain G**3** that changes in accordance with the absolute value |ω| of the rotational velocity of the motor **20**. The rotational velocity-sensitive gain G**3** is an example of a "third gain" described in the claims.

[0053] FIG. **5** is a schematic diagram of an example of characteristics of the rotational velocity-sensitive gain G**3**. The rotational velocity-sensitive gain G**3** has characteristics of being smaller when the absolute value |ω| is small than when the absolute value |ω| is large. For example, the rotational velocity-sensitive gain G**3** may have characteristics that the smaller the absolute value |ω| is, the smaller the rotational velocity-sensitive gain G**3** becomes. For example, the rotational velocity-sensitive gain G**3** may have characteristics of being maintained at a constant value within a range where the absolute value |ω| is greater than or equal to the determination threshold value @th.

[0054] In the example of the rotational velocity-sensitive gain G**3** in FIG. **5**, the rotational velocity-sensitive gain G**3** is set to the value "0" when the absolute value |ω| of the rotational velocity is the value "0", and the rotational velocity-sensitive gain G**3** is set to a value larger than "0" when the absolute value |ω| becomes larger than the value "0". In a range where the absolute value |ω| is greater than or equal to "0" and less than the determination threshold value ωth, the larger the absolute value |ω| becomes, the larger the rotational velocity-sensitive gain G**3** also becomes.

[0055] The rotational velocity-sensitive gain G**3** may non-linearly change with respect to change in the absolute value |ω| or may be proportional to the absolute value |ω| (that is, may linearly change).

[0056] In a range where the absolute value |ω| is greater than or equal to the determination threshold value ωth, the rotational velocity-sensitive gain G**3** is maintained at a constant value "1".

[0057] The rotational velocity-sensitive gain G**3** is an example of a "second component changing in accordance with change in rotational velocity of the motor" described in the claims.

[0058] No delay time is provided to the rotational velocity-sensitive gain G**3** like the delay time T**0** for the steering holding determination-dependent gain G**2***a*, and a change rate of the rotational velocity-sensitive gain G**3** is not limited by a rate limiter. Thus, change in the rotational velocity-sensitive gain G**3** with respect to change in the rotational velocity of the motor **20** has an extremely small delay (ideally, no delay). Therefore, the rotational velocity-sensitive gain G**3** changes in accordance with change in the rotational velocity ω of the motor **20** with a smaller delay than delay of the steering holding determination-dependent gain G**2***a*.

[0059] FIG. **3** is now referred to. The selector **55** selects a larger one of the steering holding determination-dependent gain G**2***a* and the rotational velocity-sensitive gain G**3** and outputs the selected one as the steering holding gain G**1**.

[0060] A dashed line in FIG. **4**B indicates the rotational velocity-sensitive gain G**3**, and a solid line indicates the steering holding gain G**1**. Since immediately after the rotational velocity w of the motor **20** changes from a state of being greater than or equal to the determination threshold value ωth to a state of being less than the determination threshold value ωth, the steering holding determination-dependent gain G**2***a* is larger than the rotational velocity-sensitive gain G**3** until a certain time length elapses, the steering holding determination-dependent gain G**2***a* is output as the steering holding gain G**1**.

[0061] Therefore, the steering holding gain G**1** changes in a delayed manner with respect to change in the rotational velocity of the motor **20** until a certain time length elapses after a time point at which the rotational velocity ω of the motor **20** changes to a state of being less than the determination threshold value ωth. Thus, even when the rotational velocity ω temporarily becomes less than the determination threshold value ωth, the steering holding gain G**1** of a certain magnitude can be maintained.

[0062] While the steering system is in the steering holding state, the rotational velocity ω is maintained less than the determination threshold value ωth. Thus, the steering holding determination-dependent gain G**2***a* gradually decreases following the value "0" of the steering holding determination-dependent gain G**2** set by the gain setting unit **52**. When the steering holding determination-dependent gain G**2***a* becomes less than the rotational velocity-sensitive gain G**3**, the rotational velocity-sensitive gain G**3** is output as the steering holding gain G**1**. Then, the steering holding gain G**1** changes with a small delay with respect to change in the rotational velocity ω (or changes without delay with respect to the rotational velocity ω). Therefore, when a driver starts steering and the rotational velocity ω increases, the steering holding gain G**1** immediately increases.

