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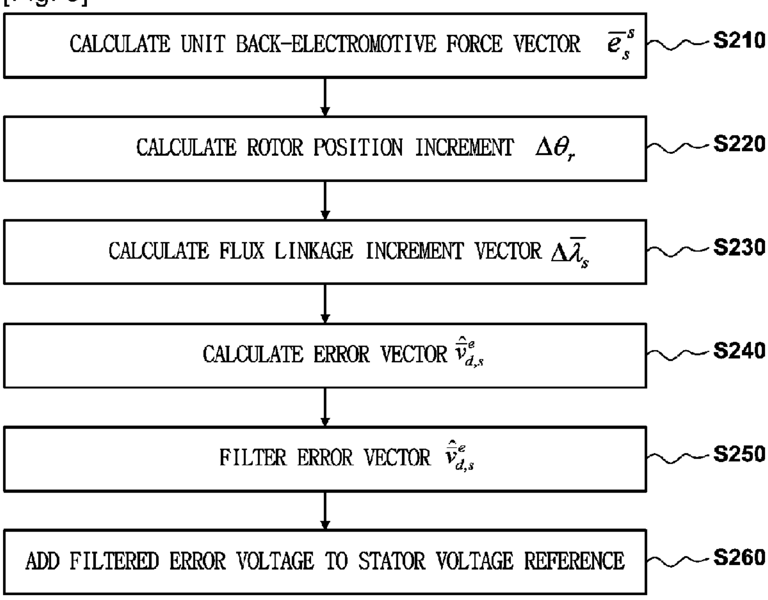
[Continued on next page]

(54) Title: DEAD-TIME COMPENSATOR AND METHOD FOR PERMANENT MAGNET SYNCHRONOUS DRIVES

[Fig. 5]



(57) Abstract: Disclosed is a dead-time compensator for a PMSM drive and a compensation method using the same. The compensator and method compensate for distortion of output voltages resulting from dead time of a PWM inverter, which drives the PMSM, and nonlinear operation characteristics of semiconductor switches for power. The method includes the steps of acquiring two-phase stationary coordinate unit back-electromotive force vector from information regarding rotor position; acquiring an increment of the rotor position with regard to a sampling period; obtaining a two-phase stationary coordinate flux linkage increment from an increment of a two-phase stationary coordinate current and a PWM inverter output reference voltage; acquiring an output error voltage of the PWM inverter from the unit back-electromotive force vector, the increment of the rotor position, and the flux linkage increment; and adding the error voltage to the synchronously rotating coordinate inverter output reference voltage.

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Description

DEAD-TIME COMPENSATOR AND METHOD FOR PERMANENT MAGNET SYNCHRONOUS DRIVES

Technical Field

[1] The present invention relates to a dead-time compensator for PMSM (Permanent Magnet Synchronous Motor) drives and a compensation method using the same. More particularly, the present invention relates to an apparatus and a method for compensating for distortion of output voltages resulting from dead time of a PWM (Pulse Width Modulation) inverter, which drives the PMSM, and nonlinear characteristics of semiconductor switches for power.

[2]

Background Art

[3] In general, a PWM VSI (Voltage Stiff Inverter) is commonly used for a PMSM drive controller having high-efficiency and high-performance characteristics.

[4] FIG. 1 is a block diagram showing the construction of a conventional PMSM drive controller.

[5] Referring to FIG. 1, the PMSM drive controller includes an encoder 50 for detecting the electrical position

θ_r

of the rotor of the PMSM; a three-phase stationary/two-phase stationary coordinate converter 71 for detecting three-phase stationary coordinate currents

i_{as}

and

i_{bs}

applied to the PMSM (detected by a current detector 72) and converting them into a two-phase stationary coordinate current

$\bar{i}_s^s$

; a stationary/synchronous rotating coordinate converter 70 for converting the two-phase stationary coordinate current

$\bar{i}_s^s$

into synchronously rotating coordinate current

$\bar{i}_s^e$

; a current controller 10 for receiving an input of current obtained by subtracting the converted synchronously rotating coordinate current

$\bar{i}_s^e$

from a synchronously rotating coordinate reference current signal

$\bar{i}_s^{e*}$

(by a subtracter 11) and outputting synchronously rotating coordinate reference voltage

$\bar{v}_{fb}^{e*}$

; a decoupling control term generator 60 for calculating a decoupling voltage

$\bar{v}_{ff}^{e'}$

for feed-forward compensation of back-electromotive force induced on the q-axis by the permanent magnet and electromotive force induced by coupling between d,q-axis currents resulting from stator inductance by using the synchronously rotating co-ordinate current

$\bar{i}_s^e$

and the electrical angular velocity

ω_r

; a synchronously rotating/stationary coordinate converter 20 for converting a synchronously rotating coordinate reference voltage

$\bar{v}_s^{e*}$

of the PWM inverter, which is obtained by adding a decoupling voltage

$\bar{v}_{ff}^{e'}$

to the synchronously rotating coordinate reference voltage

$\bar{v}_{fb}^{e*}$

, into a two-phase stationary coordinate reference voltage

$\bar{v}_s^{s*}$

of the PWM inverter; a PWM signal generator 30 for creating a three-phase voltage reference signal

$v_{an}^*, v_{bn}^*, v_{cn}^*$

according to the reference voltage

$\bar{v}_s^{s*}$

and transmitting it to the PWM inverter 40; and a PWM inverter 40 for turning on and off semiconductor switch devices for power according to the three-phase voltage reference signal

$v_{an}^*, v_{bn}^*, v_{cn}^*$

to apply electricity to the PMSM.

[6] FIG. 2 is a block diagram briefly showing decoupled current control of the PMSM with the output voltage error caused by nonlinear characteristics of the PWM inverter in the synchronously rotating coordinate.

[7] It is clear from FIGs. 1 and 2 that, although the decoupling voltage

$$\bar{v}_{ff}^{e'}$$

generated by the PMSM is subjected to feed-forward compensation, distortion resulting from dead time of the PWM inverter 40 and nonlinear characteristics of switching devices are not compensated for.

[8] In general, the above-mentioned PWM-VSI 40 adopts high-frequency switching devices to increase the fundamental component of the output waveform and to decrease the harmonic component. In addition, the PWM-VSI 40 gives switching signals delay time (also called dead time) to prevent a short circuit when semi-conductor switching devices for power, which consist of bridge circuits, are turned on and off, respectively. The semiconductor switching devices for power have nonlinear characteristics, because the switching delay time and the size of voltage drop of switches and freewheeling diodes vary depending on the motor operating conditions and environments (e.g. load condition, temperature environment).

[9] However, the above-mentioned dead time and nonlinear characteristics of the inverter involve distortion of the size of the three-phase stationary coordinate output voltage of the PWM-VSI and harmonic distortion (so-called dead-time effect). This results in distortion of current supplied to the motor and pulsation of torque. Such distortion of the inverter output voltage seriously degrades a device for estimating the flux, rotor position, or rotor velocity when applied to control the motor drive for the purpose of high-performance of position sensorless control. This may decrease the overall control performance of the PMSM drive controller.

[10] Conventional technologies for compensating for the dead-time effect include a method based on the average error value of the inverter output voltage, disclosed in "On-line Dead-Time Compensation Technique for Open-Loop PWM-VSI Drives," IEEE Trans. Power Electronics, vol. 14, pp. 683-689, July 1999, and a method based on PWM pulses, disclosed in "Pulse-Based Dead-Time Compensation for PWM Voltage Inverters," IEEE Trans. Industrial Electronics, vol. 44, pp. 191-197, Apr. 1997, as well as other compensation technologies derived from these methods.