[0063] FIG. **2** is now referred to. The filter **44** performs filter processing on a measured value Im of the driving current of the motor **20** that is detected by the motor current detector **22** and thereby outputs a measured value Im**1** obtained by reducing noise included in the measured value Im. The filter **44** may be, for example, a low-pass filter.

[0064] The current control unit **45** calculates a base voltage command value Vref**0**, based on current deviation ΔI=(Iref**1**−Im**1**) of the measured value Im**1** of the driving current with respect to the current command value Iref**1**.

[0065] For example, the current control unit **45** calculates the base voltage command value Vref**0** by at least one of proportional control (P-control), integral control (I-control), and derivative control (D-control) based on the current deviations ΔI or a combination of the foregoing. That is, the current control unit **45** calculates the base voltage command value Vref**0** by feedback control based on the current deviations ΔI. The base voltage command value Vref**0** is an example of a "first voltage command value" described in the claim.

[0066] FIG. **6** is a block diagram illustrative of an example of a functional configuration of the current control unit **45** when the base voltage command value Vref**0** is calculated by proportional-integral-derivative (PID) control. The current control unit **45** includes a subtracter **45***a*, gain multiplication units **45***b*, **45***d*, and **45***f*, an approximate differentiating unit **45***c*, an integrator **45***e*, and an adder **45***g*.

[0067] The subtracter **45***a* calculates current deviation ΔI=(Iref**1**−Im**1**) of the measured value Im**1** of the driving current with respect to the current command value Iref**1**.

[0068] The gain multiplication unit **45***b* outputs a multiplication result of the current deviation ΔI and a proportional gain Kp to the adder **45***g*.

[0069] The approximate differentiating unit **45***c* calculates a differential value of the current deviations ΔI. For example, the approximate differentiating unit **45***c* may calculate the differential value by multiplying the current deviations ΔI by a transfer function s/(Ts+1) that is obtained by combining a differential operation and a low-pass filter. The gain multiplication unit **45***d* outputs a multiplication result of the differential value of the current deviation ΔI and a differential gain Kd to the adder **45***g*.

[0070] The integrator **45***e* calculates an integrated value of the current deviations ΔI. The gain multiplication unit **45***f* outputs a multiplication result of the integrated value of the current deviation ΔI and an integral gain Ki to the adder **45***g*. The integral gain Ki is an example of a "fourth gain" described in the claims.

[0071] The adder **45***g* outputs a sum of the multiplication result of the current deviation ΔI and the proportional gain Kp, the multiplication result of the differential value of the current deviation ΔI and the differential gain Kd, and the multiplication result of the integrated value of the current deviation ΔI and the integral gain Ki, as the base voltage command value Vref**0**.

[0072] The integrator **45***e* includes a delay element **45***e***1**, an adder **45***e***2**, and a gain multiplication unit **45***e***3**.

[0073] The delay element **45***e***1** delays output from the integrator **45***e* and subsequently inputs the delayed output to the adder **45***e***2**. That is, the delay element **45***e***1** inputs a past value (a last value) of the output from the integrator **45***e* to the adder **45***e***2**. The delay element **45***e***1** is an example of a "second delay element" described in the claims.

[0074] The adder **45***e***2** outputs a sum of the current deviation ΔI and output from the delay element **45***e***1**. The gain multiplication unit **45***e***3** calculates a multiplication result of a gain depending on the steering holding gain G**1** and the output from the adder **45***e***2** as output from the integrator **45***e*.

[0075] The gain by which the gain multiplication unit **45***e***3** multiplies the output from the adder **45***e***2** may be, for example, a gain having a smaller value when the steering holding gain G**1** is small than when the steering holding gain G**1** is large. For example, the gain by which the gain multiplication unit **45***e***3** multiplies the output from the adder **45***e***2** may be a gain having characteristics that the smaller the steering holding gain G**1** is, the smaller value the gain has. For example, the gain multiplication unit **45***e***3** may multiply the output from the adder **45***e***2** by the steering holding gain G**1** itself.

[0076] FIG. **2** is now referred to. The voltage command value limiting unit **46** calculates an intermediate voltage command value Vref**1** by limiting the base voltage command value Vref**0** by the steering holding gain G**1**. For example, the voltage command value limiting unit **46** calculates a smaller intermediate voltage command value Vref**1** when the steering holding gain G**1** is small than when the steering holding gain G**1** is large.

[0077] For example, the voltage command value limiting unit **46** may be a multiplier that calculates a product of the base voltage command value Vref**0** and the steering holding gain G**1** as the intermediate voltage command value Vref**1**. The intermediate voltage command value Vref**1** is an example of a "second voltage command value" described in the claim.

[0078] The disturbance voltage suppression unit **47** calculates a voltage command value Vref by suppressing influence that counter electromotive voltage or other disturbance voltage exerts on the intermediate voltage command value Vref**1**. The voltage command value Vref is an example of a "third voltage command value" described in the claim.

[0079] FIG. **7** is a block diagram illustrative of an example of a functional configuration of the disturbance voltage suppression unit **47**. The disturbance voltage suppression unit **47** includes an adder **47***a*, a filter **47***b*, and a delay element **47***c*. The delay element **47***c* is an example of a "first delay element" described in the claims.

[0080] The adder **47***a* outputs a sum of the intermediate voltage command value Vref**1** and output from the delay element **47***c*.

[0081] The filter **47***b* reduces noise by performing filter processing on the sum of the intermediate voltage command value Vref**1** and the output from the delay element **47***c*. For example, the filter **47***b* may be a low-pass filter. Output from the filter **47***b* is output from the disturbance voltage suppression unit **47** as the voltage command value Vref and is also input to the delay element **47***c*.

[0082] The delay element **47***c* delays the output from the filter **47***b* (that is, the voltage command value Vref) and subsequently inputs the delayed output from the filter **47***b* to the adder **47***a*. That is, the delay element **47***c* inputs a past value (a last value) of the voltage command value Vref to the adder **47***a*.

[0083] FIG. **2** is now referred to. The voltage command value Vref is input to a PWM control unit **48**, and further, the motor **20** is PWM-driven by the inverter **49**. Driving current of the motor **20** is detected by the motor current detector **22** and fed back to the subtracter **45***a* in the current control unit **45** via the filter **44**.

[0084] Note that the controller **30** may perform vector control of calculating a q-axis current command value that is a component for generating torque and a d-axis current command value that is a component for generating a magnetic field as the current command values Iref**1** and generating voltage command values, based on deviation between a motor current detected value of the q-axis and the q-axis current command value and deviation between a motor current detected value of the d-axis and the d-axis current command value.

Action

[0085] Next, actions of the electric power steering device of the embodiment will be described. The steering holding gain G**1** that is set by the steering holding gain setting unit **43** has characteristics of being smaller when the absolute value |ω| of the rotational velocity of the motor **20** is small than when the absolute value |ω| is large, as illustrated in FIG. **4**B. Thus, the steering holding gain G**1** is set to a smaller value in the steering holding state than at the time of regular steering. The voltage command value limiting unit **46** calculates the intermediate voltage command value Vref**1** by limiting the base voltage command value Vref**0** by the steering holding gain G**1**.

[0086] Thus, while the steering system is in the steering holding state, the intermediate voltage command value Vref**1** becomes small. Therefore, noise included in the intermediate voltage command value Vref**1** can be prevented from influencing the voltage command value Vref. As a result, while the steering system is in the steering holding state, influence of noise included in a control signal of the electric power steering device can be suppressed. Because of this capability, influence of noise in the steering holding state can be suppressed even without switching filter characteristics of the filters **41** and **44** between at the time of regular steering and in the steering holding state.