[11] The above-mentioned compensation methods rely on polarity of the motor phase current, and proper compensation is possible only when polarity of current is correctly detected. However, in the vicinity of zero-crossing of current, there exists high-frequency current pulsation resulting from high-speed PWM switching, and accurate detection of current polarity requires complicated hardware or software configuration.

Furthermore, the conventional technologies cannot accurately consider nonlinear factors of the inverter, such as the switching delay time depending on the motor operation condition, the varying voltage drop of switches and freewheeling diodes, etc. In other words, the dead time cannot be compensated for accurately.

[12]

Disclosure of Invention

Technical Problem

[13] Therefore, the present invention has been made in view of the above-mentioned problems, and the present invention provides a dead time compensator for PMSM drives, which can compensate for current distortion resulting from dead time of the inverter and nonlinear characteristics by using a simple configuration so that easy application is guaranteed, as well as a compensation method using the same.

[14]

Technical Solution

[15] In accordance with an aspect of the present invention, there is provided a method for compensating for dead time of a PMSM drive controller to compensate for an output error of a PWM inverter (40) resulting from dead time and nonlinear characteristics of the PWM inverter (40), the method including the steps of acquiring unit back-electromotive force vector

$\bar{e}_s^s$

of two-phase stationary coordinate from information regarding rotor position

θ_r

of PMSM (S210); acquiring an increment

$\Delta\theta_r$

of the rotor position

θ_r

of the PMSM with regard to a unit sampling period

T_s

(S220); calculating an increment

$\Delta i_{ds}^s,\ \Delta i_{qs}^s$

of a two-phase stationary coordinate current

$\bar{i}_s^s$

applied to the PMSM with regard to the unit sampling period

T_s

and acquiring a two-phase stationary coordinate flux linkage increment

$\Delta\bar{\lambda}_s$

by using the calculated current increment

$\Delta i_{ds}^{s},\ \Delta i_{qs}^{s}$

and a two-phase stationary coordinate reference voltage

$\bar{v}_{s}^{s*}$

of the PWM inverter (S230); acquiring an output error voltage

$\hat{\bar{v}}_{d,s}^{e}$

of the PWM inverter (40) from the acquired unit back-electromotive force vector

$\bar{e}_{s}^{s}$

, the increment

$\Delta\theta_{r}$

of the rotor position

θ_{r}

, and the flux linkage increment

$\Delta\bar{\lambda}_{s}$

(S240); and adding the error voltage

$\hat{\bar{v}}_{d,s}^{e}$

to the synchronously rotating coordinate reference voltage

$\bar{v}_{s}^{e*}$

of the PWM inverter(S260).

[16] According to another aspect of the present invention, there is provided a dead time compensator coupled to a PMSM drive controller to compensate for an output error of a PWM inverter (40) resulting from dead time and nonlinear characteristics of the PWM inverter (40), the dead time compensator including an error voltage estimator (100) including a unit back-electromotive force vector calculator (120) for receiving an input of a rotor electrical position

θ_{r}

to acquire two-phase stationary coordinate unit back-electromotive force vector

$\bar{e}_{s}^{s}$

, a rotor position increment calculator (130) for receiving an input of the rotor electrical position

θ_{r}

to acquire a rotor position increment

$\Delta\theta_{r}$

with regard to a unit sampling period

T_{s}

, a flux linkage increment calculator (110) for calculating an increment

Δi_{ds}^{s}, Δi_{qs}^{s}

of a two-phase stationary coordinate current

$\bar{i}_{s}^{s}$

applied to the PMSM with regard to the unit sampling period

T_s

and acquiring a two-phase stationary coordinate flux linkage increment

$\Delta\bar{\lambda}_s$

from the current increment

Δi_{ds}^{s}, Δi_{qs}^{s}

and a two-phase stationary coordinate reference voltage

$\bar{v}_{s}^{s*}$

of the inverter, an inverter error voltage calculator (140) for receiving the unit back-electromotive force vector

$\bar{e}_{s}^{s}$

, the rotor position increment

$\Delta\theta_r$

, and the flux linkage increment

$\Delta\bar{\lambda}_s$

acquired by the components (110, 120, and 130), respectively, to acquire an error voltage

$\hat{\bar{v}}_{d,s}^{e}$

, and a low pass filter (150) for passing only a low band signal of the acquired error voltage

$\hat{\bar{v}}_{d,s}^{e}$

and outputting a filter error voltage

$\hat{\bar{v}}_{d,s}^{e'}$

; and an adder (22) for adding the filtered error voltage

$\hat{\bar{v}}_{d,s}^{e'}$

to the synchronously rotating coordinate reference voltage

$\bar{v}_{s}^{e*}$

of PWM inverter.

[17]

Advantageous Effects

[18] The present invention is advantageous in that distorted current is compensated for not by relying on polarity of the phase current of the motor, but by measured current

supplied to the PMSM and its rotor electric position. This requires no complicated construction for measuring current data in the zero-crossing range.

[19] Furthermore, estimation of errors of the inverter output voltage makes use of a phase current value, which sufficiently reflects dead time and nonlinear characteristics of the inverter. This efficiently compensates for effects of dead time and nonlinear characteristics of the inverter.

[20]

Brief Description of Drawings

[21] The foregoing and other objects, features and advantages of the present invention will become more apparent from the following detailed description when taken in conjunction with the accompanying drawings in which:

[22] FIG. 1 is a block diagram showing the construction of a conventional PMSM drive controller;

[23] FIG. 2 is a block diagram briefly showing decoupled current control loop of PMSM with the output voltage error caused by nonlinear characteristics of the PWM inverter;

[24] FIG. 3 is a block diagram showing the construction of a dead-time compensator according to an embodiment of the present invention, particularly its error voltage estimator 100;

[25] FIG. 4 is a block diagram showing the construction of a PMSM drive including a dead-time compensator according to an embodiment of the present invention;

[26] FIG. 5 is a flowchart showing a method for compensating for dead time according to an embodiment of the present invention; and

[27] FIG. 6 shows a detailed experiment result obtained by applying an embodiment of the present invention.

[28]

Best Mode for Carrying out the Invention

[29] Hereinafter, exemplary embodiments of the present invention will be described with reference to the accompanying drawings.

[30] Referring to FIG. 2, which is a block diagram briefly showing decoupled current control loop according to the prior art, a voltage equation of the PMSM is expressed by using a synchronous reference frame as defined by the following Equation 1. The voltage equation has a d-axis current (flux-related current signal) and a q-axis current (torque-related current signal) as its input, and defines the d,q-axis voltage. Technical information regarding this is obvious to those skilled in the art, and will be described briefly.

[31]
$$\overline{v}_s^{e*} = \begin{bmatrix} v_{ds}^{e*} \\ v_{qs}^{e*} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_r L_s \\ \omega_r L_s & R_s + L_s p \end{bmatrix} \begin{bmatrix} i_{ds}^e \\ i_{qs}^e \end{bmatrix} + \begin{bmatrix} 0 \\ p\theta_r \lambda_m \end{bmatrix} + \begin{bmatrix} v_{d,ds}^e \\ v_{d,qs}^e \end{bmatrix}$$

...(1)

[32] wherein, superscript 'e' denotes a value on a synchronously rotating coordinate system, and respective physical quantities of FIG. 2 and Equation 1 are defined as follows:

[33]
$$\bar{v}_s^{e*} = \begin{bmatrix} v_{ds}^{e*} \\ v_{qs}^{e*} \end{bmatrix}$$

: reference voltage vector of the PWM inverter (d-axis voltage, q-axis voltage)

[34] $\bar{i}_s^{e*}$

: reference current vector of the stator

[35]
$$\bar{i}_s^{e} = \begin{bmatrix} i_{ds}^{e} \\ i_{qs}^{e} \end{bmatrix}$$

: current vector of the stator (d-axis current, q-axis current)