[0087] Since the disturbance voltage suppression unit **47**, which is disposed in a succeeding stage of the voltage command value limiting unit **46**, adds the intermediate voltage command value Vref**1** to a past value of the voltage command value Vref, the disturbance voltage suppression unit **47** has an integrating function of accumulating the intermediate voltage command value Vref**1**. Thus, even when the intermediate voltage command value Vref**1** becomes small due to the state of the steering system changing to the steering holding state, the voltage command value Vref that generates a steering assist force required for steering holding can be maintained by the integrating function of the disturbance voltage suppression unit **47**.

[0088] In addition, since simply reducing the steering holding gain G**1** when the absolute value |ω| of the rotational velocity of the motor **20** becomes small causes the intermediate voltage command value Vref**1** to become small every time the absolute value |ω| of the rotational velocity becomes 0 in turning-back steering in the regular steering, the steering assist force becomes small and there is a risk that the driver feels resistance.

[0089] Therefore, as illustrated in FIG. **4**B, even when the rotational velocity ω of the motor **20** changes to less than the determination threshold value ωth, the magnitude of the steering holding gain G**1** is maintained until a certain time length elapses immediately after the change. Because of this configuration, it is possible to prevent the driver from feeling resistance in the turning-back steering.

[0090] Subsequently, the steering holding gain G**1** is changed with a small delay with respect to change in the rotational velocity ω. Because of this configuration, the steering holding gain G**1** can be increased in accordance with the steering of the steering wheel **1** or the steering shaft **2**. As a result, the steering assist force can be output even when a small steering is performed while the steering is held. In addition, the output of the steering assist force can be resumed immediately after the steering system returns from the steering holding state to a regular steering state.

[0091] Note that when, as illustrated in FIG. **6**, the feedback control performed by the current control unit **45** includes the integral control, an integrated value of the current deviation ΔI output from the integrator **45***e* increases (accumulates) since the base voltage command value Vref**0** that the current control unit **45** outputs being limited by the steering holding gain G**1** causes the current deviation ΔI to remain.

[0092] Thus, the gain multiplication unit **45***e***3** multiplies an integrated value of the current deviation ΔI by a gain depending on the steering holding gain G**1** (or the steering holding gain G**1** itself). Because of this configuration, an integrated value from the integrator **45***e* can be prevented from increasing (accumulating).

Operation

[0093] FIG. **8** is a flowchart of an example of a control method of the electric power steering device of the embodiment.

[0094] In step S**1**, the torque sensor **10**, the vehicle speed sensor **12**, the motor current detector **22**, and the rotation angle sensor **21** detect the steering torque Th, the vehicle speed Vh, and the driving current Im and the rotation angle θm of the motor **20**, respectively.

[0095] In step S**2**, the current command value calculation unit **40** calculates the base current command value Iref. The filter **41** outputs the current command value Iref**1** by reducing noise in the base current command value Iref.

[0096] In step S**3**, the angular velocity conversion unit **42** calculates the rotational velocity ω of the motor **20**, based on temporal change in the rotation angle θm.

[0097] In step S**4**, the steering holding gain setting unit **43** sets the steering holding gain G**1**, based on the rotational velocity ω of the motor **20**.

[0098] In step S**5**, the filter **44** calculates the measured value Im**1** of the driving current by reducing noise included in the measured value Im of the driving current of the motor **20**. The current control unit **45** calculates the base voltage command value Vref**0**, based on the current deviation ΔI of the measured value Im**1** of the driving current with respect to the current command value Iref**1**.

[0099] In step S**6**, the voltage command value limiting unit **46** calculates the intermediate voltage command value Vref**1** by limiting the base voltage command value Vref**0** by the steering holding gain G**1**.

[0100] In step S**7**, the disturbance voltage suppression unit **47** calculates the voltage command value Vref by suppressing influence that disturbance voltage exerts on the intermediate voltage command value Vref**1**.

[0101] In step S**8**, the PWM control unit **48** and the inverter **49** drive the motor **20**, based on the voltage command value Vref. Subsequently, the process terminates.

Variations

[0102] FIGS. **9**A and **9**B are block diagrams illustrative of examples of functional configurations of the steering holding gain setting unit **43** in variations. The steering holding gain setting unit **43** may compare a delayed rotational velocity signal obtained by delaying the rotational velocity ω of the motor **20** with the rotational velocity ω of the motor **20** and set a gain depending on a higher one of the rotational velocities as the steering holding gain G**1**.

[0103] For example, the steering holding gain setting unit **43** in FIG. **9**A includes an absolute value calculation unit (abs) **50**, a low-pass filter (LPF) **60**, a selector **61**, and a rotational velocity-sensitive gain setting unit **62**.

[0104] The absolute value calculation unit **50** calculates an absolute value |ω| of the rotational velocity of the motor **20** and inputs the calculated absolute value |ω| to the low-pass filter **60** and the selector **61**.

[0105] The low-pass filter **60** performs low-pass filter processing on the absolute value |ω| of the rotational velocity. The low-pass filter **60** inputs a rotational velocity signal ω**1** after filter processing to the selector **61**. The low-pass filter **60** acts as a delay element that delays the absolute value |ω| of the rotational velocity.

[0106] The selector **61** selects a larger one of the absolute value |ω| of the rotational velocity and the rotational velocity signal ω**1** and inputs the selected one to the rotational velocity-sensitive gain setting unit **62**.

[0107] The rotational velocity-sensitive gain setting unit **62** sets the steering holding gain G**1** depending on output from the selector **61**. Characteristics of the steering holding gain G**1** that the rotational velocity-sensitive gain setting unit **62** sets may be, for example, similar characteristics to the characteristics of the rotational velocity-sensitive gain G**3** that was described with reference to FIG. **5**.

[0108] In addition, the steering holding gain setting unit **43** in FIG. **9**B includes an absolute value calculation unit (abs) **50**, a steering holding determination unit **51**, a delay element **63**, a rate limiter **64**, a selector **61**, and a rotational velocity-sensitive gain setting unit **62**.

[0109] The steering holding determination unit **51** determines whether or not the steering system of the vehicle is in the steering holding state, based on whether or not the absolute value $|\omega|$ of the rotational velocity of the motor **20** is less than the determination threshold value ωth.

[0110] The delay element **63** outputs a rotational velocity signal $\omega 2$ obtained by delaying the absolute value $|\omega|$ of the rotational velocity when the state of the steering system changes from a state in which the steering system is determined not to be in the steering holding state to a state in which the steering system is determined to be in the steering holding state.

[0111] For example, the delay element **63** may maintain an output value at a time point at which the state of the steering system changes to the steering holding state for a predetermined delay time T**0** when the state of the steering system changes from the state in which the steering system is determined not to be in the steering holding state to the state in which the steering system is determined to be in the steering holding state.

[0112] The rate limiter **64** limits a change rate of the rotational velocity signal $\omega 2$. For example, the rate limiter **53** limits the change rate in such a way that an absolute value of the change rate of the rotational velocity signal $\omega 2$ is less than or equal to a predetermined upper limit. The rate limiter **53** inputs a rotational velocity signal $\omega 3$ the change rate of which is limited to the selector **61**.

[0113] The selector **61** selects a larger one of the absolute value $|\omega|$ of the rotational velocity and the rotational velocity signal $\omega 3$ and inputs the selected one to the rotational velocity-sensitive gain setting unit **62**.

[0114] The rotational velocity-sensitive gain setting unit **62** sets the steering holding gain G**1** depending on output from the selector **61**. Characteristics of the steering holding gain G**1** that the rotational velocity-sensitive gain setting unit **62** sets may be, for example, similar characteristics to the characteristics of the rotational velocity-sensitive gain G**3** that was described with reference to FIG. **5**.