[36] p: differential operator

[37] L_s, R_s

: stator inductance, resistance

[38] θ_r, ω_r

: rotor electrical position and angular velocity

[39] λ_m

: rotor flux linkage

[40]
$$\bar{v}_{d,s}^{e} = \begin{bmatrix} v_{d,ds}^{e} \\ v_{d,qs}^{e} \end{bmatrix}$$

: error voltage vector of inverter output voltage resulting from dead time (d-axis voltage, q-axis voltage)

[41]
$$\bar{E}_s^{e} = \begin{bmatrix} 0 \\ \omega_r \lambda_m \end{bmatrix}$$

: back-electromotive force vector

[42] Referring to FIG. 2, in the PWM inverter 40, a distorted error voltage

$\bar{v}_{d,s}^{e}$

occurs due to dead time and nonlinear operation characteristics of the inverter, and a feed-forward compensation decoupling control voltage

$\bar{v}_{ff}^{e'}$

is added to the output voltage

$\bar{v}_{fb}^{e*}$

of the current controller 10 to compensate for a coupling term resulting from the rotor angular velocity

ω_r

and phase current

$\bar{i}_s^e$

, which can confirmed from the voltage equation of each axis in Equation 1. As a result, vector control performance of each axis current controller 10 is obtained.

[43] The present invention aims to compensate for the inverter's output error voltage

$\bar{v}_{d,s}^e$

resulting from dead time of the PWM inverter 40 and its nonlinear operation characteristics. To this end, error voltage

$\bar{v}_{d,s}^e$

is estimated and is used to compensate for the reference voltage vector

$\bar{v}_s^{e*}$

outputted by the PWM inverter.

[44] Prior to describing an embodiment of the present invention with reference to FIGs. 3 and 4, an equation for estimating the error voltage

$\bar{v}_{d,s}^e$

according to an embodiment of the present invention will be described in detail.

[45] The error voltage

$\bar{v}_{d,s}^e$

depends on the electrical position

θ_r

of the rotor, and the motor voltage equation for estimating the error voltage

$\bar{v}_{d,s}^e$

must be expressed as a two-phase stationary coordinate voltage equation (or stationary model equation) including sufficient information regarding the rotor position

θ_r

. The stationary model equation can be obtained from Park s transformation of the above-mentioned Equation 1, and is defined by the following Equation 2.

[46]
$$\bar{v}_s^{s*} = P^{-1}\bar{v}_s^{e*}$$
$$= \begin{bmatrix} v_{ds}^{s*} \\ v_{qs}^{s*} \end{bmatrix} = \begin{bmatrix} R_s + L_s p & 0 \\ 0 & R_s + L_s p \end{bmatrix} \begin{bmatrix} i_{ds}^s \\ i_{qs}^s \end{bmatrix} + p\theta_r \lambda_m \begin{bmatrix} e_{ds}^s \\ e_{qs}^s \end{bmatrix} + \begin{bmatrix} v_{d,ds}^e e_{qs}^s + v_{d,qs}^e e_{ds}^s \\ -v_{d,ds}^e e_{ds}^s + v_{d,qs}^e e_{qs}^s \end{bmatrix}$$

...(2)

[47] wherein, superscript 's' denotes a stationary coordinate value, 'P' denotes a differential

operator, and 'P' refers to a Park matrix for converting a stationary coordinate variables into a synchronous rotary coordinate variables. The matrix P and its inverse matrix are defined by the following Equation 3.

[48]
$$P=\begin{bmatrix}\cos\theta_r & \sin\theta_r\\ -\sin\theta_r & \cos\theta_r\end{bmatrix},\ P^{-1}=\begin{bmatrix}\cos\theta_r & -\sin\theta_r\\ \sin\theta_r & \cos\theta_r\end{bmatrix}$$

...(3)

[49] Respective physical quantities of Equation 2 are defined by using the Park matrix P as follows:

[50]
$$\bar{v}_s^{s*}=\begin{bmatrix}v_{ds}^{s*}\\ v_{qs}^{s*}\end{bmatrix}=P^{-1}\begin{bmatrix}v_{ds}^{e*}\\ v_{qs}^{e*}\end{bmatrix}$$

: two-phase stationary coordinate reference voltage vector of the PWM inverter (d-axis voltage, q-axis voltage)

[51]
$$\bar{i}_s^{s}=\begin{bmatrix}i_{ds}^{s}\\ i_{qs}^{s}\end{bmatrix}=P^{-1}\bar{i}_s^{e}$$

: two-phase stationary coordinate stator current vector (d-axis current, q-axis current)

[52]
$$\bar{e}_s^{s}=\begin{bmatrix}e_{ds}^{s}\\ e_{qs}^{s}\end{bmatrix}=\begin{bmatrix}-\sin\theta_r\\ \cos\theta_r\end{bmatrix}$$

: unit back-electromotive force vector regarding

θ_r

[53] Furthermore, assuming a discrete system having a sufficiently large sample frequency, Equation 2 gives a difference equation, which can be used to express the increment of stator flux linkage as d-axis and q-axis components, as defined by the following Equations 4 and 5.

[54]
$$\Delta\bar{\lambda}_s=\begin{bmatrix}\Delta\lambda_{ds}\\ \Delta\lambda_{qs}\end{bmatrix}=\begin{bmatrix}(v_{ds}^{s*}-R_s i_{ds}^{s})T_s-L_s\Delta i_{ds}^{s}\\ (v_{qs}^{s*}-R_s i_{qs}^{s})T_s-L_s\Delta i_{qs}^{s}\end{bmatrix}$$
$$=\begin{bmatrix}(\Delta\theta_r\lambda_m+T_s\hat{v}_{d,qs}^{e})e_{ds}^{s}+T_s\hat{v}_{d,ds}^{e}e_{qs}^{s}\\ (\Delta\theta_r\lambda_m+T_s\hat{v}_{d,qs}^{e})e_{qs}^{s}-T_s\hat{v}_{d,ds}^{e}e_{ds}^{s}\end{bmatrix}$$

...(4)

[55]
$$\begin{bmatrix}\Delta\lambda_{ds}\\ \Delta\lambda_{qs}\end{bmatrix}=\begin{bmatrix}(\Delta\theta_r\lambda_m+T_s\hat{v}_{d,qs}^{e})e_{ds}^{s}+T_s\hat{v}_{d,ds}^{e}e_{qs}^{s}\\ (\Delta\theta_r\lambda_m+T_s\hat{v}_{d,qs}^{e})e_{qs}^{s}-T_s\hat{v}_{d,ds}^{e}e_{ds}^{s}\end{bmatrix}$$

...(5)

[56] wherein,

T_s

is a sampling period, Δ is an operator indicating the increment of a corresponding physical quantity occurring for the unit sampling frequency

T_s

, and

$\hat{v}^e_{d,ds}$

and

$\hat{v}^e_{d,qs}$

are error estimation values of the inverter output voltage on the synchronous rotary co-ordinate-based d-axis and q-axis.

[57] A process of solving the simultaneous equation of Equation 5 to obtain an equation of

$\hat{v}^e_{d,ds}$

and

$\hat{v}^e_{d,qs}$

is as follows. The d-axis component is multiplied by

e^e_{qs}

, and the q-axis component is multiplied by

e^e_{ds}

. Then, the q-axis component is subtracted from the d-axis component, and the following Equation 6 is obtained. In addition, the d-axis component of Equation 5 is multiplied by

e^e_{ds}

, and the q-axis component is multiplied by

e^e_{qs}

. Then, the q-axis component is added to the d-axis component, and the following Equation 7 is obtained.