Advantageous Effects of Embodiment

[0115] (1) An electric power steering device includes: a motor configured to generate a steering assist force to be provided to a steering system of a vehicle; a current command value calculation unit configured to calculate a current command value to control driving current of the motor; a current control unit configured to output a first voltage command value, based on current deviation of a measured value of driving current of the motor with respect to the current command value; a first gain setting unit configured to set a first gain depending on rotational velocity of the motor; a disturbance voltage suppression unit configured to calculate a third voltage command value by adding output from a first delay element to a second voltage command value obtained by limiting the first voltage command value by the first gain and also input the third voltage command value to the first delay element; and a driving circuit configured to drive the motor, based on the third voltage command value.

[0116] Because of this configuration, while the steering system is in the steering holding state, noise included in the first voltage command value can be prevented from influencing the steering assist force only by limiting the first voltage command value by the first gain. Thus, it is possible to easily achieve at the same time both responsiveness of control of the electric power steering device at the time of regular steering and suppression of influence from noise while the steering system is in the steering holding state.

[0117] In addition, the disturbance voltage suppression unit having a function of integrating the second voltage command value enables the steering assist force required for steering holding to be maintained.

[0118] (2) The first gain setting unit may set a first gain in accordance with a larger one of a first component changing in a delayed manner with respect to change in rotational velocity of the motor and a second component changing in accordance with change in rotational velocity of the motor. For example, the second component may be a component that changes in accordance with change in rotational velocity of the motor with delay smaller than delay of the first component.

[0119] Because of this configuration, it is possible to prevent the driver from feeling resistance in the turning-back steering and also possible to output a steering assist force for a small steering while steering is held. In addition, the output of the steering assist force can be resumed immediately after the steering system returns from the steering holding state to a regular steering state.

[0120] (3) The first gain setting unit may include: a second gain setting unit configured to set a second gain according to whether or not the steering system is in a steering holding state, based on rotational velocity of the motor; and a rate limiter configured to limit a change rate of the second gain and output the limited second gain as the first component.

[0121] Because of this configuration, a first component that changes in a delayed manner with respect to change in the rotational velocity of the motor can be generated.

[0122] (4) The second gain setting unit may delay change in the second gain when a state of the steering system changes from a state of not being the steering holding state to the steering holding state.

[0123] Because of this configuration, a first component that changes in a delayed manner with respect to change in the rotational velocity of the motor can be generated.

[0124] (5) The first gain setting unit may include a low-pass filter configured to output the first component by performing low-pass filter processing on rotational velocity of the motor.

[0125] Because of this configuration, a first component that changes in a delayed manner with respect to change in the rotational velocity of the motor can be generated.

[0126] (6) The first gain setting unit may include: a third gain setting unit configured to set a third gain depending on rotational velocity of the motor; and a selector configured to select a larger one of the first component and the third gain as the first gain.

[0127] Alternatively, the first gain setting unit may include: a selector configured to select and output a larger one of the first component and the second component; and a gain setting unit configured to set a gain depending on output from the selector as the first gain.

[0128] Because of this configuration, a first gain can be set in accordance with a larger component of a first component that changes in a delayed manner with respect to change in the rotational velocity of the motor and a second component that changes in accordance with change in the rotational velocity of the motor.

[0129] (7) The current control unit may output the first voltage command value including an integral component proportional to an integral of the current deviation and suppress the integral component by the first gain. For example, the current control unit may include: an integrator configured to calculate an integrated value of the current deviation by multiplying a sum of the current deviation and output from a second delay element by a gain depending on the first gain and input the integrated value to the second delay element; and a multiplier configured to calculate the integral component by multiplying output from the integrator by a fourth gain.

[0130] Because of this configuration, an integrated value of the integrator can be prevented from increasing (accumulating) even when the first voltage command value that the current control unit outputs being limited by the first gain causes current deviation of the measured value of the driving current of the motor with respect to a current command value to remain.