[58] $$T_s\hat{v}^e_{d,ds}({e^s_{ds}}^2 + {e^s_{qs}}^2) = \Delta\lambda_{ds}e^s_{qs} - \Delta\lambda_{qs}e^s_{ds}$$

...(6)

[59] $$(\Delta\theta_r\lambda_m + T_s\hat{v}^e_{d,qs})({e^s_{ds}}^2 + {e^s_{qs}}^2) = \Delta\lambda_{ds}e^s_{ds} + \Delta\lambda_{qs}e^s_{qs}$$

...(7)

[60] Finally, by using

$${e^s_{ds}}^2 + {e^s_{qs}}^2 = \sin\theta_r^2 + \cos_r^2 = 1$$

, Equations 6 and 7 are arranged with regard to the estimated error voltage, and the following Equation 8 is obtained.

[61]

$$\hat{\bar{v}}_{d,s}^{e} = \begin{bmatrix} \hat{v}_{d,ds}^{e} \\ \hat{v}_{d,qs}^{e} \end{bmatrix} = \begin{bmatrix} (\Delta\lambda_{ds} e_{qs}^{s} - \Delta\lambda_{qs} e_{ds}^{s}) / T_s \\ (\Delta\lambda_{ds} e_{ds}^{s} + \Delta\lambda_{qs} e_{qs}^{s} - \Delta\theta_r \lambda_m) / T_s \end{bmatrix}$$
$$= \begin{bmatrix} \Delta\bar{\lambda}_s \times \bar{e}_s^{s} / T_s \\ (\Delta\bar{\lambda}_s \cdot \bar{e}_s^{s} - \Delta\theta_r \lambda_m) / T_s \end{bmatrix}$$

...(8)

[62] wherein, vector operator *x* refers to outer product, and vector operator ·refers to inner product.

[63] In order to prevent measurement noise, which is generated when current is detected by the current detector 72, from being amplified and outputted in the process of calculating the error voltage

$\hat{\bar{v}}_{d,s}^{e}$

, the calculated error voltage

$\hat{\bar{v}}_{d,s}^{e}$

is preferably filtered by a low pass filter to obtain a compensation voltage, as defined by the following Equation 9, so that dead time and inverter nonlinearity can be compensated for.

[64] $\hat{\bar{v}}_{d,s}^{e'} = LPF(\hat{\bar{v}}_{d,s}^{e})$

...(9)

[65] A dead-time compensator for a PMSM drive, which includes the low pass filter, and a compensation method using the same will now be described with reference to FIGs. 3 and 5 in connection with the above-mentioned equation for estimating error voltage

$\bar{v}_{d,s}^{e}$

(Equation 8) according to the present invention.

[66] FIG. 3 is a block diagram showing the construction of a dead-time compensator according to an embodiment of the present invention, particularly its error voltage estimator 100.

[67] FIG. 4 is a block diagram showing the construction of a PMSM drive controller including a dead-time compensator according to an embodiment of the present invention.

[68] FIG. 5 is a flowchart of a method for compensating for dead time according to an embodiment of the present invention.

[69] Referring to FIG. 3, the error voltage estimator 100 receives an input of a two-phase stationary coordinate actual measurement stator current

$\bar{i}_s^{s}$

, an inverter output reference voltage

$\bar{v}_s^{s*}$

, and a rotor position

θ_r

, estimates an error voltage

$\bar{v}_{d,s}^{e}$

, subjects it to lower pass filtering, and outputs it. To this end, the error voltage estimator 100 includes a stator flux linkage increment calculator 110 for realizing the above mentioned equation for estimating the error voltage

$\bar{v}_{d,s}^{e}$

(Equation 8), a unit back-electromotive force vector calculator 120, a rotor position increment calculator 130, an inverter error voltage calculator 140, and a low pass filter 150 for removing measurement noise.

[70] Referring to FIG. 4, the dead-time compensator for a PMSM drive according to an embodiment of the present invention includes the error voltage estimator 100, and an adder 22 for adding the filtered error voltage

$\hat{\bar{v}}_{d,s}^{e'}$

, which is outputted by the error voltage estimator 100, to the decoupling control component voltage

$\bar{v}_{ff}^{e'}$

.

[71] This will be described in detail with reference to the above-mentioned Equations 4, 8, and 9.

[72] The unit back-electromotive force vector calculator 120 receives an input of the rotor electrical position

θ_r

and calculates a two-phase stationary coordinate unit back-electromotive force vector (S210).

[73]
$$\bar{e}_s^s = \begin{bmatrix} e_{ds}^s \\ e_{qs}^s \end{bmatrix} = \begin{bmatrix} -\sin\theta_r \\ \cos\theta_r \end{bmatrix}$$

[74] The rotor position increment calculator 130 receives an input of the rotor position

θ_r

and calculates a rotor position increment

$\Delta\theta_r$

with regard to a unit sample period

T_s

(S220).

[75] The flux linkage increment calculator 110 obtains the increment

$\Delta i_{ds}^{s}, \ \Delta i_{qs}^{s}$

of the two-phase stationary coordinate current

$\bar{i}_{s}^{s}$

of stator current applied to the PMSM with regard to the unit sample period

T_s

, and calculates a two-phase stationary coordinate flux linkage increment from the obtained current increment

$\Delta i_{ds}^{s}, \ \Delta i_{qs}^{s}$

and the inverter output reference voltage

$\bar{v}_{s}^{s*}$

, as defined by the following equation (S230).

[76]
$$\Delta\bar{\lambda}_s = \begin{bmatrix} \Delta\lambda_{ds} \\ \Delta\lambda_{qs} \end{bmatrix} = \begin{bmatrix} (v_{ds}^{s*} - R_s i_{ds}^{s})T_s - L_s \Delta i_{ds}^{s} \\ (v_{qs}^{s*} - R_s i_{qs}^{s})T_s - L_s \Delta i_{qs}^{s} \end{bmatrix}$$

[77] The inverter error voltage calculator 140 receives the unit back-electromotive force vector

$\bar{e}_{s}^{s}$

, the rotor position increment

$\Delta\theta_r$

, and the flux linkage increment

$\Delta\bar{\lambda}_s$

, which have been calculated by the above components 110, 120, and 130, respectively, and calculates error voltage

$\hat{\bar{v}}_{d,s}^{e}$

according to the following equation (S240).

[78]
$$\hat{\bar{v}}_{d,s}^{e} = \begin{bmatrix} \hat{v}_{d,ds}^{e} \\ \hat{v}_{d,qs}^{e} \end{bmatrix} = \begin{bmatrix} \Delta\bar{\lambda}_s \times \bar{e}_s^s / T_s \\ (\Delta\bar{\lambda}_s \cdot \bar{e}_s^s - \Delta\theta_r \lambda_m)/T_s \end{bmatrix}$$

[79] The low pass filter 150 solely passes low band signals of the calculated error voltage

$\hat{\bar{v}}_{d,s}^{e}$

, and outputs a filtered error vector

$\hat{\bar{v}}_{d,s}^{e'}$

with noise removed (S250).

[80] The filtered error voltage

$\hat{\bar{v}}_{d,s}^{e'}$

outputted from the low pass filter 150 of the error voltage estimator 100 is added to the decoupling control component voltage

$\bar{v}_{ff}^{e'}$

of the decoupling control term generator 60 the adder 22. In other words, the filtered error vector

$\hat{\bar{v}}_{d,s}^{e'}$

and the decoupling control component voltage

$\bar{v}_{ff}^{e'}$

are added to the synchronously rotating coordinate reference voltage

$\bar{v}_{fb}^{e*}$

by the adder 21, and a synchronously rotating coordinate PWM inverter output reference voltage

$\bar{v}_{s}^{e*}$

(S260).