REFERENCE SIGNS LIST

[0131] **1** Steering wheel
[0132] **2** Steering shaft
[0133] **3** Reduction gear
[0134] **4***a*, **4***b* Universal joint
[0135] **5** Pinion rack mechanism
[0136] **5***a* Pinion
[0137] **5***b* Rack
[0138] **6***a*, **6***b* Tie rod
[0139] **7***a*, **7***b* Hub unit
[0140] **8**L, **8**R Steered wheel
[0141] **10** Torque sensor
[0142] **111** Ignition key
[0143] **112** Vehicle speed sensor
[0144] **13** Battery
[0145] **14** Steering angle sensor
[0146] **20** Motor
[0147] **21** Rotation angle sensor
[0148] **22** Motor current detector
[0149] **30** Controller
[0150] **40** Current command value calculation unit
[0151] **41**, **44**, **47***b* Filter
[0152] **42** Angular velocity conversion unit
[0153] **43** Steering holding gain setting unit
[0154] **45** Current control unit
[0155] **45***a* Subtracter
[0156] **45***b*, **45***d*, **45***e***3**, **45***f* Gain multiplication unit
[0157] **45***c* Approximate differentiating unit
[0158] **45***e* Integrator
[0159] **45***e***1**, **47***c*, **63** Delay element
[0160] **45***e***2**, **45***g*, **47***a* Adder
[0161] **46** Voltage command value limiting unit
[0162] **47** Disturbance voltage suppression unit
[0163] **48** PWM control unit
[0164] **49** Inverter
[0165] **50** Absolute value calculation unit
[0166] **51** Steering holding determination unit
[0167] **52** Gain setting unit
[0168] **53**, **64** Rate limiter
[0169] **54**, **62** Rotational velocity-sensitive gain setting unit
[0170] **55**, **61** Selector
[0171] **60** Low-pass filter

1. An electric power steering device comprising:
a motor configured to generate a steering assist force to be provided to a steering system of a vehicle;
a current command value calculation unit configured to calculate a current command value to control driving current of the motor;
a current control unit configured to output a first voltage command value, based on current deviation of a measured value of driving current of the motor with respect to the current command value;
a first gain setting unit configured to set a first gain depending on rotational velocity of the motor;
a disturbance voltage suppression unit configured to calculate a third voltage command value by adding output from a first delay element to a second voltage command value obtained by limiting the first voltage command value by the first gain and also input the third voltage command value to the first delay element; and
a driving circuit configured to drive the motor, based on the third voltage command value.

2. The electric power steering device according to claim **1**, wherein the first gain setting unit sets the first gain in accordance with a larger one of a first component changing in a delayed manner with respect to change in rotational velocity of the motor and a second component changing in accordance with change in rotational velocity of the motor.

3. The electric power steering device according to claim **2**, wherein the second component changes in accordance with change in rotational velocity of the motor with delay smaller than delay of the first component.

4. The electric power steering device according to claim **2**, wherein
the first gain setting unit includes:
a second gain setting unit configured to set a second gain according to whether or not the steering system is in a steering holding state, based on rotational velocity of the motor; and
a rate limiter configured to limit a change rate of the second gain and output the limited second gain as the first component.

5. The electric power steering device according to claim **4**, wherein the second gain setting unit delays change in the second gain when a state of the steering system changes from a state of not being the steering holding state to the steering holding state.

6. The electric power steering device according to claim **2**, wherein the first gain setting unit includes a low-pass filter configured to output the first component by performing low-pass filter processing on rotational velocity of the motor.

7. The electric power steering device according to claim **2**, wherein
the first gain setting unit includes:
a third gain setting unit configured to set a third gain depending on rotational velocity of the motor; and
a selector configured to select a larger one of the first component and the third gain as the first gain.

8. The electric power steering device according to claim **2**, wherein
the first gain setting unit includes:
a selector configured to select and output a larger one of the first component and the second component; and
a gain setting unit configured to set a gain depending on output from the selector as the first gain.

9. The electric power steering device according to claim **1**, wherein the current control unit outputs the first voltage command value including an integral component proportional to an integral of the current deviation and suppresses the integral component by the first gain.

10. The electric power steering device according to claim **9**, wherein

the current control unit includes:

an integrator configured to calculate an integrated value of the current deviation by multiplying a sum of the current deviation and output from a second delay element by a gain depending on the first gain and input the integrated value to the second delay element; and

a multiplier configured to calculate the integral component by multiplying output from the integrator by a fourth gain.

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