[81] The synchronously rotating coordinate PWM inverter output reference voltage

$\bar{v}_{s}^{e*}$

created according to an embodiment of the present invention will be described in detail. Back-electromotive force induced on the q-axis by the permanent magnet is

$$\overline{E}_s^e = \begin{bmatrix} 0 \\ \omega_r \lambda_m \end{bmatrix}$$

, and a coupling term including electromotive force caused by coupling between d,q-axis currents due to stator inductance is

$$\begin{bmatrix} -L_s i_{qs}^s \omega_r \\ L_s i_{ds}^s \omega_r \end{bmatrix}$$

. Then, decoupling control component voltage

$\bar{v}_{ff}^{e'}$

becomes

$$\bar{v}_{ff}^{e'} = \begin{bmatrix} -L_s i_{qs}^s \omega_r \\ L_s i_{ds}^s \omega_r \end{bmatrix} + \begin{bmatrix} 0 \\ \lambda_m \omega_r \end{bmatrix}$$

.

[82] As such, the estimated error voltage

$\hat{\bar{v}}_{d,s}^{e'}$

is added to the decoupling control component voltage

$\bar{v}_{ff}^{e'}$

, and the resulting modified decoupling control component voltage

$\overline{v}^{e}_{ff} = \overline{v}^{e'}_{ff} + \hat{\overline{v}}^{e'}_{d,s}$

is added to the output voltage

$\overline{v}^{e*}_{fb}$

of the current controller 10 by the adder 21. As a result, the synchronously rotating coordinate PWM inverter output reference voltage

$\overline{v}^{e*}_{s}$

is given by the following Equation 10.

[83]

$$\overline{v}^{e*}_{s} = \overline{v}^{e*}_{fb} + \overline{v}^{e}_{ff} = \overline{v}^{e*}_{fb} + (\overline{v}^{e'}_{ff} + \hat{\overline{v}}^{e'}_{d,s})$$
$$= \overline{v}^{e*}_{fb} + \begin{bmatrix} -L_s i^s_{qs}\omega_r \\ L_s i^s_{ds}\omega_r \end{bmatrix} + \begin{bmatrix} 0 \\ \lambda_m \omega_r \end{bmatrix} + \begin{bmatrix} \hat{v}^{e'}_{d,ds} \\ \hat{v}^{e'}_{d,qs} \end{bmatrix}$$

...(10)

[84] In addition, the PWM inverter output reference voltage

$\overline{v}^{e*}_{s}$

defined by Equation 10 is converted into a two-phase stationary coordinate reference voltage

$\overline{v}^{s*}_{s}$

by the rotary/stationary coordinate converter 20, and is inputted to the PWM signal generator 30. As a result, a three-phase inverter output reference voltage is outputted. This compensates for the error voltage

$\overline{v}^{e}_{d,s}$

generated by dead time resulting from switching operation of the PWM inverter 40 and the nonlinear operation characteristics.

[85] It is to be noted that, although measurement of rotor position

θ_r

by the encoder 50 has been assumed with regard to FIGs. 1 and 3, the present invention is also applicable to a sensorless drive controller having no encoder 50. Furthermore, the drive controller, to which the present invention is applicable, is not limited to the PMSM drive controller shown in FIG. 1. As described with regard to an embodiment of present invention, a two-phase stationary coordinate actual measurement current

$\overline{i}^{s}_{s}$

, an inverter output reference voltage

$\overline{v}^{s*}_{s}$

, and a rotor position

θ_r

are received as an input to estimate an error voltage

$\overline{v}_{d,s}^{e}$

, which is added to the synchronously rotating coordinate stator reference voltage

$\overline{v}_{s}^{e*}$

.

[86] FIG. 6 shows a detailed experiment result obtained by applying an embodiment of the present invention.

[87] Particularly, FIGs. 6a and 6b show experiment results before and after dead time compensation, respectively. The experiment conditions are as follows: the PMSM has a rating of 750W, dc-link voltage supplied to the inverter is 310V, the pulse period of the PWM is 66μs, dead time is 3μs, stator current is 3A, rotor velocity is 200r/min (10Hz, electrically), and the sample period for compensation is 33μs.

[88] It is clear from FIG. 6a that the stationary coordinate dq-axis current has a hexagonal shape due to distortion caused by dead time, as shown as x-y plot, and serious ripples occur in the a-phase current and in the synchronous rotary coordinate-based d-axis and q-axis currents. The result of analysis of the frequency component of the a-phase current distorted by the ripple component shows that the 5^{th} and 7^{th} harmonic components appear more markedly than the fundamental component.

[89] It is clear from FIG. 6b, which shows a state after dead time compensation, that the stationary coordinate dq-axis currents have a sinusoidal shape as shown as x-y plot, and the ripple component of the a-phase current and that of the synchronously rotating coordinate d-axis and q-axis currents have decreased substantially compared with FIG. 6a. The result of analysis of the a-phase current frequency component shows that the 5^{th} and 7^{th} harmonic components have decreased by about 20dB.

[90] FIG. 6c shows a synchronously rotating coordinate distorted voltage measurement estimated by the error voltage estimator 100. It is clear from FIG. 6c that the size of dq-axis error voltages caused by distortion is about 20V. The dq-axis error voltages are theoretically calculated as 19.5V according to the prior art disclosed in "On-Line Dead-Time Compensation Technique for Open-Loop PWM-VSI Drives", IEEE Trans. Power Electronics, vol. 14, pp. 683-689, July 1999. This confirms that the error voltage estimated by the present invention is very close to the theoretical value.

[91] Although several exemplary embodiments of the present invention have been described for illustrative purposes, those skilled in the art will appreciate that various modifications, additions and substitutions are possible, without departing from the scope and spirit of the invention as disclosed in the accompanying claims.

[92]

Claims

[1] A method for compensating for dead time of a PMSM drive to compensate for an output error of a PWM inverter (40) resulting from dead time and nonlinear operation characteristics of the PWM inverter (40), the method comprising the steps of:
acquiring two-phase stationary coordinate unit back-electromotive force vector
$\bar{e}_s^s$
from information regarding rotor position
θ_r
of a PMSM (S210);
acquiring an increment
$\Delta\theta_r$
of the rotor position
θ_r
of the PMSM with regard to a unit sampling period
T_s
(S220);
calculating an increment
$\Delta i_{ds}^s,\ \Delta i_{qs}^s$
of a two-phase stationary coordinate current
$\bar{i}_s^s$
applied to the PMSM with regard to the unit sampling period
T_s
and acquiring a two-phase stationary coordinate flux linkage increment
$\Delta\bar{\lambda}_s$
by using the calculated current increment
$\Delta i_{ds}^s,\ \Delta i_{qs}^s$
and a two-phase stationary coordinate PWM inverter output reference voltage
$\bar{v}_s^{s*}$
(S230);
acquiring an output error voltage
$\hat{\bar{v}}_{d,s}^e$
of the PWM inverter (40) from the acquired unit back-electromotive force vector
$\bar{e}_s^s$
, the increment

$\Delta\theta_r$

of the rotor position

θ_r

, and the flux linkage increment

$\Delta\bar{\lambda}_s$

(S240); and

adding the error voltage

$\hat{\bar{v}}^e_{d,s}$

to the synchronously rotating coordinate PWM inverter output reference voltage

$\bar{v}^{e*}_s$

(S260).

[2] The method as claimed in claim 1, further comprising a step of filtering the output error voltage

$\hat{\bar{v}}^e_{d,s}$

of the PWM inverter (40) acquired in step S240 by a low pass filter (150) and conducting step S260 by using the filtered output error voltage

$\hat{\bar{v}}^{e'}_{d,s}$

(S250).

[3] The method as claimed in claim 1, wherein the two-phase stationary coordinate unit back-electromotive force vector

$\bar{e}^s_s$

in step S210 is

$$\bar{e}^s_s = \begin{bmatrix} e^s_{ds} \\ e^s_{qs} \end{bmatrix} = \begin{bmatrix} -\sin\theta_r \\ \cos\theta_r \end{bmatrix}$$

, the flux linkage increment

$\Delta\bar{\lambda}_s$

in step 230 is acquired by equation

$$\Delta\bar{\lambda}_s = \begin{bmatrix} \Delta\lambda_{ds} \\ \Delta\lambda_{qs} \end{bmatrix} = \begin{bmatrix} (v^{s*}_{ds} - R_s i^s_{ds})T_s - L_s\Delta i^s_{ds} \\ (v^{s*}_{qs} - R_s i^s_{qs})T_s - L_s\Delta i^s_{qs} \end{bmatrix}$$

, and the output error voltage

$\hat{\bar{v}}^e_{d,s}$

of the PWM inverter (40) in step S240 is acquired by equation

$$\hat{\bar{v}}^e_{d,s} = \begin{bmatrix} \hat{v}^e_{d,ds} \\ \hat{v}^e_{d,qs} \end{bmatrix} = \begin{bmatrix} \Delta\bar{\lambda}_s \times \bar{e}^s_s / T_s \\ (\Delta\bar{\lambda}_s \cdot \bar{e}^s_s - \Delta\theta_r\lambda_m)/T_s \end{bmatrix}$$

.

[4] A dead time compensator coupled to a PMSM drive controller to compensate for an output error of a PWM inverter (40) resulting from dead time and nonlinear operation characteristics of the PWM inverter (40), the dead time compensator comprising:
an error voltage estimator (100) comprising a unit back-electromotive force vector calculator (120) for receiving an input of a rotor electrical position
θ_r
to acquire two-phase stationary coordinate unit back-electromotive force vector
$\bar{e}_s^s$
, a rotor position increment calculator (130) for receiving an input of the rotor electrical position
θ_r
to acquire a rotor position increment
$\Delta\theta_r$
with regard to a unit sampling period
T_s
, a flux linkage increment calculator (110) for calculating an increment
Δi_{ds}^s, Δi_{qs}^s
of a two-phase stationary coordinate current
$\bar{i}_s^s$
of stator current applied to the PMSM with regard to the unit sampling period
T_s
and acquiring a two-phase stationary coordinate flux linkage increment
$\Delta\bar{\lambda}_s$
from the current increment
Δi_{ds}^s, Δi_{qs}^s
and a two-phase stationary coordinate inverter output reference voltage
$\bar{v}_s^{s*}$
, an inverter error voltage calculator (140) for receiving the unit back-electromotive force vector
$\bar{e}_s^s$
, the rotor position increment
$\Delta\theta_r$
, and the flux linkage increment
$\Delta\bar{\lambda}_s$

acquired by the components (110, 120, and 130), respectively, to acquire an error voltage
$\hat{\bar{v}}_{d,s}^{e}$
, and a low pass filter (150) for passing only a low band signal of the acquired error voltage
$\hat{\bar{v}}_{d,s}^{e}$
and outputting a filter error voltage
$\hat{\bar{v}}_{d,s}^{e'}$
; and
an adder (22) for adding the filtered error voltage
$\hat{\bar{v}}_{d,s}^{e'}$
to the synchronously rotating coordinate-based PWM inverter output reference voltage
$\bar{v}_{s}^{e*}$
.

[5] The dead time compensator as claimed in claim 4, wherein the error voltage estimator (100) receives the rotor electric position
θ_r
, the two-phase stationary coordinate current
$\bar{i}_s^s$
, and the inverter output reference voltage
$\bar{v}_s^{s*}$
, acquires the unit back-electromotive force vector
$\bar{e}_s^s$
according to

$$\bar{e}_s^s = \begin{bmatrix} e_{ds}^s \\ e_{qs}^s \end{bmatrix} = \begin{bmatrix} -\sin\theta_r \\ \cos\theta_r \end{bmatrix}$$

, acquires the flux linkage increment
$\Delta\bar{\lambda}_s$
according to

$$\Delta\bar{\lambda}_s = \begin{bmatrix} \Delta\lambda_{ds} \\ \Delta\lambda_{qs} \end{bmatrix} = \begin{bmatrix} (v_{ds}^{s*} - R_s i_{ds}^s)T_s - L_s\Delta i_{ds}^s \\ (v_{qs}^{s*} - R_s i_{qs}^s)T_s - L_s\Delta i_{qs}^s \end{bmatrix}$$

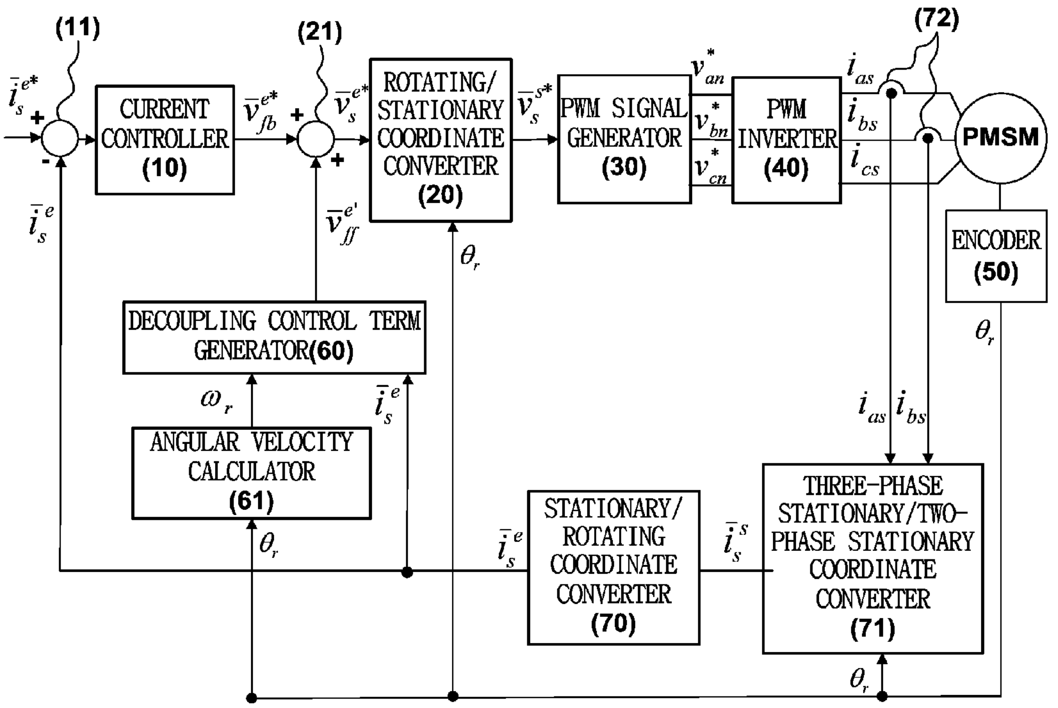
, and acquires the error voltage
$\hat{\bar{v}}_{d,s}^{e}$

according to

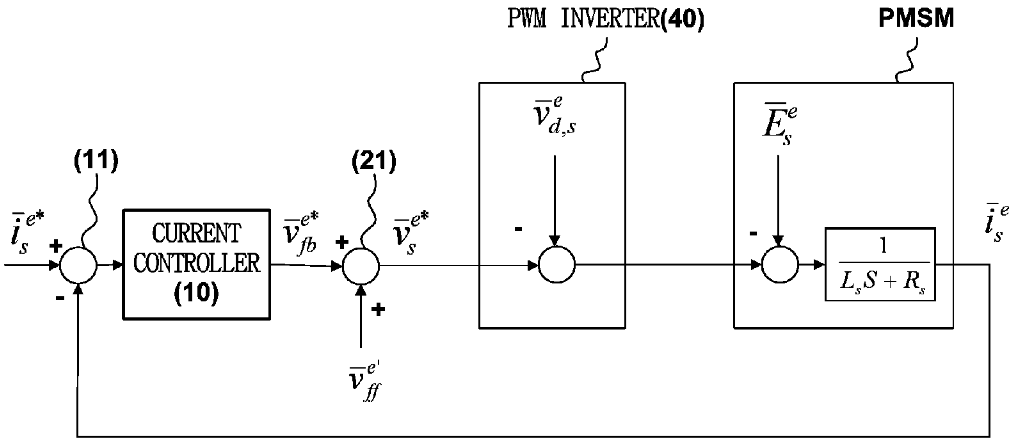
$$\hat{\bar{v}}_{d,s}^{e} = \begin{bmatrix} \tilde{v}_{d,ds}^{e} \\ \tilde{v}_{d,qs}^{e} \end{bmatrix} = \begin{bmatrix} \Delta\bar{\lambda}_{s} \times \bar{e}_{s}^{s} / T_{s} \\ (\Delta\bar{\lambda}_{s} \cdot \bar{e}_{s}^{s} - \Delta\theta_{r}\lambda_{m}) / T_{s} \end{bmatrix}$$

.

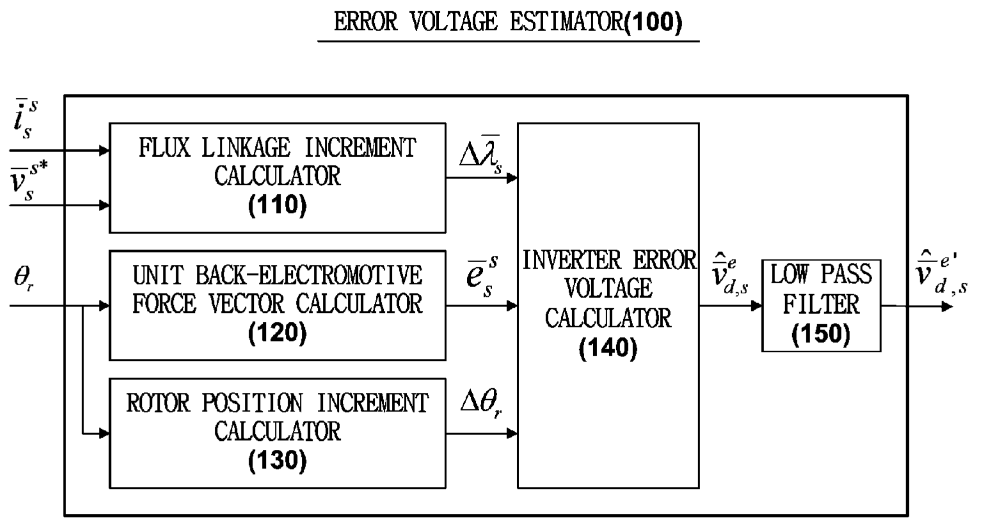
[Fig. 1]



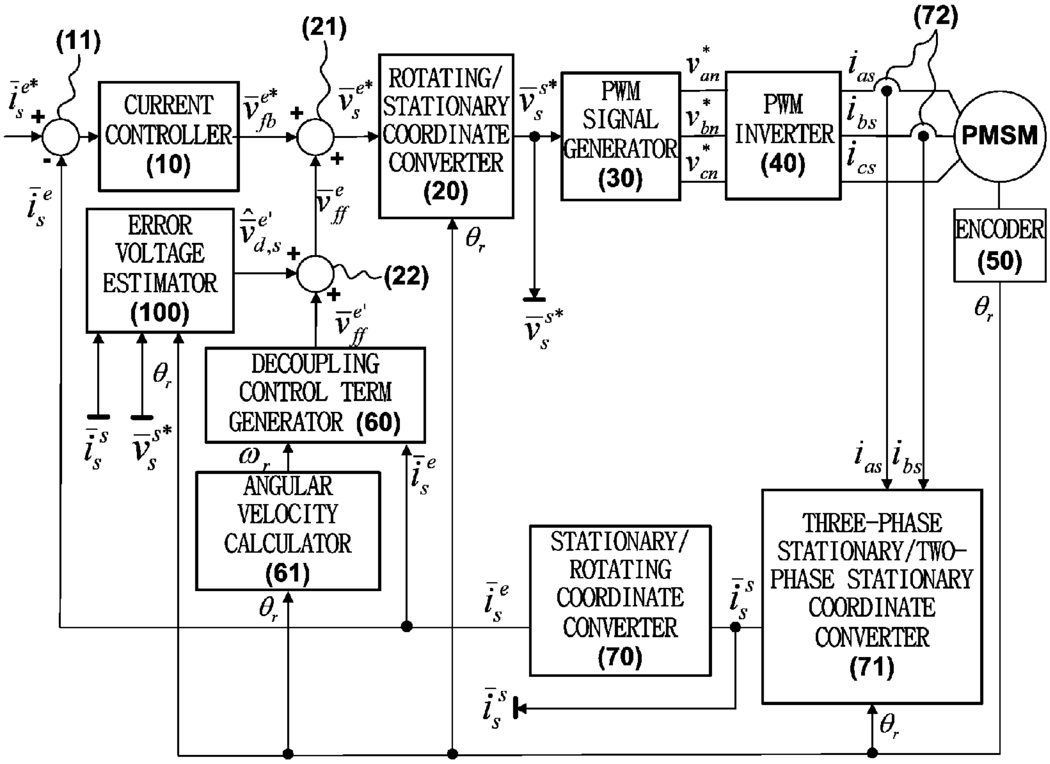
[Fig. 2]



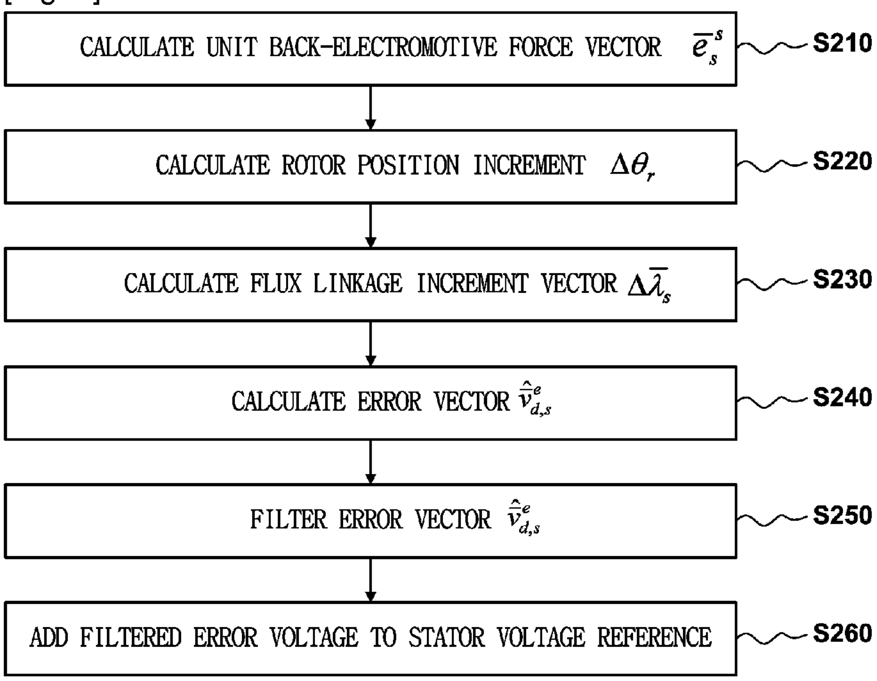
[Fig. 3]



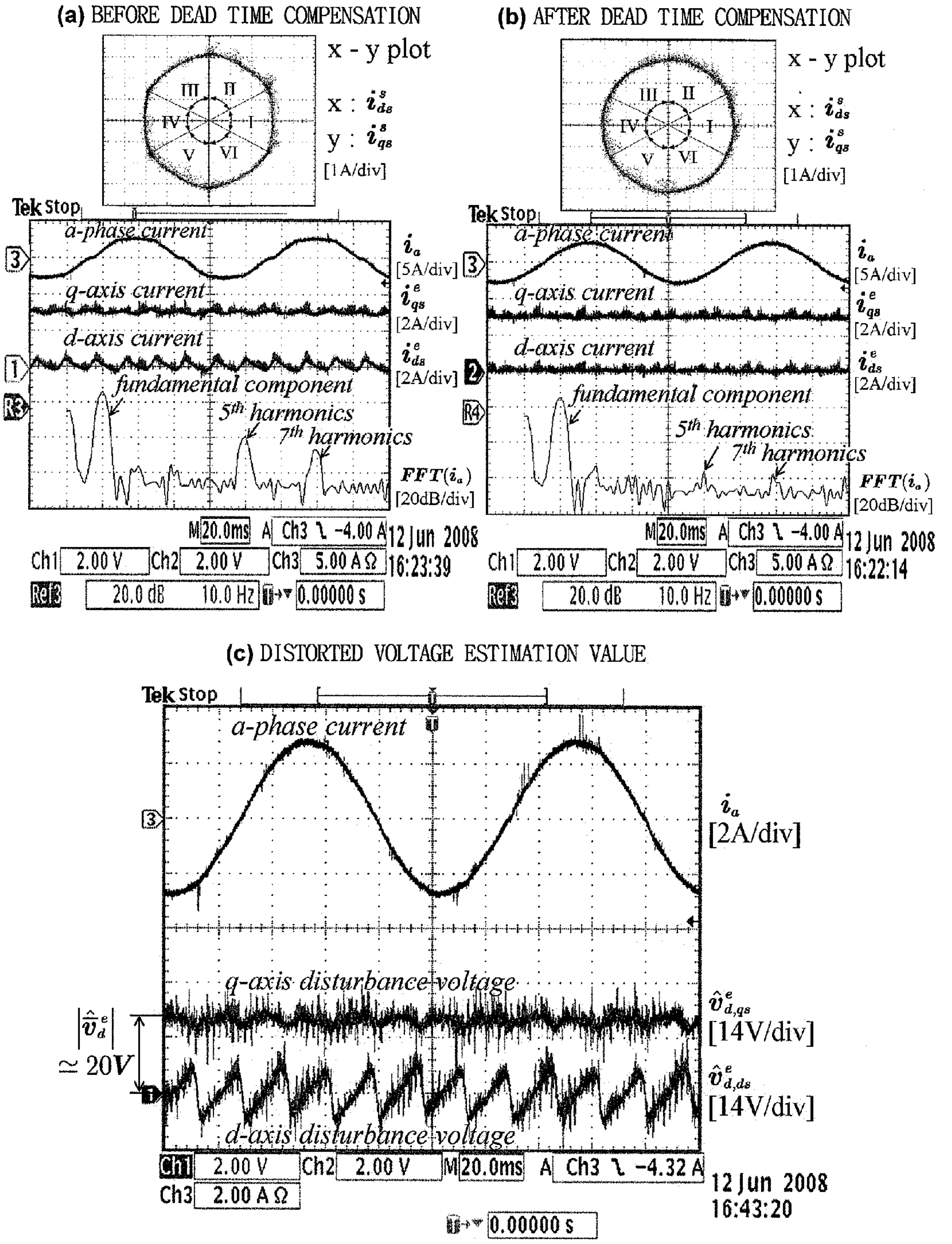
[Fig. 4]


(11)
(21)
(72)
CURRENT CONTROLLER (10)
ROTATING/ STATIONARY COORDINATE CONVERTER (20)
PWM SIGNAL GENERATOR (30)
PWM INVERTER (40)
PMSM
ENCODER (50)
ERROR VOLTAGE ESTIMATOR (100)
(22)
DECOUPLING CONTROL TERM GENERATOR (60)
ANGULAR VELOCITY CALCULATOR (61)
STATIONARY/ ROTATING COORDINATE CONVERTER (70)
THREE-PHASE STATIONARY/TWO-PHASE STATIONARY COORDINATE CONVERTER (71)

[Fig. 5]


CALCULATE UNIT BACK-ELECTROMOTIVE FORCE VECTOR $\bar{e}_s^s$
S210
CALCULATE ROTOR POSITION INCREMENT $\Delta\theta_r$
S220
CALCULATE FLUX LINKAGE INCREMENT VECTOR $\Delta\bar{\lambda}_s$
S230
CALCULATE ERROR VECTOR $\hat{\bar{v}}_{d,s}^e$
S240
FILTER ERROR VECTOR $\hat{\bar{v}}_{d,s}^e$
S250
ADD FILTERED ERROR VOLTAGE TO STATOR VOLTAGE REFERENCE
S260

[Fig. 6]


(a) BEFORE DEAD TIME COMPENSATION
x - y plot
x : i_{ds}^{s}
y : i_{qs}^{s}
[1A/div]
a-phase current
i_a [5A/div]
q-axis current
i_{qs}^{e} [2A/div]
d-axis current
i_{ds}^{e} [2A/div]
fundamental component
5th harmonics
7th harmonics
FFT(i_a) [20dB/div]
12 Jun 2008
16:23:39
(b) AFTER DEAD TIME COMPENSATION
x - y plot
x : i_{ds}^{s}
y : i_{qs}^{s}
[1A/div]
a-phase current
i_a [5A/div]
q-axis current
i_{qs}^{e} [2A/div]
d-axis current
i_{ds}^{e} [2A/div]
fundamental component
5th harmonics
7th harmonics
FFT(i_a) [20dB/div]
12 Jun 2008
16:22:14
(c) DISTORTED VOLTAGE ESTIMATION VALUE
a-phase current
i_a [2A/div]
q-axis disturbance voltage
$\hat{v}_{d,qs}^{e}$ [14V/div]
$|\hat{\bar{v}}_{d}^{e}| \simeq 20V$
$\hat{v}_{d,ds}^{e}$ [14V/div]
d-axis disturbance voltage
12 Jun 2008
16:43:20

INTERNATIONAL SEARCH REPORT

International application No.
PCT/KR2008/005275

A. CLASSIFICATION OF SUBJECT MATTER

H02P 27/08(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC : H02P 27/08, 7/63, 23/00, 25/00, 27/00, 27/04, H02M 7/00, 7/48

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean Utility Models and applications for Utility Models since 1975
Japanese Utility Models and applications for Utility Models since 1975

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKIPASS(KIPO internal) & keywords : dead, time, compensator, motor

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	KR 10-1999-0062203 A (LG IND. SYSTEMS CO., LTD) 26 JULY 1999 See the whole document	1-5
A	KR 10-1996-0012678 A (LG IND. SYSTEMS CO., LTD) 20 APRIL 1996 See the whole document	1-5
A	JP 09-47029 A (AISIN AW CO LTD) 14 FEBRUARY 1997 See the whole document	1-5
A	JP 03-89868 A (MEIDENSHA CORP) 15 APRIL 1991 See the whole document	1-5
A	US 7,230,403 A (Eddy Ying Yin Ho) 12 june 2007 See the whole document	1-5

☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 MAY 2009 (12.05.2009)	**12 MAY 2009 (12.05.2009)**

Name and mailing address of the ISA/KR
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Facsimile No. 82-42-472-7140

Authorized officer
KWAK, Joon Young
Telephone No. 82-42-481-5650

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KR 10-1996-0012678 A	20 APRIL 1996	NONE	
JP 09-47029 A	14 FEBRUARY 1997	JP 3353559	03 DECEMBER 2002
JP 03-89868 A	15 APRIL 1991	NONE	
US 7,230,403 A	12 june 2007	NONE	